AN APPROACH TO IMPROVE INDIVIDUAL THERMAL COMFORT BASED ON MOBILE MEASUREMENT OF BIOLOGICAL REACTION TO PROXIMATE THERMAL ENVIRONMENT

SHUN KIMURA[1] and YASUSHI IKEDA[2]
[1]*Keio University Graduate School of Media and Governance, Japan*
[2]*Tokyo University, Japan*
[1]*shun.k@keio.jp 0009-0008-9142-9342*
[2]*yasushi@arch1.t.u-tokyo.ac.jp 0000-0002-2016-4083*

Abstract. Thermal comfort is a critical research field because it affects people's health, productivity, and well-being in an architectural space. Numerous previous studies have attempted to find thermal environment conditions where average people feel comfortable. Recently, researchers have focused more on estimating and improving thermal comfort on an individual level to improve the accuracy of previous methods, leveraging recent developments in sensing technologies. However, there are still some remaining issues, such as limited scalability due to the use of in-place sensors and the assumption of a uniform thermal environment, making it unable to recognize locational differences. This study is fundamental research that proposes a human-based approach based on a mobile measurement system to overcome these issues. Firstly, the concept and the benefits are clarified and then, the methodologies and results of two fundamental experiments are explained. One was a field experiment to investigate its validity in estimating individual thermal comfort in real-life situations. The other one was to consider and examine ways to improve individual thermal comfort by the human-based approach. The results suggest that the human-based approach can be beneficial in a way never seen although some issues need to be addressed in future research.

Keywords. Individual Thermal Comfort, Mobile Sensing, HCI, Human-Centric Modeling, Interactive Environment

1. Introduction

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment. Previous research on thermal comfort has analyzed the environmental factors causing comfort or discomfort in humans and how humans perceive it. Conventional research attempted to tackle the question by empirical and physiological approaches and the most recognized achievements are PMV and SET*, which are accepted by international standards, ISSO and ASHRAE, to standardize architecture designs and HVAC control strategies to create thermal environments where average people feel comfortable. Recent research has shifted a focus to thermal comfort of

ACCELERATED DESIGN, Proceedings of the 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2024, Volume 1, 425-434.

individuals, leveraging advancements in sensing technologies to enhance the precision of conventional average methods. Nevertheless, current research on individual thermal comfort also has some limitations. Firstly, it has limited scalability because many studies employed in-place sensors to monitor environmental thermal factors, which makes the estimation in another place impossible. Secondly, as a uniform thermal environment is often assumed, locational variations are neglected. Within the field of environmental engineering, there is growing interest in leveraging thermal environment unevenness to enhance occupants' comfort, necessitating their integration into research on individual thermal comfort. Thirdly, the only purpose of the research is the estimation of thermal comfort of individuals, and the network of individuals is often overlooked even though it could be useful to improve overall individual thermal comfort.

To address these issues, this paper proposes a novel human-based approach and introduces methodologies and results of our several fundamental experiments.

2. Previous Paper

The main characteristic of the research on individual thermal comfort is to attempt to estimate thermal comfort of individuals by monitoring the data of biological reactions of the human body. Initial studies about individual thermal comfort discovered the correlation between thermal comfort of the subjects and biological reactions, such as skin temperature, electroencephalography (EEG) and heart rate variability (HRV), through an experiment in a climate chamber (Wang et al., 2007)(Yao et al., 2009). Recently, with rapidly developing sensing technologies, researchers have focused more on making estimations under more diverse conditions and creating interactive environments with installed actuators to improve subjects' thermal comfort. One of the typical approaches to utilize developed sensing technologies is using infrared sensors to measure facial skin temperature to estimate individual thermal comfort (Ghahramani et al., 2016). Another study proposed a new approach using occupants' cooling and heating behavior to derive an individually tailored thermal comfort estimation model to deal with the subjectivity and the high cost of collecting user feedback (Kim et al., 2018). Lu et al. (2019) proposed a design of an interactive environment, using personal cooling devices to improve thermal comfort of each subject based on the estimation derived from infrared sensor data. These new studies indicated that the relationship between architectural space and users has become more dynamic and interactive with new technologies. Still, issues related to locational limitations and the assumption of uniformity in thermal environments have yet to be addressed.

Looking at other research fields, another approach taking advantage of the non-uniformity of thermal environments to improve occupants' thermal comfort is proposed in environmental engineering. It is suggested that a non-uniform thermal environment intentionally created by non-uniform ventilation modes could reduce Predicted Percentage of Dissatisfied (PPD) by 33% (Fan et al. 2022). Also, Taniguchi et al., (2023) illustrated that an appropriate combination of indoor thermal environment distribution and individual thermal preferences could improve occupants' thermal comfort by CFD and multi-agent simulation supported by a subject experiment. In healthcare, mobile sensing is becoming increasingly important in delivering personalized healthcare services based on monitored biological and behavioral data

(Baig et al., 2014).

This paper proposes a novel human-based approach to which the assumption of non-uniformity of thermal environments and mobile measurement are applied from the other research fields for the estimation and the improvement of individual thermal comfort.

3. Motivation

The motivation behind this study is to improve people's individual thermal comfort by introducing a human-based approach to solve the challenges mentioned in the preceding sections. In this study, a human-based approach is defined as one that is mobile and independent of any specific location or attached technologies. Employing a human-based methodology offers several advantages due to its independence. The first is the capacity to collect data at any location and time, even in real-life scenarios. The second is its ability to recognize locational differences in environmental factors, such as air temperature and relative humidity. The third is that data can be measured in the most efficient way because there is no need to spend time and money to introduce sensors to all places of interest. The last and foremost one is that a human-based approach inherently optimizes sensor distribution for humans, automatically placing necessary sensors in necessary locations. Fig 1 depicts a conceptual diagram of a society embracing a human-based approach to enhance individuals' thermal comfort.

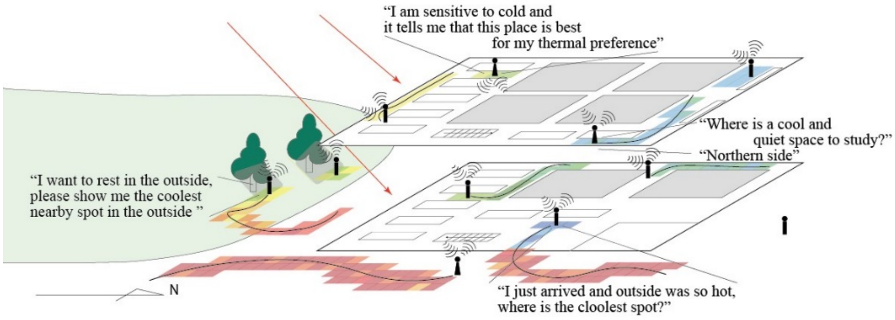

Fig 1. Concept of Human-based Approach for Thermal Comfort Estimation and Improvement

To validate the effectiveness of the human-based approach, our study comprises two fundamental experiments. The first one is a field experiment demonstrating that the human-based approach enables the estimation of individual thermal comfort at any location and time. This experiment was complemented by the development of a mobile thermal comfort measurement system that continuously measures environmental and biological data. At the end of this step, an estimation model to predict the author's individual thermal comfort was constructed. Based on the estimation model, a use case experiment was conducted as a second experiment to show that there is a high possibility that individuals can improve their own thermal comfort with minimal cost and labor by matching non-uniform thermal environment distribution and individual thermal preferences. These experiments were conducted only by the author since this study, unlike previous studies, focused on measuring much data about intrapersonal differences in biological conditions under given constraints of time and money. To reduce subjectivity, our study was divided into two experiments so that the subject's feedback did not affect the examination of the second experiments, and some additional measurements are applied in each step, which will be described in following sections.

4. Experiment

4.1. PURPOSE

The purpose of this experiment is to investigate the validity of a human-based approach in estimating individual thermal comfort in real-life and to create an estimation model for the second experiments. In the first stage, we developed a mobile thermal comfort measurement system that measures data about proximate thermal environment and the corresponding biological reactions. Subsequently, a field experiment was conducted to investigate the validity in a real-life situation.

4.2. DEVELOPMENT OF MOBILE THERMAL COMFORT MEASUREMENT SYSTEM

The first stage of the experiment is the development of a mobile thermal comfort measurement system. Before the hardware design, independent and dependent variables to measure are determined. As independent variables, we chose air temperature and air relative humidity as environmental factors and skin temperature of the wrist and chest, skin peripheral relative humidity of the wrist and chest, heart rate and clothing level as human factors to estimate individual thermal comfort. The dependent variable chosen was the 7-point thermal sensation scale accepted by ASHRAE (-3: cold - +3: hot) and was named as Subjective Thermal Comfort Vote (STCV) in this study. The requirement for the human-based measurement system was to be able to monitor these data robustly and precisely in a mobile way.

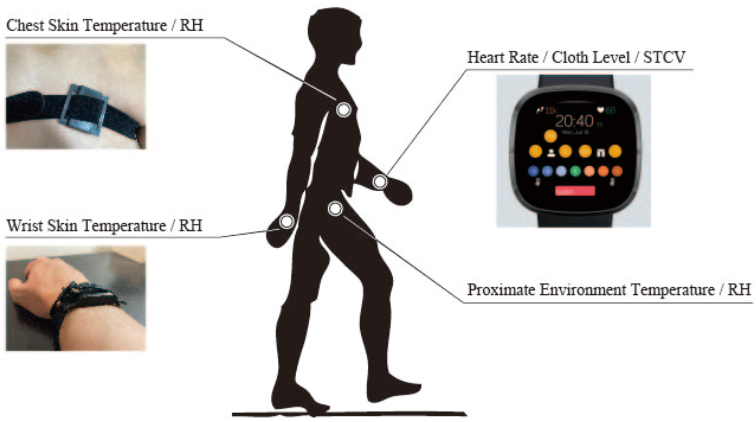

Fig 2. Mobile thermal comfort measurement system

To monitor temperature and relative humidity, iButton DS1923 was chosen. iButton DS1923 is a button-type data logger manufactured by Maxim Integrated for temperature and relative humidity. Its advantage is its ability to log data with higher resolution and sampling rate compared to other sensors within the same price range. The iButtons were affixed to each location, using holders fabricated by a 3D printer, with simple belts to secure them (Figure 2.). Data collected by the iButtons was stored in the sensor and could be retrieved to a laptop using the 1-wire protocol. This could make measured values invisible from the subject to deal with the subjectivity issue.

Another device to monitor the other variables was Fitbit Sense, one of the smartwatches manufactured and sold by Fitbit. The reason why it was chosen was because it is so customizable in terms of measuring data and interface design by utilizing Fitbit SDK that it provides flexibility to this study. For this experiment, the interface was designed like Figure 2. Data collected by Fitbit Sense was transferred and saved in a database in AWS.

4.3. METHODOLOGY

The data had been collected in real life by the author, a 25-year-old man, for 35 days from the second half of May (late spring) to the first half of August (summer). A sampling rate is set to 1 minute and a reminder is set every 10 minutes for a user to submit clothing level and STCV. The data collected less than 10 minutes after the start of the experiment was excluded from the dataset. The number of data points for each clothing level and each STCV is shown in Table 1 and Table 2.

Shorts & Short Sleeve T-shirt	Pants & Short Sleeve T-shirt	Pants & Long Sleeve T-shirt	sum
7509	3554	513	11576

Table 1. The number of data points for each clothing level

-1	0	1	2	3	sum
413	9657	1341	137	28	11576

Table 2. The number of data points for each STCV

4.4. RESULT

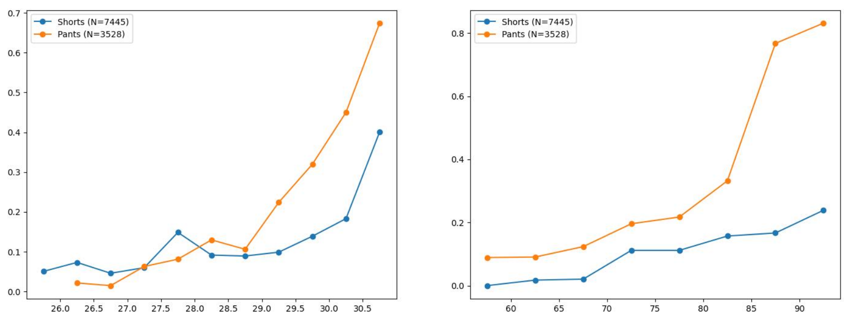

Figure 3. The probability of STCV≥1 for air temperature (Left) and 10-minute mean of HR (Right)

As a first step, the relationship between measured variables and STCV was analyzed. As expected, a strong relationship with STCV was confirmed in air temperature, air humidity and 10-minute mean of heart rate. Figure 3 shows two plots of probabilities of STCV≥1 for each data range of air temperature and 10-minute mean of heart rate when wearing pants and shorts. According to the plots, there is an over 40% chance of feeling warm/hot when air temperature is above 30.0°C and the probability is over 70% when 10-minute mean of heart rate surpasses 85%.

Figure 4 presents the same plots for wrist skin temperature and wrist peripheral skin relative humidity. For wrist skin temperature, the probability is higher when the skin temperature exceeds 35.0°C as expected, while it is also relatively higher around 34.0°C. The additional analysis shows that when feeling warm/hot (STCV≥1), the mean heart rate is about ten higher when the temperature is below 34.5°C than when the temperature is above it. Thus, it is presumed that feeling warm/hot with a low wrist temperature is mainly because of increased metabolism and, in contrast, feeling warm/hot with a high wrist temperature is mainly due to heat exchange between the outside and the body. The right side of Figure 4 shows that the probability is higher when the wrist peripheral relative humidity is around 80% although a simple positive correlation was expected. In real-life scenarios, it is normal for a person to take some measurements when feeling hot/cold, so the condition becomes different when the relative humidity reaches 90%. Thus, it is crucial to detect the initial increase in the relative humidity to identify when the subject starts to feel hot. In fact, Figure 5 shows the strong correlation between the 5-minute lag of the wrist skin peripheral relative humidity and STCV. These results suggest that the mobile human-comfort estimation system can identify a dynamic relationship between thermal comfort and some biological reactions.

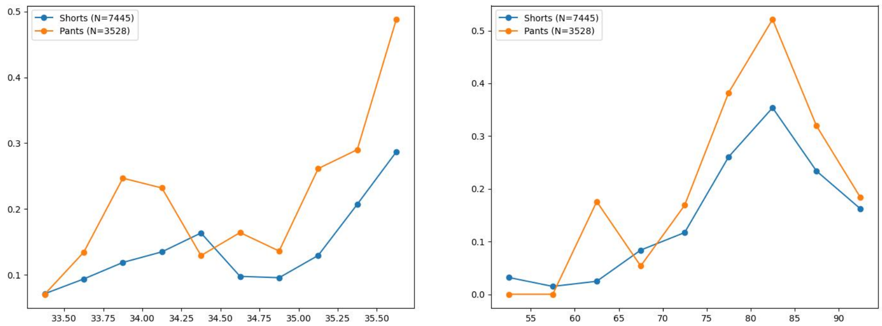

Figure 4. The probability of STCV≥1 for wrist skin temperature (Left) and peripheral relative humidity (Right)

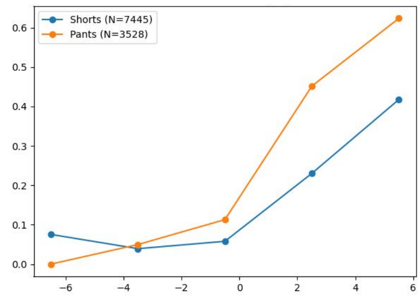

Figure 5. The probability of STCV≥1 for 5-minute lag of wrist skin peripheral relative humidity

Since the correlation between measured variables and thermal comfort expressed by STCV was confirmed, a Machine Learning (ML) model was constructed based on the dataset. SVC was chosen as a classifier model and all eight variables were used as independent variables. To split the dataset into train data and test data, the dataset is divided into sub-datasets based on a combination of clothing level and STCV, and the first 80% of the chronologically ordered sub-dataset is extracted for train data and, the rest is reserved for test data. Due to the unbalanced dataset, a f1 score is selected as an evaluation function, treating STCV=1,2,3 as the same label in the evaluation step due to the limited number of data points when STCV=2,3. The hyperparameters chosen by grid search were C=0.5 and gamma=0.1. F1, recall, precision, and accuracy for test data are 0.53, 0.51, 0.77, and 0.81, respectively. This ML model was used in the next experiment, Use Case, to detect discomfort of the user by calculating Predicted STCV, the average of STCV labels weighted by probabilities that one data point is estimated to belong to each label calculated by the Platt scaling method.

5. Use Case

5.1. PURPOSE

The purpose of a use case experiment is to conduct a demonstration experiment assuming one of the specific situations in which the invented system will be used to investigate whether and how it can help individuals improve their own thermal comfort when it is used by multiple users. In this study, the application of the system in a library in our campus was selected as a specific situation. It was because improving occupants' thermal comfort during desk work in an environment with unified air conditioning control is one of the most expected solutions, considering the advantages of human-based approach that can match thermal environment distribution and thermal preferences of occupants to improve their thermal comfort.

5.2. METHODOLOGY

Fig 6. Library

The experiment site was a main space in a 3-floor library building (32m*80m) in our campus (Figure 6). The biggest problem for this use case was time and money to prepare the invented system for multiple people and collect data for each person. In this use case, we pseudo-solved the problem by the author changing his location in a short period of time (3min) so that we could pseudo-measure data for around 20 individuals with thermal comfort preferences similar to the author in 1hour. The threshold of 3 minutes was chosen because it did not cause a measuring lag and allowed measurement for a sufficient number of locations. As GPS is ineffective indoors, indoor location estimation was made by pedestrian dead reckoning (PDR). PDR is one of the most famous and simplest ways to estimate a pedestrian's indoor locations based on an acceleration sensor to detect steps and a geomagnetic sensor to determine walking direction. WitMotion WT901BLECL BLE5.0 was selected as a device for PDR. Due to the limitation of PDR, data collection was conducted one floor by one floor, and four rounds of measurement were conducted in a single day, with one round consisting of measuring data for around 18 locations on 3 floors over 1 hour. This setting allowed us to compare data from 18 locations in the site in the analysis step under our hypothesis that occupants change their location in 1 hour on average. Measured variables was the subject location and all the variables in the experiment but STCV. Data had been collected for 9 days from August 17 to September 12. Figure 7 is a plot that shows the location of the subject and measured air temperature for each place in one day.

In the analysis, the room for the improvement for the subject's thermal comfort was investigated while the subject's thermal comfort was calculated by Predicted STCV to reduce subjectivity.

Fig 7. An example plot for the subject location and air temperature on 9/11

5.3. RESULT

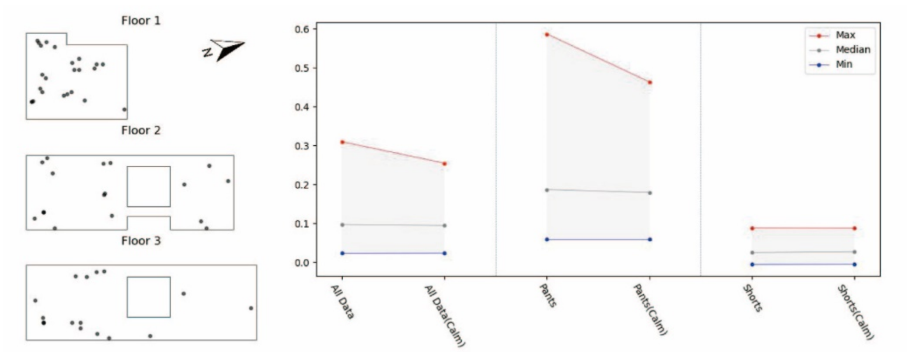

Fig 8. (Left) Subject location when the subject is predicted to feel hot
(Right) Mean of the maximum, the median, the minimum of Predicted STCV in one round

The left side of Figure 8 plots the subject's location when the Predicted STCV calculated by the ML model is higher than 0.5. The threshold of 0.5 was chosen as a level beyond which productivity in desk work may decline. According to the plot, there is always a chance that the subject feels hot anywhere in the library. It means that thermal condition changes from time to time even in the same place, and also from place to place and so does body condition, which always affects thermal comfort. Consequently, it is imperative to measure locational and chronological differences in thermal conditions and the corresponding biological reactions to estimate individual thermal comfort accurately. The invented system is useful in this way because it can frequently measure both data across diverse locations without presuming uniform thermal environments.

To investigate whether the invented system is helpful for individuals to improve their own thermal comfort by suggesting a thermally optimal place for each one, the values of Predicted STCV were compared in one round to calculate potential improvement in the subject's individual thermal comfort. To make a comparison, the mean of the maximum, the median, and the minimum of Predicted STCV in one round are calculated for each clothing level. These values are depicted on the right side of Figure 8, representing a simulated calculation of the potential improvement in thermal comfort if the subject were to relocate to a thermally optimal place. For each pair of values within the same category, the left one is calculated from all the data belonging to the category, and the right one is calculated from the data when a heart rate of the subject<80 (Calm). The plot indicates an average potential improvement in thermal comfort ranging from 0.2 to 0.3 at the most. Specifically, when wearing pants, the improvement is approximately 0.5, while for shorts, it hovers around 0.1. This result suggests that there is a high possibility that the human-based approach can help individuals improve their thermal comfort with minimum dependence on HVAC machines.

6. Conclusion and Discussion

In this study, the concept and the benefit of the human-based approach are proposed. Our fundamental studies showed that the invented mobile thermal comfort measurement system can recognize locational and chronological differences in thermal environment and human biological reactions to help estimate individual thermal comfort. Furthermore, one way to improve people's thermal comfort by the human-based approach was proposed and investigated, then it was proven highly probable from the use case that the mobile measurement system can help individuals improve their own thermal comfort with minimum cost and labor even in a space with unified air conditioning control in a situation where the human-based approach is widely accepted.

This study is still ongoing research and can be developed in the following ways.

- Important variables that affect individual thermal comfort, such as radiation and wind, are missing from this study. Mobile methods for measuring these data should be explored.
- The number of subjects is quite few even though the main purpose of this study is to propose the concept and prove an advantage of the human-based approach, not

the comparison in ways to feel thermal comfort among different people. Still, more subjects are helpful in proving its validity.

- Standardization of data collection methods and evaluation models is imperative to facilitate comparisons across different studies on individual thermal comfort.

Despite the limitations mentioned above, this study is valuable in proposing the concept of the human-based approach that enables an individually customized thermal comfort estimation model and improvements in real-life situations. The human-based approach has the potential to solve the remaining issues in previous research and lead to better people's thermal comfort due to its advantages. Furthermore, widespread adoption of the human-based approach could potentially reduce reliance on HVAC systems, leading to more energy-efficient improvements in individual thermal comfort. In a broader context, because of these advantages, the human-based approach is effective not only for thermal comfort but also for many other factors that influence the quality of the experience in architectural space. We hope that the human-based approach will be one way to improve the design quality of the increasingly dynamic relationship between buildings and humans.

References

Baig, M. M., GholamHosseini, H., & Connolly, M. (2014). Mobile healthcare applications: system design review, critical issues and challenges. *Australasian Physical & Engineering Sciences in Medicine, 38*(1), 23–38. https://doi.org/10.1007/s13246-014-0315-4

Fan, M., Fu, Z., Wang, J., Wang, Z., Suo, H., Kong, X., & Li, H. (2022). A review of different ventilation modes on thermal comfort, air quality and virus spread control. *Building and Environment, 212*, 108831. https://doi.org/10.1016/j.buildenv.2022.108831

Ghahramani, A., Castro, G., Becerik-Gerber, B., & Yu, X. (2016). Infrared thermography of human face for monitoring thermoregulation performance and estimating personal thermal comfort. *Building and Environment, 109*, 1–11. https://doi.org/10.1016/j.buildenv.2016.09.005

Kim, J., Zhou, Y., Schiavon, S., Raftery, P., & Brager, G. (2018). Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. *Building and Environment, 129*, 96–106. https://doi.org/10.1016/j.buildenv.2017.12.011

Lu, S., Wang, S., Cochran Hameen, E., Shi, J., & Zou, Y. (2019). Comfort-Based Integrative HVAC System with Non-Intrusive Sensing in Office Buildings*. In 24th International Conference on Computer-Aided Architectural Design Research in Asia: Intelligent and Informed, CAADRIA 2019* (pp. 785-794). The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA). https://doi.org/10.52842/conf.caadria.2019.1.785

Taniguchi, K., Ishiura, K., Miyata, S., & Akashi, Y. (2023). The effect of seating movement based on indoor thermal environmental distribution on overall occupant thermal satisfaction*. Nihon Kenchiku Gakkai Kankyokei Ronbunshu, 88*(808), 511–520. https://doi.org/10.3130/aije.88.511

Wang, D., Zhang, H., Arens, E., & Huizenga, C. (2007). Observations of upper-extremity skin temperature and corresponding overall-body thermal sensations and comfort*. Building and Environment, 42*(12), 3933–3943. https://doi.org/10.1016/j.buildenv.2006.06.035

Yao, Y., Lian, Z., Liu, W., Jiang, C., Liu, Y., & Lu, H. (2009). Heart rate variation and electroencephalograph - the potential physiological factors for thermal comfort study. *Indoor Air, 19*(2), 93–101. https://doi.org/10.1111/j.1600-0668.2008.00565.x