Adolescents' thermal comfort and skin temperature compared to young adults

Jeongseo LEE[1] and Chungyoon CHUN[*1]

[1] Department of Interior architecture & Built environment, Yonsei university, Seoul, Korea
* *Corresponding author: chun@yonsei.ac.kr*

ABSTRACT

This study compared thermal comfort and skin temperature of adolescents and young adults to analyze the difference in their thermal responses. In a climate chamber with increasing air temperature from 18 ℃ to 32 ℃, skin temperature was measured at seven body parts with survey responses. As a result, the indoor environment, thermal comfort, and skin temperature have significant correlations, and there were differences between adolescents and adults in their responses. The neutral temperature of adolescents was slightly lower than that of adults. Generally, adolescents have a higher mean skin temperature than adults, and the hand skin temperature of the adult male group changed much sensitively corresponding to their thermal sensation than others. The difference in thermal comfort and related skin temperature implies the need for investigating adolescents as a separate group from adults for accurate thermal comfort prediction. The results are expected to be used for optimal environmental settings for adolescents.

INTRODUCTION

The majority of adolescents spend most of their daytime at school as students, and the indoor environment of the classroom affects students' satisfaction, health, attention, and academic performance (Frontczak, M., et al., 2012; Barrett, P., et al., 2015; Wargocki, P., et al., 2005). Among the four indoor environmental factors, the thermal environment is known to be most influential to building occupants (Humphreys, 2005). To provide appropriate thermal environment, it is crucial to understand the occupants' response and requirements regarding their thermal comfort. Currently, personal comfort models based on physiological signals are being suggested to predict the thermal comfort of individual occupants more precisely (Ghahramani, A., et al., 2018; Sim, S. Y., et al., 2016). Former studies showed that physiological signals such as skin temperature have a significant relationship with occupant's thermal status (Gerrett et al., 2013; Liu et al., 2008; Sim et al., 2016; Yao et al., 2008).

However, most of the studies focused on the case of adults and the physiological signals related to the thermal comfort of adolescent occupants have not been investigated thoroughly. There is a need to examine adolescents as a separate group since their thermal response could be inconsistent with adult occupants. According to the former studies, adolescent students preferred a cooler environment compared to adults and have a lower neutral temperature (Richard de Dear et al., 2015; Ruey Lung Hwang et al., 2009). Also, since they are in the process of physical development, their metabolic rate could be unlike the grown-ups. Thus, the thermal comfort and physiological response of adolescents might have different aspects compared to that of adult occupants.

In this regard, this study aims to investigate the thermal comfort and skin temperature of adolescents and analyze the correlations among the indoor environmental factors, subjective response, and skin temperature through chamber experiments. Also, the comparison between adults and adolescents was conducted to examine the distinctive feature of each group in their thermal responses.

METHODS

A chamber experiment was conducted to inspect the relationship between thermal comfort, indoor temperature, and skin temperature of adolescents. The experiment was carried out in the environmental chamber at Yonsei University from June to September 2020.

Participants

In this experiment, there was a total of 38 participants, and they were divided into two groups based on their age; adolescents aged -12-18 and adults in their 2-30s. In both groups, there were nine male and ten female participants. Table 1 presents the demographic information of participants in this study.

During the experimental session, all participants wore the same clothes, which have Clo value of 0.63(long-sleeved t-shirt, sweatpants, underwear, and socks)and were required to stay in sedentary position reading books for maintaining their metabolic rate at 1.0 MET equally.

Table 1. Participants' demographic information

	Sample size	Age	Height (cm)	Weight (kg)	BMI (kg/m2)
Adolescent Male	9	16.1± 1	174.3 ± 4	65.8 ±4	21.6 ±2
Adolescent Female	10	16.7± 1	162.7 ± 4	54.0 ± 9	20.5 ± 3
Adult Male	9	25.2 ± 1	173.6 ± 6	73.7± 9	24.5± 3
Adult Female	10	26.6 ± 2	161.2 ± 6	58.1 ± 10	22.4 ± 4

Experimental procedure

Prior to the experimental session, participants stayed in the pre-chamber for 30 minutes to stabilized their thermal status. During the pre-session, participants changed their clothes, and the sensors were attached to measure the skin temperature. Then they moved to the main chamber, and the experimental session continued for 90minutes. In the main chamber, during the experimental session, participants were asked to answer the questionnaires every 5-minutes, 19 times, while their skin temperature was measured continuously.

Experimental condition

The pre-chamber maintained a steady and neutral environment at 25℃ air temperature and 50% relative humidity. Meanwhile, in the main chamber, the air temperature and relative humidity were set to increase from 18℃, 40% (set point 1) to 25℃, 50% (set point 2), and then to 32℃, 50% (set point 3). Each set points were designed to expose participants in a broad range of thermal environmental condition. For the first 10 minutes, the air temperature stayed at 18℃ and then increased to 25℃ for 30minutes. Again, from 40 to 50 minutes of the experimental session, the air temperature was maintained at 25℃ for 10minutes, and increased to 32℃ for over 30minutes, and stayed at 32℃ for 10 minutes. Figure 1 shows the desired and measured temperature condition of the environmental chamber during the experimental session.

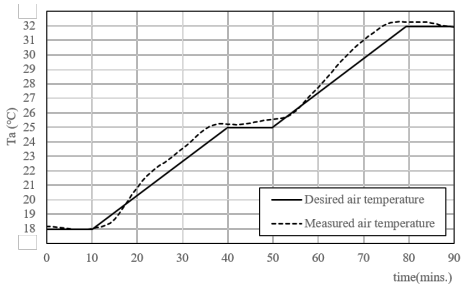

Figure 1. Desired and measured temperature condition of the environmental chamber

Measurement

During the experiment, the air temperature and relative humidity in the climate chamber were recorded in 1-minute interval.

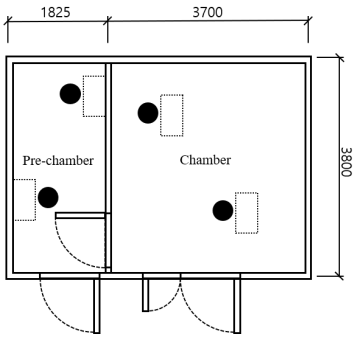

Figure 2. Layout of environmental chamber

Table 2. Summary of the questionnaire

Questionnaire item	Measuring scale (coding)
Thermal sensation vote (TSV)	Very cold (-3)
	Cold (-2)
	Slightly cold (-1)
	Neutral (0)
	Slightly hot (+1)
	Hot (+2)
	Very hot (+3)
Thermal comfort vote (TCV)	Very uncomfortable (-2)
	Uncomfortable (-1)
	Slightly uncomfortable (-0.1)
	Slightly comfortable (0.1)
	Comfortable (1)
Thermal preference	Very comfortable (2)
	Prefer warmer (-1)
	No change (0)
	Prefer cooler (1)

A questionnaire survey was conducted to identify participant's subjective thermal comfort status. It included questions on thermal sensation (TSV, 7-point scale), thermal comfort (TCV, 4-point scale), and thermal preference (3-point scale). Table2 shows the summary of the questionnaire used in this experiment.

The skin temperature of participants was measured continuously during the experiment. TSK 7+1 (Songkitopia, accuracy ±0.1℃, eight-channel, Technox, Inc., Incheon, Korea) were used to collect the local skin temperature at seven parts of the body in 10 seconds interval. The measuring points were head, abdomen, arm, hand, thigh, calf, and foot. A mean skin temperature was calculated using equation 1 of Hardy et al. (1938) for the comprehensive analysis.

Mean skin temperature

$$= 0.07 * (T_{Head}) + 0.35 * (T_{Chest}) + 0.14 * (T_{LowerArm}) + 0.07 * (T_{Foot}) + 0.13 * (T_{LowerLeg}) + 0.19 * (T_{Thigh}) + 0.05 * (T_{Hand}) \quad (1)$$

RESULTS

Thermal comfort and indoor environment

The relationship between the indoor environment and participants' thermal comfort was examined with

Pearson correlation analysis between air temperature, thermal sensation vote and thermal preference. The result shows that the air temperature significantly correlates with thermal sensation vote and thermal preference for both adult and adolescent groups.

Table 3. Correlation of survey responses and air temperature

		Ta	
		Adolescent	Adult
TSV	Pearson R	.830**	.719**
	p-value	0.000	0.000
Thermal Preference	Pearson R	.732**	.787**
	p-value	0.001	0.001

The neutral temperature is defined as the air temperature at which the occupants identify the thermal environment as neither hot nor cold, and it is often supposed to be an optimal condition for a comfortable thermal environment(Fanger, 1970).

In this study, the neutral temperature was calculated with linear regression analysis on the thermal sensation vote against the air temperature. Figure 3 shows the distribution of thermal sensation vote corresponding to the air temperature. The linear equations are expressed as equations (2) and (3) for the adolescent and adult participants. The neutral temperature, the air temperature (Ta) value when the mean thermal sensation vote (MTSV) is 0, for the adolescent and adult group was 24.96℃ and 25.17℃ each. The result shows that the adolescent group has a slightly lower temperature than adults with a difference of 0.21℃.

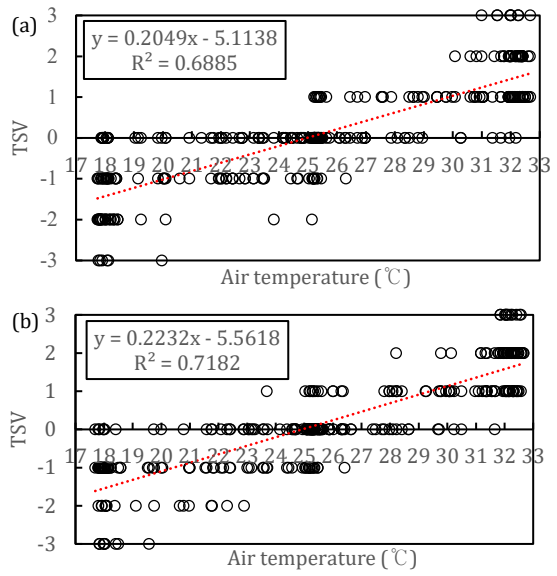

Figure 3. Distribution of thermal sensation vote by air temperature of (a) adolescent and (b) adult group

$$\text{Adolescent}: \text{MTSV} = 0.2 \times \text{Ta} - 5.11,\ R^2 = 0.69 \quad (2)$$

$$\text{Adult}: \text{MTSV} = 0.22 \times \text{Ta} - 5.62,\ R^2 = 0.72 \quad (3)$$

Thermal comfort and skin temperature

In this chamber experiment, participants' skin temperature was measured in a 10-sec interval. Figure 4 illustrates the mean skin temperature and hand skin temperature at the time of the survey during the experimental session. Generally, the mean skin temperature of adolescent participants was slightly higher than that of adults during the whole experimental session. In the case of hand skin temperature, the adolescent group showed a broader range of temperature drop at the beginning but soon increased to a level similar to that of adults.

The correlation analysis was performed to identify the relationship between the skin temperature from 7 body parts (head, abdomen, arm, hand, thigh, calf, foot), mean skin temperature(MST), thermal sensation vote, and thermal preference vote. As shown in table 3, all of the skin temperature features correlated with the survey responses significantly. For both adolescent and adult group, the hand skin temperature(Tskin hand) was correlated with the survey responses showing the highest correlation coefficient value. Also, the arm skin temperature and mean skin temperature showed a strong correlation with the survey responses.

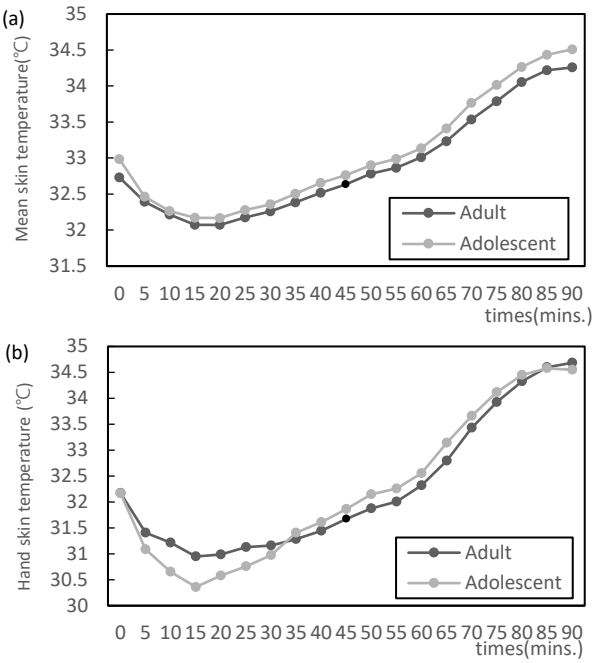

Figure 4. (a) Mean skin temperature (b) hand skin temperature of adult and adolescent group

The linear regression analysis was conducted on the thermal sensation vote against the skin temperature for further analysis. Since the hand skin temperature and mean skin temperature have a relatively strong correlation with survey responses, these features were chosen to be analyzed among all the skin temperature features.

Table 4. Correlation of survey response and skin temperature

			MST	head	abdomen	arm	hand	thigh	calf	foot
Adolescent	TSV	Pearson R	.584**	.620**	.447**	.616**	.627**	.594**	.492**	.183**
		p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
	Thermal Preference	Pearson R	.612**	.596**	.493**	.638**	.640**	.567**	.554**	.231**
		p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Adult	TSV	Pearson R	.546**	.537**	.333**	.536**	.569**	.484**	.512**	.203**
		p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Thermal Preference	Pearson R	.625**	.508**	.350**	.647**	.699**	.562**	.592**	.300**
		p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Figure 5 presents the distribution of thermal sensation vote corresponding to the mean skin temperature, and the linear equation is expressed as equations (4) and (5). With the equation's slope, which reflects the sensitivity, the MST value for one thermal sensation scale change was calculated. The adolescent and adult group showed a value of 1.28℃ and 1.22℃ each.

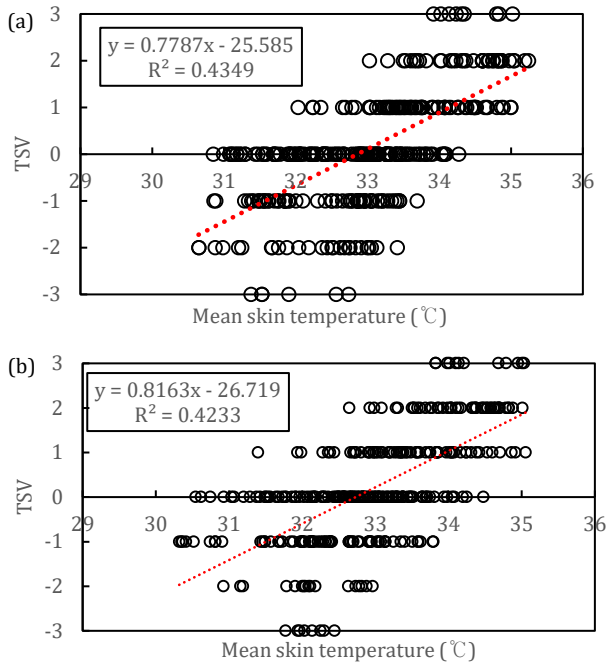

Figure 5. Distribution of thermal sensation vote by MST of (a) adolescent (b) adult

$$\text{Adolescent}: \text{MTSV} = 0.78 \times \text{MST} - 22.599 \quad R^2 = 0.43 \qquad (4)$$

$$\text{Adult}: \text{MTSV} = 0.82 \times \text{MST} - 26.72 \quad R^2 = 0.42 \qquad (5)$$

Also, for further analysis, the linear equation of thermal sensation votes regressed against each age and gender group's mean skin temperature. Based on the slope of the equation, the sensitivity to the temperature change of each group is calculated. The value mean skin temperature for changing one-scale of thermal sensation were 1.43℃, 1.26℃, 1.15℃, and 1.22℃ for adolescent male, adult male, adolescent female, and adult female group.

$$\text{Adolescent male}: \text{MTSV} = 0.70 \times \text{MST} - 22.89 \quad R^2 = 0.39 \qquad (6)$$

$$\text{Adult male}: \text{MTSV} = 0.79 \times \text{MST} - 25.61 \quad R^2 = 0.45 \qquad (7)$$

$$\text{Adolescent female}: \text{MTSV} = 0.87 \times \text{MST} - 28.66 \quad R^2 = 0.49 \qquad (8)$$

$$\text{Adult female}: \text{MTSV} = 0.82 \times \text{MST} - 27.03 \quad R^2 = 0.39 \qquad (9)$$

To investigate the relationship between hand skin temperature and thermal sensation vote, linear regression analyses were conducted. Figure 6 shows the distribution of thermal sensation vote (TSV) corresponding to the mean value of hand skin temperature. The linear equation of TSV with the hand skin temperature is expressed as equation (10) and (11). The slope of the equation was almost identical with the value of 0.41 and 0.40.

$$\text{Adolescent}: \text{MTSV} = 0.41 \times T_{skin}\text{hand} - 13.13 \quad R^2 = 0.39 \qquad (10)$$

$$\text{Adult}: \text{MTSV} = 0.40 \times T_{skin}\text{hand} - 12.88 \quad R^2 = 0.44 \qquad (11)$$

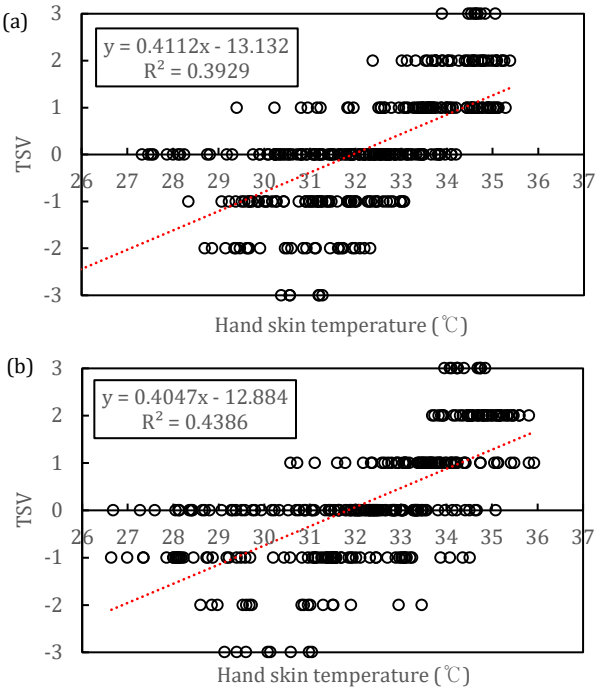

Figure 6. Distribution of thermal sensation vote by hand skin temperature of (a) adolescent (b) adult

Then for further understanding, the regression analysis of the TSV was performed against the hand

skin temperature of the adolescent male, adult male, adolescent female, and adult female group. The resulted equations are (12), (13), (14), and (15) accordingly. The value of hand skin temperature for one thermal sensation change was derived with the equation's slope, and the result was 2.32℃, 1.25℃, 2.43℃ and 2.27℃ for adolescent male, adult male, adolescent female, and adult female. It shows that the hand skin temperature of adult males are much sensitive to the temperatur change in terms of their thermal sensation compared to other groups of participants.

$$\text{Adolescent male}: \text{MTSV} = 0.43 \times T_{skin}\text{hand} - 13.44 \quad R^2 = 0.45 \quad (12)$$

$$\text{Adult male}: \text{MTSV} = 0.80 \times T_{skin}\text{hand} - 25.96 \quad R^2 = 0.69 \quad (13)$$

$$\text{Adolescent female}: \text{MTSV} = 0.41 \times T_{skin}\text{hand} - 13.18 \quad R^2 = 0.37 \quad (14)$$

$$\text{Adult female}: \text{MTSV} = 0.44 \times T_{skin}\text{hand} - 13.90 \quad R^2 = 0.52 \quad (15)$$

DISCUSSION

Adolescents' thermal comfort and indoor environment

In this study, the thermal sensation, thermal comfort, thermal preference of adolescents aged 12-18 and adult participants in their 20-30s were collected in the climate chamber. The result shows that under the same condition of indoor environment, there were differences in the thermal response between adolescent and adult participants. The neutral temperature of adolescents was lower than adults, and the thermal sensation of adolescents seem to be less sensitive to the temperature change compared to that of adults. These results, adolescents' lower neutral temperature than adults, are in line with the former research(Xavier & Lamberts, 2000; Richard de Dear et al., 2015). Meanwhile, the difference in neutral temperature between adolescents and adults in this study was less than 1K, which is a relatively small value compared to 2-3K differences from other field studies. This might be caused by the different levels of control in the experimental design between field and chamber research since more variables that can affect occupant's thermal comfort are controlled in the climate chamber than in the field environment.

Though the trend and degree of difference might vary, it is obvious that adolescents' thermal response differs from that of adults. Thus, it is needed to study adolescents aged 12-18 separately from the adults regarding their thermal comfort for providing a comfortable and appropriate environment for adolescent occupants.

Adolescents' thermal comfort and skin temperature

In the climate chamber, the skin temperature of seven body parts was measured with a thermal comfort survey. The skin temperature of both adults and adolescents positively correlated with thermal sensation and thermal preferences. Especially, the mean skin temperature and hand skin temperature have a relatively strong correlation with participants' survey responses, as reported in several other studies(Choi & Loftness, 2012; Jacquot et al., 2014). Compared to adults, adolescents have slightly higher mean skin temperature during the experimental session. In the case of hand skin temperature, there were no distinctive differences between adults and adolescents. However, when participants are further classified by their gender, the hand skin temperature of the adult male group changed much sensitively, corresponding to the thermal sensation compared to other groups.

The age difference in skin temperature in relation to thermal sensation has been investigated in some studies, and most of them compared cases of young adults and elderly(Lee, J. S., Song, M. K., & Kim, 2009; Schellen et al., 2010; N. A. S. Taylor et al., 1995; Yochihara et al., 1993). These studies reported that elders in their 6-70s have lower skin temperature than young adults. Also, van Hoof, J., & Hensen(2006) explained that the older adults have lower activity levels; thus, their metabolic rate is lower than young adults, which resulted in wanting warmer indoor environment. This tendency of lower skin temperature might be caused by the decrease in skin blood flow with aging.

In case of adolescentage adolescents and young adults in their 2-30s, there might not be many differences in their physical condition in comparison to the case of elderly and young adults. However, since adolescents are going through their physical development process, there are still some chances that their metabolic rate or physiological responses differ from that of grown-ups. This distinctive feature of adolescents might be one of the reasons for the difference in skin temperature between adolescents and adult participants in this experiment.

Considering the result of this study, the relationship between skin temperature and thermal comfort of adolescents have different aspect and trend compared to adults. Thus, there might be a need to be more research investigating adolescents as a distinctive group from adults in terms of their physiological responses related to thermal comfort. Also, since there were only 9-10 participants in each test group in this study, future studies with more participants could help to earn more reliable results.

CONCLUSION

In this study, skin temperature was measured at seven body parts with survey responses in a climate chamber. The comparison between adults in their 20-30s and adolescents aged 12-18 was conducted to examine the age difference in their subjective and physiological responses to the thermal environment.

The result from the chamber experiment shows that there is difference in the relationship between indoor environment, thermal comfort, and skin temperature between adolescents and adults. The air temperature correlated significantly with thermal comfort, and the neutral temperature of adolescents was slightly lower than that of adults. The mean skin temperature and hand skin temperature have a strong correlation with the participant's thermal comfort. During the experimental session, adolescents have a slightly higher mean skin temperature than adults. Also, the hand skin temperature of adult male group changed much sensitively, corresponding to the thermal sensation compared to other groups. The age difference in thermal comfort and related skin temperature proposes the need for investigating adolescents as a separate group from adults for accurate thermal comfort prediction. The results are expected to be used for optimal environmental setting for adolescent students in the classroom, supporting personal comfort model or system based on their physiological signals in the future.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(2020R1A2B5B01002206)

REFERENCES

ASHRAE Standard 55(2013). Thermal environmental conditions for human occupancy, ASHRAE, Atlanta.

Barrett, P., Davies, F., Zhang, Y., & Barrett, L. (2015). The impact of classroom design on pupils' learning: Final results of a holistic, multi-level analysis. Building and Environment, 89, 118–133. https://doi.org/10.1016/j.buildenv.2015.02.013

Chen, C. P., Hwang, R. L., Chang, S. Y., & Lu, Y. T. (2011). Effects of temperature steps on human skin physiology and thermal sensation response. Building and Environment, 46(11), 2387–2397. https://doi.org/10.1016/j.buildenv.2011.05.021

Choi, J. H., & Loftness, V. (2012). Investigation of human body skin temperatures as a bio-signal to indicate overall thermal sensations. Building and Environment, 58, 258–269. https://doi.org/10.1016/j.buildenv.2012.07.003

Corgnati, S. P., Filippi, M., & Viazzo, S. (2007). Perception of the thermal environment in high school and university classrooms: Subjective preferences and thermal comfort. Building and Environment, 42(2), 951–959. https://doi.org/10.1016/j.buildenv.2005.10.027

de Dear, Richard, Kim, J., Candido, C., & Deuble, M. (2015). Adaptive thermal comfort in australian school classrooms. Building Research and Information, 43(3), 383–398. https://doi.org/10.1080/09613218.2015.991627

Fanger, P. O. (1970). Thermal comfort. Analysis and applications in environmental engineering. Copenhagen: Danish Technical Press. https://www.cabdirect.org/cabdirect/abstract/19722700268

Haverinen-Shaughnessy, U., Shaughnessy, R. J., Cole, E. C., Toyinbo, O., & Moschandreas, D. J. (2015). An assessment of indoor environmental quality in schools and its association with health and performance. Building and Environment, 93(P1), 35–40. https://doi.org/10.1016/j.buildenv.2015.03.006

Haverinen-Shaughnessy, U., Turunen, M., Metsämuuronen, J., Palonen, J., Putus, T., Kurnitski, J., & Shaughnessy, R. (2012). Sixth Grade Pupils' Health and Performance and Indoor Environmental Quality in Finnish School Buildings. In British Journal of Educational Research (Vol. 2, Issue 1). www.sciencedomain.org

Hwang, R. L., & Chen, C. P. (2010). Field study on behaviors and adaptation of elderly people and their thermal comfort requirements in residential environments. Indoor Air, 20(3), 235–245. https://doi.org/10.1111/j.1600-0668.2010.00649.x

Hwang, Ruey Lung, Lin, T. P., Chen, C. P., & Kuo, N. J. (2009). Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan. International Journal of Biometeorology, 53(2), 189–200. https://doi.org/10.1007/ s00484-008-0203-2

ISO Standard 7730: Moderate Thermal Environments—Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort, International Organisation for Standardisation, Geneva, 1994

Jacquot, C. M. C., Schellen, L., Kingma, B. R., van Baak, M. A., & van Marken Lichtenbelt, W. D. (2014). Influence of thermophysiology on thermal behavior: The essentials of categorization. Physiology and Behavior, 128, 180–187. https://doi.org/10.1016/j.physbeh.2014.01.025

Kwok, A. G. (1998). Thermal comfort in tropical classrooms. ASHRAE Transactions, 104(Pt 1B), 1031–1047.

Lee, J. S., Song, M. K., & Kim, H. E. (2009). Physiological responses and subjective sensations by age through seasonal condition. Fashion & Textile Research Journal, 11(5), 833–839.

Liu, W., Lian, Z., & Liu, Y. (2008). Heart rate variability at different thermal comfort levels. European Journal of Applied Physiology, 103(3), 361–366. https://doi.org/10.1007/s00421-008-0718-6

Metzmacher, H., Wölki, D., Schmidt, C., Frisch, J., & van Treeck, C. (2018). Real-time human skin temperature analysis using thermal image recognition for thermal comfort assessment. Energy and Buildings, 158, 1063–1078. https://doi.org/10.1016/j.enbuild.2017.09.032

Papazoglou, E., Moustris, K. P., Nikas, K.-S. P., Nastos, P. T., & Statharas, J. C. (2019). Assessment of human thermal comfort perception in a non-air-conditioned school building in Athens, Greece. Energy Procedia, 157, 1343–1352. https://doi.org/https://doi.org/10.1016/j.egypro.2018.11.299

Romanovsky, A. A. (2014). Skin temperature: its role in thermoregulation. Acta Physiologica, 210(3), 498–507. https://doi.org/https://doi.org/10.1111/apha.12231

Schellen, L., van Marken Lichtenbelt, W. D., Loomans, M. G. L. C., Toftum, J., & de Wit, M. H. (2010). Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition. Indoor Air, 20(4), 273–283. https://doi.org/https://doi.org/10.1111/j.1600-0668.2010.00657.x

Sim, S. Y., Koh, M. J., Joo, K. M., Noh, S., Park, S., Kim, Y. H., & Park, K. S. (2016). Estimation of thermal sensation based on wrist skin temperatures. Sensors (Switzerland), 16(4), 1–11. https://doi.org/10.3390/s16040420

Singh, M. K., Ooka, R., Rijal, H. B., Kumar, S., Kumar, A., & Mahapatra, S. (2019). Progress in thermal comfort studies in classrooms over last 50 years and way forward. Energy and Buildings, 188–189, 149–174. https://doi.org/10.1016/j.enbuild.2019.01.051

Taylor, N. A. S., Allsopp, N. K., & Parkes, D. G. (1995). Preferred Room Temperature of Young vs Aged Males: The Influence of Thermal Sensation, Thermal Comfort, and Affect. The Journals of Gerontology: Series A, 50A(4), M216–M221. https://doi.org/10.1093/gerona/50A.4.M216

van Marken Lichtenbelt, W. D., & Daanen, H. A. M. (2003). Cold-induced metabolism. Current Opinion in Clinical Nutrition & Metabolic Care, 6(4). https://journals.lww.com/co-clinicalnutrition/Fulltext/2003/07000/Cold_induced_metabolism.18.aspx

Wang, D., Jiang, J., Liu, Y., Wang, Y., Xu, Y., & Liu, J. (2017). Student responses to classroom thermal environments in rural primary and secondary schools in winter. Building and Environment, 115, 104–117. https://doi.org/10.1016/j.buildenv.2017.01.006

Wargocki, P., Porras-Salazar, J. A., & Contreras-Espinoza, S. (2019). The relationship between classroom temperature and children's performance in school. Building and Environment, 157(February), 197–204. https://doi.org/10.1016/j.buildenv.2019.04.046

Yao, Y., Lian, Z., Liu, W., & Shen, Q. (2008). Experimental study on physiological responses and thermal comfort under various ambient temperatures. Physiology and Behavior, 93(1–2), 310–321. https://doi.org/10.1016/j.physbeh.2007.09.012

Yochihara, Y., Ohnaka, T., Nagai, Y., Tokuda, T., & Kawashima, Y. (1993). Physiological responses and thermal sensations of the elderly in cold and hot environments. Journal of Thermal Biology, 18(5), 355–361. https://doi.org/https://doi.org/10.1016/0306-4565(93)90059-3

Zomorodian, Z. S., Tahsildoost, M., & Hafezi, M. (2016). Thermal comfort in educational buildings: A review article. Renewable and Sustainable Energy Reviews, 59, 895–906. https://doi.org/10.1016/j.rser.2016.01.033