

Original Article

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Influencing factors on thermal comfort and biosignals of occupant-a review

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- Thermal comfort
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- Biosignal
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- Heart rate variability
- Electroencephalogram

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Abstract Thermal comfort has become one of the most important factors to be considered for the working efficiency and health of occupants in an indoor space. In addition, it is considered in the design of heating, ventilation, and air-conditioning systems for the management of building energy. In this study, the key factors influencing thermal comfort are briefly discussed, such as air temperature, air velocity, radiant temperature, relative humidity, insulation of clothes, and metabolic rate. These factors act in a complex manner, affecting people and causing physical and psychological changes. Also, human physical changes have a significant impact on the human body, including skin temperature, heart rate variability, and electroencephalogram measurements, and are modified by the surrounding thermal environment. In this article, the factors influencing thermal comfort and biosignals of humans are discussed, and recent related studies are introduced.

1. Introduction

With the development of modern society, the lives of people are becoming more convenient, and the demand for satisfaction is accordingly increasing. To improve the quality of human life, several studies are being conducted to achieve convergence of information and communication technology corresponding to the fourth industrial revolution. The quality of life goes beyond just living, food, clothing, shelter, and mental factors such as health, physical factors, or stress reduction such as the absence of pain, comfortable state, and thermal comfort. As people spend a lot of time in an indoor environment, it has a significant influence on the quality of life and comfort of a person. The state of mind that expresses satisfaction with an indoor environment is evaluated subjectively by thermal comfort. Thermal comfort is the most attractive topic in indoor environments and heating, ventilation, and air-conditioning (HVAC) systems [1]. As air-conditioning for maintaining suitable thermal comfort of occupants in an indoor environment accounts for a high percentage of the energy used in buildings, the management of thermal comfort is essential in terms of energy management. Moreover, because occupants perform different activities, such as studying, working, or other indoor activities, the optimal conditions change according to the indoor environment. Therefore, it is important to maintain the proper thermal comfort of occupants according to various activities and conditions to create a comfortable indoor environment. An advanced and appropriate climate control system can improve air quality and thermal comfort and reduce energy usage for cooling a small environment like a vehicle cabin [2].

Since thermal comfort is subjective, the index can be obtained through evaluation and prediction rather than measurement or calculation. Thermal sensation vote (TSV), thermal comfort vote (TCV), predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD) indexes are evaluated through a survey to determine thermal comfort. TSV is a subjective questionnaire that evaluates the rate at which people feel hot or cold, and TCV is a subjective questionnaire that evaluates whether a person feels thermally comfortable in their senses. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) specifies a seven-point scale for TSV and TCV, as listed in Table 1. As TSV and TCV are subjective

Table 1. Questionnaires used to determine thermal sensation vote and thermal comfort vote.

Value	Thermal sensation vote	Thermal comfort vote
-3	Very cold	Very uncomfortable
-2	Cold	Uncomfortable
-1	Cool	Marginally uncomfortable
0	Neutral	Neutral
1	Warm	Marginally comfortable
2	Hot	Comfortable
3	Very hot	Very comfortable

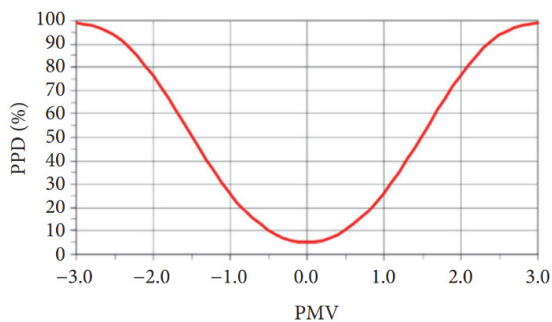


Fig. 1. Correlation between predicted mean vote value and predicted percentage of dissatisfaction [6].

questionnaires, they are sometimes used after being transformed into a 5-, 4-, or 3-point scale according to the characteristics of the study, when used in various studies [3]. The thermal comfort evaluation using PMV and PPD indicators was proposed in 1974 by Fanger [4]. PMV is a prediction of the sense of warmth in a person, and it is a measure of metabolism, clothing insulation, air temperature, mean radiant temperature (MRT), air velocity, and partial water vapor pressure. It can be calculated by ISO 7730 [5].

PMV predicts the average value of the intention to express the warmth of several people exposed to the same environment. However, the actual individual expression values are in a wide range around the average value. To use it more practically, the number of people who feel hot or cold is calculated because it is necessary to predict the PPD. The correlation between PMV and PPD is shown in Fig. 1 [6]. In addition, at the most pleasant condition where $-0.5 < PMV < 0.5$, it can be observed that approximately 10 % of people feel dissatisfied because the pleasant conditions felt by different individuals are different; moreover, physical factors and psychological factors also have a serious impact.

As the thermal comfort of a person is a subjective feeling, it is directly related to changes in the body due to the thermal environment. These changes in the body appear as biosignals, and various studies were conducted to measure thermal comfort by using the changes in biosignals. In this paper, various factors affecting thermal comfort and measurable biosignals related to thermal comfort are summarized and presented

briefly. Previous studies on thermal comfort are mostly based on various factors suggested by Fanger [3], and recent researches on thermal comfort have actively conducted using biosignals. However, it is hardly found to present the summarized paper for both views simultaneously. Thus, in this paper, various factors affecting thermal comfort and measurable biosignals related to thermal comfort are summarized and presented briefly. For this, this study introduces the research trends of thermal comfort and shows the possibility of evaluating thermal comfort using biosignals. For this, this study presents the research trends of thermal comfort as well as shows the possibility of evaluating thermal comfort using biosignals. Furthermore, it can be used as a basic study of system research that connects the resident's real-time condition and their thermal environment and develops an automatic system to improve the thermal environment using biosignals.

In Sec. 2, the key factors influencing the thermal comfort of humans are presented, and representative studies and results are summarized and introduced. Researches on thermal comfort have been conducted by using subjective surveys about the surrounding environment and people, which are influencing factors on thermal comfort. In recent studies, some researches on thermal comfort are being carried out by measuring and analyzing biosignals and subjective evaluations simultaneously. In Sec. 3, various measurable biosignals and recent studies on biosignals are presented to achieve thermal comfort, which is objectively evaluated. In particular, this study introduces studies on various biosignals and thermal comfort evaluation and shows the results of the relationship between biosignals and thermal comfort.

2. Influencing factors on thermal comfort

It is not easy to determine the optimum condition for everyone in a given space because of significant differences between people in terms of human physiology and psychological satisfaction. Generally, six representative factors affect thermal comfort, and these are classified into environmental and individual factors. Environmental factors include air temperature, air velocity, radiant temperature, and relative humidity. Besides, personal factors include clothing insulation and metabolism. These factors have a complex effect on human thermal comfort [7]. This section introduces the key factors on thermal comfort and summarizes the representative studies related to them.

2.1 Environmental factors pertaining to thermal comfort

2.1.1 Air temperature

The air temperature significantly affects the skin temperature of the occupant, and the skin temperature is highly influenced by the heat transfer between the occupant and the surrounding [7]. Thus, the air temperature directly affects the thermal comfort of the occupants. Shimazaki et al. [8] evaluated and compared thermal sensation and thermal comfort at constant tem-

peratures of 16 °C (cold), 26 °C (neutral), and 36 °C (hot). The thermal sensation was measured to be -1.7, 0.1, and 0.9 at cold, neutral, and hot temperatures, respectively, which were obtained through a seven-point questionnaire-based survey with points ranging from -3 to 3. Moreover, under the same conditions, thermal comfort was measured to be -1.0, 0.8, and 0.2, respectively, using five-level questionnaires with points ranging from -2 to 2. The authors reported that the air temperature affected the thermal sensation and thermal comfort of a person. The occupants felt thermally comfortable as the thermal sensation approached neutral (0), and was rather unpleasant when the thermal sensation was too hot or too cold. Lan et al. [9] conducted a study on the effect of air temperature on sleep quality in summer through physical measurement and a subjective questionnaire. The subjects wore pajamas with clothing and thermal insulation of 0.6 clo, and the thermal comfort and skin temperature were measured during, before, and after sleep under three temperature conditions of 23 °C (cool), 26 °C (neutral), and 30 °C (warm). Consequently, during sleep, at an air temperature of 23 °C, 26 °C, and 30 °C, the subjects felt neutral, marginally warm, and warm, respectively, and skin temperature increased with a similar tendency to ambient air temperature. Also, the quality of sleep was sensitive to changes in ambient air temperature, and the neutral temperature during sleeping was higher in thermal sensation than that during awakening.

Thermal comfort is significantly influenced by changes in air temperature as well as the value of air temperature. Wu et al.

[10] evaluated thermal comfort by changing the indoor temperature at a rate of ± 2 and ± 1 °C for cooling and heating in the conditions of 20 °C (cold), 22 °C (marginally cold), 26 °C (neutral), 30 °C (marginally hot), 32 °C (hot). The relationship between air temperature, thermal sensation, and thermal comfort was presented in these studies, as shown in Figs. 2 and 3. The circle in Fig. 3 indicates the thermal comfort zone of the occupants. Besides, the rate of change in skin temperature was affected by the rate of change of thermal sensation and air temperature for all conditions, and it showed that the temperature change significantly affected the rate of change of skin temperature in a cold environment. In contrast, the skin temperature was hardly affected in a hot environment.

Korukçu et al. [11] used infrared thermography to determine the instant and transient temperature distributions inside surfaces of the automobile and investigate the thermal discomfort caused by the surfaces of the automobile. Kilic et al. [12] investigated thermal environment changes of a vehicle using air conditioning system in summer with measuring temperature, relative humidity, and air velocity. As a result, the vertical temperature difference in the vehicle was about 25 °C at the beginning of the experiment, and it decreased to 3 °C-4 °C using an air conditioning system.

Some studies reported that thermal sensation changes linearly with average skin temperature under certain conditions; however, some cases do not change linearly. Ciuha et al. [13] conducted an experiment to confirm the range of formation of the thermal comfort zone (TCZ) according to the rate of change

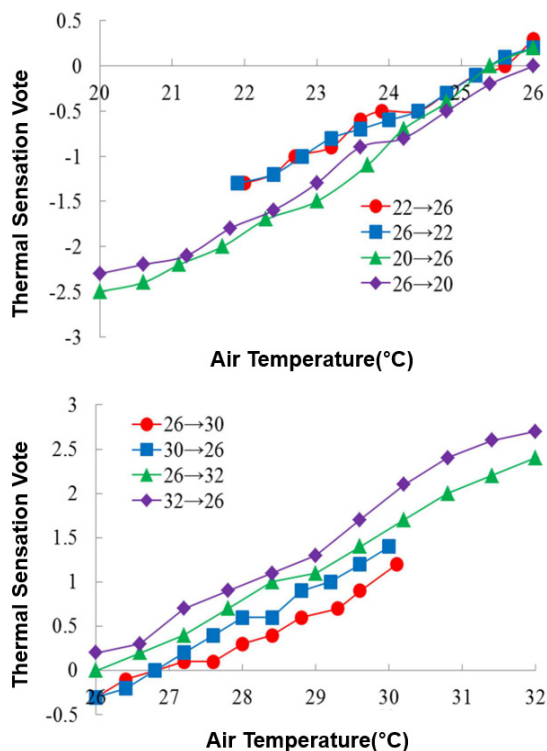


Fig. 2. Relationship between air temperature and thermal sensation vote (TSV) [10].

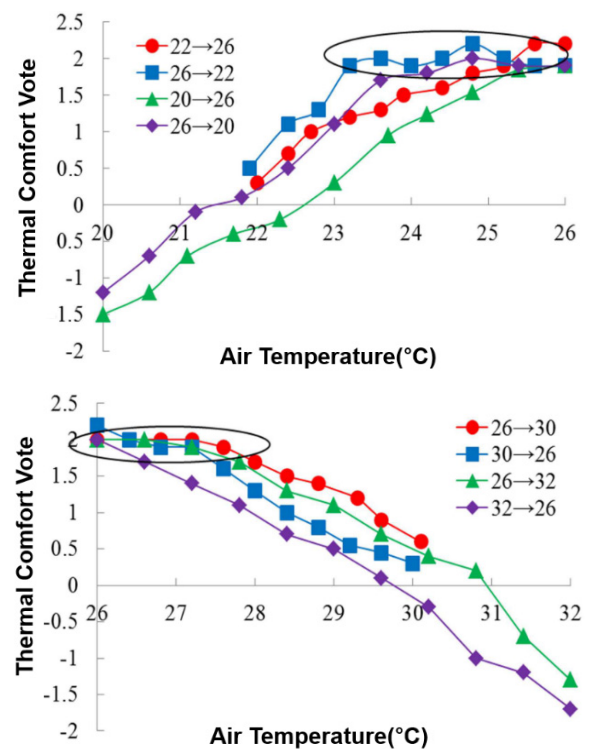


Fig. 3. Relationship between air temperature and thermal comfort vote (TCV) [10].

and direction of the room temperature when the air temperature increased from 15 °C to 40 °C and then decreased to 15 °C quickly (1 °C/min) and slowly (0.5 °C/min). While evaluating the thermal comfort at 3 min intervals, in the fast case, under heating and cooling conditions, TCZ was determined to be between 22±4 °C and 30±4 °C and between 25±3 °C and 33±4 °C, respectively. In the slow case, it was confirmed that the TCZ was between 21±3 °C and 33±4 °C and between 23±4 °C and 34±3 °C under heating and cooling conditions, respectively. It was also reported that the TCZ in the heating condition was lower than that in the cooling condition, and TCZ was affected not only by the air temperature but also by the change rate and direction of temperature change.

2.1.2 Air velocity

Air velocity is an important factor directly related to thermal comfort because it affects convective heat transfer between the skin and its surroundings, which significantly affects skin temperature changes. Gueritee et al. [14] experimented on the relationship between radiant heat, air velocity, and skin temperature under of rest and minimal motion conditions. The temperatures were set to 18, 22, and 26 °C, and the air velocities were set to 0, 1.5, 2, 3, 0, and 3 m/s for 5 min. Subjects were wearing swimming trunks and exposed to increasing air velocities of up to 3 m/s. It was observed that they self-adjusted the intensity of the direct radiant heat received on the front of the body to maintain the overall thermal comfort at rest or while cycling. At all air temperatures, high correlation coefficients were observed between the air velocity and the radiant heat load. It was confirmed that the thermal comfort decreased as the wind strength increased. Fig. 4 shows the changes in mean skin temperature according to wind strength and air temperature. The lower the air temperature, the more the mean skin temperature changes according to the wind speed.

Tian et al. [15] studied the thermal comfort of occupants according to the wind type and distance from the wind discharge part in an indoor space. Two wind types were used: one was a constant air supply, and the other was a pulsating air supply (repeated high and low wind speeds). The thermal comfort from the experience was measured and evaluated while sitting in two rows at a certain distance from the wind discharge port while the wind speed and air temperature were changed. When occupants were seated in the first row, the wind speed was higher than when they were seated in the second row, and it was confirmed that the thermal comfort and thermal sensation were relatively low owing to the direct influence of the wind. Putra et al. [16] investigated the effect of indoor heating equipped with mechanical ventilation on the thermal satisfaction of occupants in a building. To visualize the quality of the indoor environment, modeling and simulation methods were performed by using COMSOL Multiphysics software, and a questionnaire-based method was also utilized to obtain the thermal comfort of building users. Consequently, it was confirmed that 40 % of the indoor occupants were unsatisfied with the indoor environment due to the central air-conditioning system.

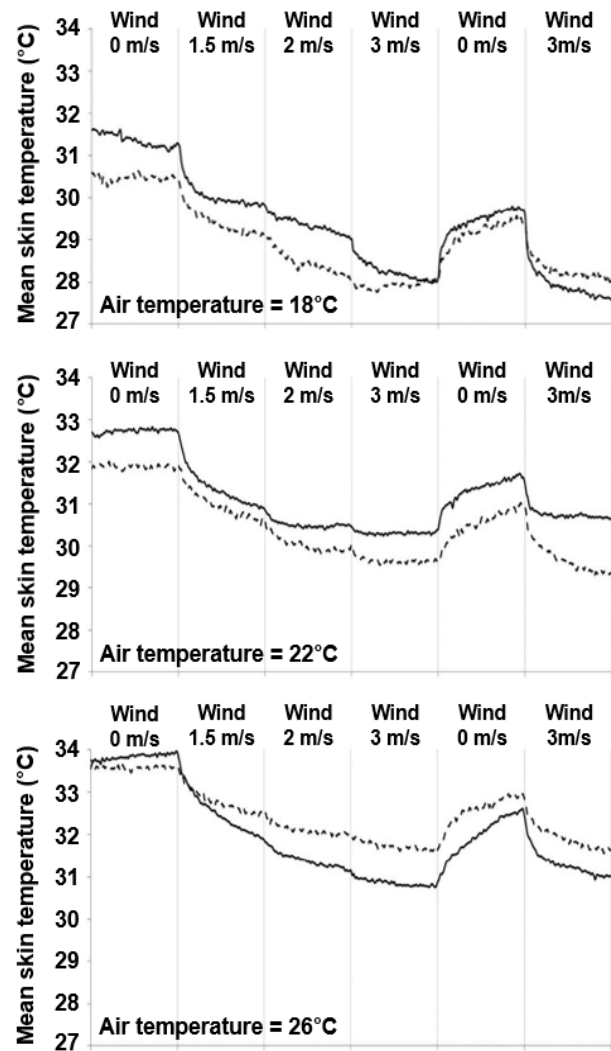


Fig. 4. Average mean skin temperature of volunteers exposed to various wind speeds at rest or when exercising, in swimming trunks at three different temperatures [14].

Maher et al. [17] conducted a study on the comprehensive verification of indoor airflow in empty buildings with natural convection. For this, a commercial computational fluid dynamics package (ANSYS CFX 15) was used to analyze air flow and temperature distribution in the chamber, and the simulation results were evaluated based on the experimental results in an empty chamber with the same boundary conditions and similar flow. The comfort level was evaluated using the air diffusion performance index (ADPI). Consequently, it was confirmed that the ADPI value of 83 % was the closest to the acceptable comfort level when the air velocity was 0.15 m/s. Kiliç et al. [18, 19] investigated temperature distributions of the vehicle cabin in cooling mode with transient numerical analysis. Steady-state conditions in velocity and temperature distributions were reached at 10 min and 30 min of cooling time, respectively. Also, the surface temperature decreased slowly more than the other parts because of constant solar radiation.

Du et al. [20] studied the appropriate airflow for a widely used

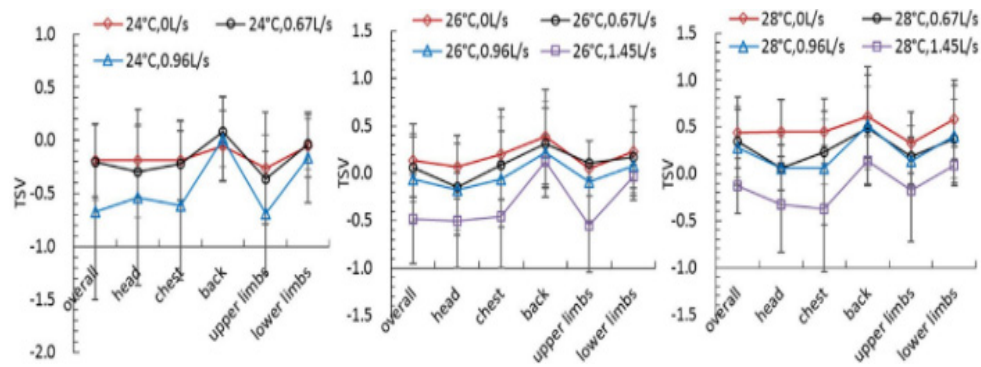


Fig. 5. Overall and local thermal sensations at different conditions [20].

nozzle to provide optimum thermal comfort in a Boeing and an Airbus. Airflow and human thermal comfort were measured in a three-row aircraft cabin. Experiments were conducted at four airflow velocities (0, 0.67, 0.96, and 1.45 L/s) at the nozzle and at three different room temperatures (24 °C, 26 °C, and 28 °C). Their results confirmed that when the airflow rate was increased, the thermal sensation of passengers decreased in a cool direction and air movement also increased. As shown in Fig. 5, the proper airflow velocity at normal pressure at the nozzle ranged from -0.5 to +0.5 of thermal sensation for all body parts at air temperatures of 24 °C, 26 °C, and 28 °C with air flow rates of 0-0.86, 0.12-1.09, and 0.26-1.30 L/s, respectively. Shimazaki et al. [8] conducted an experiment on the thermal satisfaction under different experimental conditions (air temperature = 36 °C, 26 °C, and 16 °C) and variable conditions (air velocity = 0, 2, and 5 m/s, and airflow angle = 0°, 45°, and 90°) to investigate the effect of air temperature and wind speed on human thermal comfort. Consequently, it was concluded that the air temperature satisfied the standard of human thermal sensation; moreover, when the wind blows, the thermal sensation affected the human thermal comfort. The wind did not independently affect the thermal comfort, but the air temperature and wind speed should be considered simultaneously. Heat flux was measured as an influencing factor of the wind angle. It was confirmed that the heat flux at airflow angles of 45 and 90° was lower than when the airflow angles were 0 and 45°. The heat flux at an airflow angle of 45° was the lowest and demonstrated the greatest effect on human thermal comfort.

Lee et al. [21] compared the effects of air flow, air temperature, pollutants, and air distribution in indoor space between traditional displacement ventilation (TDV) and under-floor air distribution (UFAD) systems using both experimental and numerical approaches. As a result, perforated-corner, swirl, and perforated floor panel diffuser created low air velocity in the occupied area. However, the perforated corner TDV and perforated floor panel diffusers could generate a high difference of temperature between the head and ankle part of an occupant. Then, the linear diffuser created the fastest velocity in the occupied zone, making a high risk of the potential draft. The TDV and UFAD systems had a better performance of ventilation than the mixing ventilation system in cooling mode. In the case

of heating mode, the TDV and UFAD system made mixing conditions except for the vicinity of the floor.

2.1.3 Radiant temperature

In general, the radiant temperature is one of the major factors affecting human thermal comfort; however, only air temperature is commonly used in simulations; however, the MRT is often ignored. This may be because the measurement of radiant temperature in an indoor environment is significantly complex. Therefore, the MRT is generally used and defined as a uniform temperature in a virtual black space, exchanging the same amount of radiant heat as a nonuniform space [22].

In representative studies related to radiant temperature, Liu et al. [23] observed changes in skin temperature at stable and unstable radiant temperatures to study the relationship between radiant temperature and human skin temperature. They divided 48 people into three groups. Group 1 was exposed to a stable thermal environment, and the radiant temperatures were 26, 28, 30, 32, 36, 38, 36, 34, 32, 30, 28, and 26 °C. Groups 2 and 3 were exposed to an unstable thermal environment. The radiant temperature increased from 26 °C to 38 °C at a rate of increase of 2 °C every 5 and 10 min for groups 2 and 3, respectively, and then decreased from 38 °C to 26 °C at the same rate. Consequently, it was confirmed that the temperature changes at the feet and hands were caused by the environmental temperature change, which was larger than that of other parts of the body. The adaptation to the temperature occurred more slowly when the radiant temperature decreased than when the radiant temperature increased. It was reported that a lower temperature fluctuation rate lowers the rate of change of mean skin temperature. Atmaca et al. [24] investigated the local differences between body segments caused by high radiation temperature and analyzed the internal surface temperature of wall and ceiling structures that influence thermal comfort. Consequently, it was determined that body segments close to the relatively hot surface were more affected than other surfaces, and the internal surface temperature of walls and ceilings exposed to strong solar radiation reached a high level, causing thermal discomfort to occupants in the building.

Alfano et al. [25] conducted a study on the role of the measuring method and equipment utilized to measure the average

radiant temperature in a thermal environment. To recreate this environment, a study was conducted using a special room to reproduce typical microclimatic conditions in both summer and winter environments. The deviation of the PMV value associated with the use of other sensors (three to six decimal places depending on the season) and sensitivity of the index was not usable when the average radiant temperature changed within the accuracy requirements set by the ISO 7726 standard. It was reported that it exceeded significantly (two to three decimal points depending on the season). Further, it was concluded that the use of other devices by conforming to ISO 7726 could obtain an average radiant temperature; however, the results of the thermal environment evaluation were often ambiguous. Marino et al. [26] analyzed the effect of solar radiation on the local thermal comfort of a subject in an indoor environment considering both direct and diffuse components of solar radiation. They confirmed that solar radiation significantly influences the symmetry of the radiant field. In addition, it was a major cause of local discomfort owing to the allowable value of radiation asymmetry. Yang et al. [27] proposed a corrected PMV (CPMV) to evaluate the impact of solar radiation. Solar radiation and thermal comfort were evaluated in a building with a glass structure. Consequently, when CPMV was used rather than PMV, which is similar to TSV, it was determined that CPMV was applicable throughout the year. In addition, while solar radiation negatively affected human thermal comfort in summer, it showed two aspects in winter: temperature and solar radiation preferences differed according to gender. Male subjects tended to be more sensitive to temperature, while female subjects reported that they were sensitive to solar radiation when both temperature and solar radiation were high.

Chung et al. [28] conducted a study on the system design, energy efficiency, comfortable performance, and thermal stratification of an underfloor air distribution (UFAD) system to investigate the effect of MRT on thermal comfort. Room airflow varied in the range of approximately 0.8-1.6 m/s (approximately 0.144-0.288 m³/s, airflow rate of 8-16 air changes per hour) and the temperature of the supplied air was continuously provided ranging to approximately 14.0 °C-18.5 °C. As a result, a considerable discrepancy was observed in thermal comfort when the air temperature was used rather than MRT in the evaluation of PMV. However, a more thorough analysis, including full radiation simulation, reported no significant difference in PMV distribution. Fig. 6 shows the effects of radiant temperature on thermal comfort for the UFAD system under the following measurement conditions: PMV distribution evaluated using MRT, air temperature, and MRT in the case of full radiation simulation. The results indicate that the radiant temperature was also important in the evaluation of PMV. Dong et al. [29] analyzed the effect of solar radiation on whether the radiant heat system affected indoor thermal comfort through CFD simulations and experiments. They confirmed that there were sunspots on the floor and that the heated windows significantly influenced the indoor heat change. Besides, the occupants confirmed the feeling of partial thermal discomfort in the vicinity

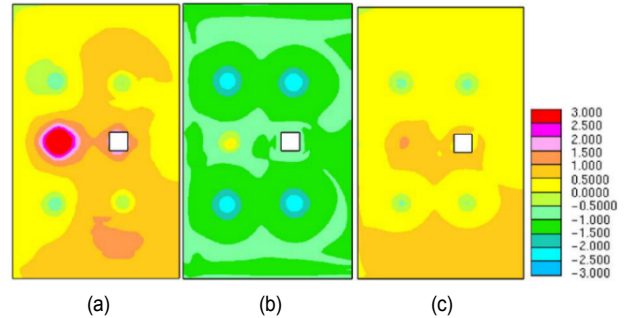


Fig. 6. Effect of mean radiant temperature (MRT) on thermal comfort for the underfloor air distribution system on the condition of supply air temperature = 18.5 °C, V_{in} = 1.2 m/s: (a) PMV distribution evaluated by using MRT; (b) PMV distribution evaluated by using air temperature; (c) PMV distribution evaluated by using MRT in case of full radiation simulation [28].

of the overheated surface, although the overall thermal comfort was maintained in most areas of the room in consideration of solar radiation. Radiation from humans should be considered to study thermal comfort. Kilic et al. [30] used a combined computational model of a room with CFD to determine heat and mass transfer between virtual thermal manikin, ambient, and human body physiological response. As a result, the radiative heat transfer coefficient of the whole-body was 4.6 W/m²·K, which closely similar to the generally accepted whole-body value of 4.7 W/m²·K. Sevilgen et al. [31] estimated the effect of different outer wall heat transfer values and radiator surface temperature on the occupant's thermal comfort with three-dimensional CFD. They concluded that a panel radiator with a high surface temperature and outer wall with good insulation would improve thermal comfort because cold surfaces could cause discomfort for humans due to significant convective and radiant heat losses.

2.1.4 Relative humidity

Relative humidity should be considered to evaluate the air quality of indoor spaces, and it is a factor that significantly affects the thermal comfort of people. When the relative humidity is low, a person feels dryness and may experience a physically unpleasant feeling, such as drying of the respiratory tract or dry eyes. While the relative humidity is high, the moist air in contact with the skin causes thermal discomfort or adversely affects existing bad health conditions due to the influx of fungi. In the long term, it can have a significant effect on health as it can affect the transmission of cancer [32]. Based on these backgrounds, because the effect of relative humidity on the thermal comfort of the human body has a huge impact, proper maintenance of humidity is essential to human health and thermal comfort. Based on these backgrounds, because the effect of relative humidity on the thermal comfort of the human body has a huge impact, proper maintenance of humidity is essential on human health and thermal comfort. There are several methods to control high humidity indoors, but it is roughly divided into three ways as follows; 1. Heat pump dehumidifier, 2. Dehumidifying ventilator, 3. Chemical absorbent dehumidifier. Recently,

one recommended way to control high relative humidity problems is to use the air conditioning system with desiccant dehumidifiers like a rotary desiccant wheel. In the desiccant dehumidifier, moisture in air is removed by a desiccant and the moisture-removed air is cooled and supplied in the occupied area by air-conditioning system. The air-conditioning system with desiccant dehumidifier requires less energy than a common air condition system for cooling under high humidity conditions because it remove sensible heat in the air. In addition, it is possible to control the temperature and humidity of the air independently. Therefore, it can be used to improve thermal comfort.

As a representative study based on relative humidity, Jing et al. [33] determined the effect of relative humidity on the response of occupants in a warm environment. Skin temperature was measured, and a subjective questionnaire was administered. High relative humidity could cause an increase in skin temperature; it was reported to provide uniformity of skin temperature, and it was suggested that with the rise in relative humidity, there was an increase in the thermal discomfort of occupants. Besides, when the air temperature was 30 °C, and relative humidity was more than 80 %, the survey results suggested that occupants desired a reduction in humidity. Kim et al. [34] analyzed the differences in psychological and physiological responses through electroencephalogram (EEG) mutation analysis to study changes in the body according to changes in humidity. The relative humidity was changed from 30 % to 80 % at a room temperature of 25 °C, and the comfort and concentration of the subject were investigated. As their results, when the relative humidity was in the ranges of 50-60 %, the comfort and concentration of the subject were the highest and the reduction of stress was the highest; moreover, it was confirmed that the heart rate also maintained a stable state at 60 % relative humidity. Thus, an appropriate humidity could seriously affect the thermal comfort, concentration, and physical stability of a person.

Several experimental studies on relative humidity and thermal comfort have been conducted [35-43]. Buonocore et al. [43] conducted an experimental study in the city of Lewis, Brazil, to determine the effect of the change in humidity on thermal comfort and thermal acceptability vote (TAV) in a humid tropical climate. Fig. 7 shows the results of the TSV corresponding to changes in room temperature and relative humidity. A place with good natural ventilation was selected in the building. It was confirmed that relative humidity had a significantly negative

effect on thermal sensation when the internal temperature was above 30 °C with respect to thermal comfort. Wind speed played an essential role in reducing thermal discomfort. Also, it was reported that atmospheric humidity significantly affected TSV, TCV, and TAV when the relative humidity exceeded 70 %, and mechanical cooling was required to achieve thermal comfort when the indoor operative temperature exceeded 31 °C.

2.2 Personal factors pertaining to thermal comfort

2.2.1 Clothing insulation

Humans have a similar basic structure, but thermal comfort is also affected by the metabolism and insulation of clothing. In a steady-state situation, heat is generated from the human body, and this heat must be gradually lost through heat exchange with the surroundings [44]. If heat loss does not occur properly, it causes thermal discomfort due to the accumulation of heat in the body; conversely, if heat loss occurs excessively, it has a negative effect on health. Clothing acts as an interface between the body and the environment, and this interaction between the body and the environment influences the perception of comfort in people. The physical condition is determined by physical processes in the surrounding environment and the properties of the clothes, such as heat and moisture transfer from the clothes and interactions between the clothes and the body. The reflection and absorption of light by the clothes provide physical stimulation to the body; moreover, the physical conditions such as thermoregulation reactions in the environment are decided by these environments.

As a representative study on the influence of clothing, Wang et al. [45] investigated thermal comfort according to the ratio of insulation offered by the clothing between the upper and lower body of a person. Thermal comfort was evaluated by clothing the upper body in clothes with short sleeves or long sleeves, knitwear, and jackets, either worn alone or in combination, and clothing the lower body in shorts, long pants, tights, and warm pants individually or in combination. As a result, it was confirmed that when there was minimal insulation in the lower body in a 20 °C environment, the thermal sensation decreased and the proportion of subjects who prefer a warm environment increased. People are accustomed to wearing more clothing in the upper body than on the lower body in a cold environment; however, they reported that it was better to distribute more clothing to the lower body in order to keep the body warm. Nam et al. [46] investigated the thermal comfort of preschoolers aged 4-6 years according to their clothes in Korea. For four seasons, the indoor and outdoor dry bulb temperature, wet bulb temperature, and airflow velocity in a total of 85 kindergarten schools were investigated. Fig. 8 shows the results of the thermal sensation of boys and girls at the indoor operating temperature. When the TSV is close to 0, the change of TSV is small according to the change in operating temperature. The average seasonal clothing amount of young children was measured to be 0.29 and 0.81 clo in summer and winter, re-

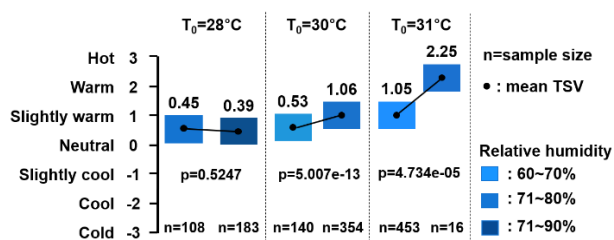


Fig. 7. TSV versus relative humidity per T_0 bin [43].

spectively, which was less than that required for adults as suggested by ASHRAE. The TSV showed relatively higher satisfaction in spring and autumn than other seasons, and children preferred a lower temperature than that normally preferred by adults (approximately 0.5 °C in summer and 3.3 °C in winter, respectively). It was also reported that children have a higher metabolic rate per unit weight; therefore, the satisfaction range of thermal comfort is relatively smaller than that of adults; thus, they are more affected by clothing than adults.

Jiao et al. [47] surveyed 672 elderly people in 17 facilities in China to confirm that insulation of clothing is an important factor in providing thermal comfort to the elderly in the thermal environment. Therefore, the average insulation of winter and summer clothes was determined to be 1.38 and 0.44 clo for men and 1.39 and 0.45 clo for women, respectively. In addition, the insulation of winter clothing was linearly related to age. The insulation of clothing in winter was negatively correlated with air and operating temperatures, which are the indoor temperature parameters for elderly men, and negatively correlated with transition space and outdoor temperature, which are the indoor temperature parameters for elderly women. In summer, both men and women reported that clothing insulation had a negative correlation with outdoor temperature and indoor parameters.

2.2.2 Metabolism

The amount of calories generated by a person varies significantly depending on physical characteristics such as body size, weight, and muscle mass. Human metabolism is a term used to describe all the chemical reactions involved in keeping cells and organisms alive. Metabolism is divided into catabolism, which is the decomposition of molecules for energy, and anabolism, which synthesizes all the compounds necessary for cells. Metabolism works in the body to maintain a constant body temperature. Therefore, metabolism is related to human thermal sensation, and thermal comfort can be evaluated based on metabolism. Tables 2-5 list examples of the metabolic rate (MET) measurement method proposed according to human behavior, occupation, and MET evaluation of people who scrape leaves [48].

Zhang et al. [49, 50] conducted an experimental study on thermal comfort in an outdoor space with an eave in which a subject walked for 20 min and rested for 10 min at a temperature of 34 °C and relative humidity of 85 %. Fig. 9 shows the results of the TCV according to walking speed. As walking speed increases, metabolic rate increases, and TSV increases. The metabolic rate was calculated by measuring the heart rate. Based on the experiment, it was determined that the thermal comfort of the subjects in the transition condition was affected

Table 2. Six methods for estimating metabolic heat production [48].

Level	Method	Accuracy	Inspection of the workplace
1	A: Classification according to type of activity	Approximate information where the risk of error is significantly great	Not necessary
	B: Classification according to occupation		Information on technical equipment, work organization
2	A: Use of tables or group assessment	High error risk: Accuracy ± 15 %	Time study required
	B: Use of estimation tables for specific activities		Not required
3	C: Use of heart rate defined conditions	Risk of errors within the limits of the measurement accuracy and time study: Accuracy ± 15 %	Time study required
	Measurement		

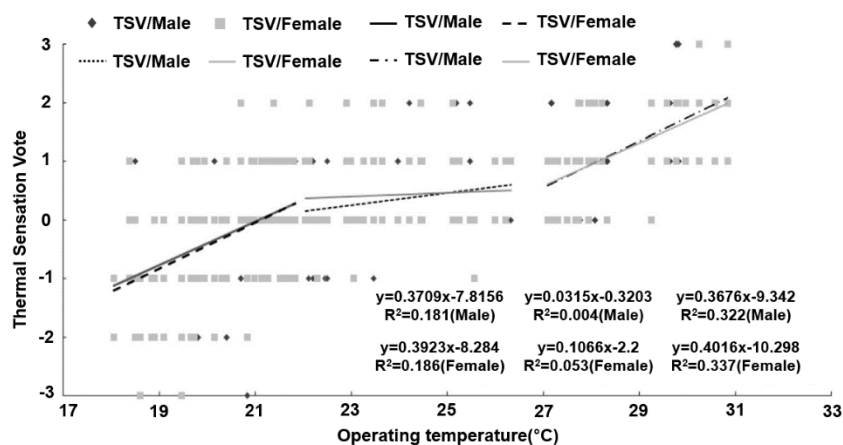


Fig. 8. Distribution of TSVs of male/female children in operating temperature [46].

Table 3. Classification of metabolic rates by activity [48].

Class	Mean metabolic rate (W/m ²)	Example
Resting	65	Resting
Low	100	Sitting at ease/standing
Moderate	165	Sustained hand/arm work
High	230	Intense work
Very high	290	Significantly intense to maximum activity

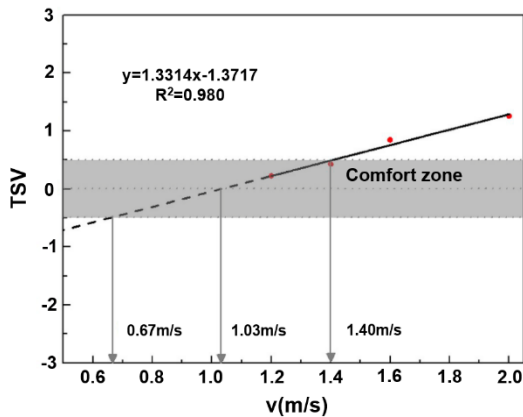


Fig. 9. Variation of TSV with respect to walking speed [50].

directly by the air velocity. Moreover, the stable metabolism, TSV, physiologically equivalent temperature (PET), and universal thermal climate index (UTCI) showed a linear relationship with air velocity. Further, it was reported that the change in metabolic rate to predict thermal comfort should be sufficiently considered. Luo et al. [51] studied the effect of changes in air temperature on the change in temperature. The base temperature was 26 °C, and the temperature ranges were divided into two groups: the cold temperature groups (24 °C, 21 °C, 18 °C, and 16 °C) and hot temperature group (31 °C and 28 °C). The measured metabolic rate was calculated using the following equations [51-53].

$$M = \frac{21(0.23RQ + 0.77)Q_{O_2}}{A_d}, \quad (1)$$

$$A_d = 0.202H^{0.725}W^{0.425} \quad (2)$$

where M (W/m²) is the metabolic rate, RQ is the respiratory quotient, which is the molar ratio between the volumetric rate of carbon dioxide production (Q_{CO_2}) and oxygen (Q_{O_2}) consumption at conditions of 0 °C and 101.3 kPa. A_d is the Dunois surface area (m²), H is the height (m), and W is the weight (kg).

Thus, it was determined that, in general, the metabolic rate showed the lowest value at the baseline temperature; however, it was confirmed that the metabolic rate increased when the baseline temperature was changed to cold and hot temperatures. Human metabolism could be affected by specific thermal

conditions.

Havenith et al. [48] studied the expression and measurement of clothing parameters and metabolic rates corresponding to the PMV. According to their study, in the case of clothing insulation, these factors must be considered in the modeling for predicting thermal comfort because the influence of body and air movements is significantly large. Also, it was confirmed that the decrease in air resistance and skin wetness according to air and body movement had a significant effect on the thermal comfort of people. The metabolism should be precisely measured for accurate thermal comfort evaluation, and the previously proposed evaluation method did not provide accurate thermal comfort measurement. Yang et al. [54] attempted to investigate the influencing factors of a permissible range in metabolic rate and pleasant range of thermal environmental parameters. They developed a mathematical model between thermal environmental parameters and the permissible range of metabolic changes using orthogonal experimental design and multiple regression analysis. It was confirmed that the fluctuation range of the metabolic rate was relatively slow when the temperature range was 18 °C-24 °C, while the fluctuation range of the metabolic rate was relatively fast when the temperature range was 24 °C-33 °C. It was confirmed that the most important factor influencing the allowable range of metabolic changes within the range of thermal comfort was air temperature, followed by relative humidity and air velocity. In addition, a linear relationship was established between these three factors and the range of changes in metabolic rate.

In this section, key factors influencing the thermal comfort of a person are explained, and representative studies are presented. Environmental factors such as air temperature, air velocity, radiant temperature, and relative humidity work comprehensively to create an indoor environment. Through clothing worn by a person, heat transfer occurs to the skin of a person, which causes physical and psychological changes in people as well as variations in emotional feelings. The air temperature is an important factor that is affected by the thermal environment, and when it is too high or low, the occupants experience thermal discomfort. Therefore, it is important to determine an appropriate TCZ. The TCZ is formed separately according to the direction and rate of change in air temperature. The TCZ in the heating condition is generated at lower temperature ranges than that in the cooling condition. The effect of air velocity on thermal comfort varies depending on the air temperature. For occupants, a temporary warm wind in winter and a temporary cold wind in summer help to improve thermal comfort; however, a consistently high air velocity can reduce thermal comfort. In addition, it is difficult to measure and calculate the exact radiant temperature in an indoor space, but it is a major factor that cannot be ignored. When the radiation temperature is too high, it may cause thermal discomfort because it affects the air temperature and occupants simultaneously. When the air temperature is low, the radiant temperature can help improve the thermal comfort of occupants. The relative humidity is also an important factor in maintaining good thermal comfort. When the

air temperature is low, and relative humidity is high, it achieves a uniform skin temperature distribution for the occupant. However, when the air temperature and relative humidity is high, sweat secretion occurs due to increased skin temperature. However, the evaporation of sweat does not occur actively owing to the high relative humidity; thus, the occupant may feel thermally unpleasant because it is not favorable for reducing the skin temperature.

The amount of clothing varies depending on the season, gender, and age group. Young children prefer lower temperatures than adults; therefore, the amount of clothing is lower; moreover, men prefer lesser clothing than women. Metabolism also varies according to human behavior and condition, and it increases as the amount of human activity increases. Under the same thermal environment, the increase in metabolism helps to improve thermal comfort, but a continuous increase in metabolism causes thermal discomfort. As various factors work in combination and affect the thermal comfort of the occupants, it is difficult to accurately define these factors, and it is important to understand the influence of these complex factors.

Based on an understanding of the significant factors that affect the thermal comfort of the human body, the next section presents representative studies on biosignals, which indicate physical changes caused by the surrounding environment. When the surrounding environment changes, physical changes as well as thermal sensations occur immediately. For instance, when the air temperature increases, the skin temperature, and pulse rate increase simultaneously. The primary biosignals to be measured in recent studies, including skin temperature, heart rate variability (HRV), and electrical activities of the brain measured through an EEG. In the next section, each biosignal is described briefly, and recent representative studies related to these biosignals are presented; further, the relationship between the biosignal and thermal comfort is introduced. In addition, the case of a complex study that links two or more biosignals is also presented.

3. Biosignals related to thermal comfort

As thermal comfort is a subjective evaluation based on what a person experiences, psychological factors have reflected these changes. These psychological changes occur owing to physical changes, which are generated by the effect of the thermal environment. Physical changes can be confirmed by measuring biosignals. Among the measurable biosignals, most studies measured skin temperature, HRV, and EEG values. In this section, the study of thermal comfort using these three biosignals is introduced, and the relationship between biosignal and thermal comfort is discussed.

3.1 Skin temperature

Thermoregulation is crucial to human life. The human body would cease to function without thermoregulation [55]. The skin is one of the most important organs in the human body through

heat flow to or from the surrounding environment in order to maintain the heat balance of the body [56]. There are numerous cold and hot spots in the skin of the human body that contact to the cloth or external air.

The skin performs various actions to maintain a constant human skin temperature by sensing the temperature from the surrounding environment and sending a signal to the brain to contract and relax human blood vessels. Therefore, skin temperature is one of the most important factors pertaining to human body temperature control, and most of the senses of a person under thermal conditions occur from skin temperature. Besides, body core temperature is also a key parameter to control human heat balance. However, most of the previous study focused on the skin temperature in studying thermal comfort of human with subjective evaluations because human maintains the body core temperature within small temperature ranges of 36 °C-38 °C, and the measurement of the body core temperature is relatively more difficult than that of skin temperature.

Steven et al. [57] investigated the effects of core body temperature and skin temperature by measuring thermal comfort, vasomotor changes, metabolic heat production, and systemic catecholaminergic responses in order to study the relative contributions of core body temperature and skin temperature to thermal comfort. Subjects lie down in cold of 14 °C, neutral of 34 °C, and warm of 42 °C between two circulating water mattresses, respectively. As a result of experiment, fingertip blood flow decreased to minimum level in all three treatment of core cooling. Metabolic heat production increased two and three times for the neutral and cold level, respectively. Concentrations increased three times during core cooling in the cold level, but it was unchanged the other conditions. Consequentially, body core temperature and skin temperature contributed equally to thermal comfort, whereas the body core temperature predominates in regulation of the autonomic and metabolic heat production.

To analyze the studies related to skin temperature changes according to various environmental changes, Yao et al. [58] conducted studies on overall and local thermal sensation and thermal comfort as well as the distribution of skin temperature in the body in a resting posture at different environmental temperatures (21 °C, 24 °C, 26 °C, and 29 °C). They confirmed that the overall thermal sensation of the human body is primarily affected by the body part that has the greatest thermal sensation under a given condition under a uniform thermal environment. They also reported that the overall heat detection followed the heat detection of the head and trunk parts, which are the warmest parts in a warm environment, and the temperature detection of cold limbs is considered in a cool environment. Moreover, 14 measurement methods for the average skin temperature were investigated and statistically analyzed. As a result of obtaining the average skin temperature ($p > 0.25$), it was confirmed that there was no significant difference between the Burton (three points) method and other methods. Liu et al. [59] measured ECG and skin temperature to study human

thermal comfort according to various air temperatures. To measure skin temperature, 26 calculation methods of mean skin temperature were investigated. The results indicated that the calculation method of mean skin temperature with 10 sites was the most reasonable with high reliability. Fig. 10 shows the skin temperature measurement location for the calculation of the mean skin temperature, and Table 4 lists the calculation methods for various mean skin temperatures for each location. The numbers of Table 4 are the ratio of each body part in the equation to calculate mean skin temperature. And each body part of the alphabet in Table 4 is presented in Fig. 10.

Yang et al. [60] investigated the discordance between PMV and actual mean vote in an air-conditioned environment through a laboratory study, and certain factors contributing to this discrepancy were identified. Consequently, it was confirmed that the adaptation of psychological and physical factors to the thermal environment was one of the factors of mismatch due to long-term life in a specific environmental condition. In addition, it was reported that psychological adaptation could neutralize the actual thermal sensation of occupants by regulating the thermal sensitivity of the skin. Tejedor et al. [61] studied a method of determining the thermal comfort of elderly people who are vulnerable to the cold environment using infrared thermography as an automatic control method of an HVAC system. As a result, it was confirmed that the PMV model from ASHRAE 55 overestimated the warm discomfort states of older people. Therefore, they suggested a new PMV method based on Infrared thermography. Thermal discomfort of elderly people was given when $19\text{ }^{\circ}\text{C} < \text{indoor temperature} < 20\text{ }^{\circ}\text{C}$, relative humidity $< 50\%$ (cold environment), or indoor temperature $> 24\text{ }^{\circ}\text{C}$ and relative humidity $> 54\%$ (warm environment). Chen et al. [62] investigated changes in temperature regulation and thermal perception that occurred simultaneously in response to temperature changes in a transient thermal state. The experiment was simultaneously evaluated based on thermal sensitivity as well as skin physiological characteristics, including skin capillary blood flow (SCBF), skin moisture, transepidermal water loss (TEWL), and skin temperature during the adaptation process. According to the test results, the decrease in thermal sensitivity, skin temperature, and SCBF of the subject was presented for 1 min after the temperature decreased from $32\text{ }^{\circ}\text{C}$ to $24\text{ }^{\circ}\text{C}$. When the air temperature decreased to $28\text{ }^{\circ}\text{C}$, it was confirmed that there was a close correlation between the skin temperature, appropriate skin moisture, and TEWL ($r = 0.42\text{-}0.54$). Ghahramani et al. [63] conducted a study using a new infrared thermal imaging technology that monitors temperature control and thermal comfort levels by measuring skin temperature at various points on the human face. They reported that there were significant variations in temperature control performance and cooling conditions between men and women. Also, the temperature control system response of women was less sensitive to warm conditions. Choi et al. [64] analyzed the correlation between skin temperature and heat sensation using the skin temperature at 10 different body parts by changing the indoor temperature from $20\text{ }^{\circ}\text{C}$ to $30\text{ }^{\circ}\text{C}$ at a

rate of $1\text{ }^{\circ}\text{C}/10\text{ min}$. Further, they investigated the possibility of using skin temperature as an indicator of warmth. Consequently, the skin temperature changed according to the indoor temperature. However, the rate of change in skin temperature was more consistent with thermal comfort than the actual skin temperature.

In particular, the measured skin temperature at the wrist was more sensitive than that at other parts of the body, and it provided more accurate data. It was reported that it is more appropriate to use skin temperature to indicate thermal sensitivity in a uniform environment than in a non-uniform environment.

Jian et al. [102] conducted an experimental study on the human thermal response in an actual air conditioner to explore the physiological thermal response and effect on the off schedule of the air conditioner. The experiment showed a strong correlation between skin temperature and TSV, and the relationship between the physiological thermal response, TSV, and off schedule of an air conditioner was presented. Research on the evaluation of thermal comfort through skin temperature was conducted not only in indoor spaces but also in automobile space. Zhou et al. [103] measured the skin temperature and TSV of the driver according to the external weather conditions that controlled the internal air and surface temperature of the vehicle while driving the vehicle in summer. It was confirmed that the air and surface temperatures of the vehicle were uneven and rapidly decreased during the first 15 min after the air-conditioning system was turned on. The thermal comfort of the vehicle did not reach a steady-state even after 2 h. Further, it was confirmed that there was a fairly close correlation between the average skin temperature and the average heat sensation. The thermal sensitivity of the driver in outdoor driving conditions was different from the thermal sensitivity in parking conditions.

The research on the relationship between human thermal comfort and skin temperature and the development of an algorithm or model to predict the relationship between them was also actively conducted recently. In the representative studies related to this research, Liu et al. [104] developed a support vector machine model and predicted the feelings of cool discomfort, comfort, and warm discomfort in an outdoor environment by using local skin temperature and heat load. The average skin temperature and average TSV of the simulation in this study are shown in Fig. 11. When a single local skin temperature was used as an input, the skin temperature of the exposed body part showed the highest prediction accuracy (66 %-70 %), while the skin temperature of the abdomen or chest showed the lowest prediction accuracy (42 %-58 %). When heat load was added, the prediction accuracy of the simulation model was increased by 1 %-5 %. Conversely, when the skin temperature of two body parts was used as input values, the prediction accuracy was increased by 4 %-7 %. Katic et al. [105] attempted to develop a mechanical algorithm model to predict the thermal preference by combining a personal comfort system, the skin temperature, time, and environmental data under heating conditions. When several models were used to analyze

Table 4. Mean skin temperature calculation methods [59].

Method	U	T	S	R	Q	P	O	N	M	L	K	J	I
3a					0.36						0.5		
3b			0.25										
4a					0.18		0.33				0.34		
4b					0.2		0.2				0.3		
4c					0.28							0.28	
5a					0.20		0.18				0.50		
5b						0.39			0.175	0.175			
6a							0.32				0.19	0.19	
6b						0.186	0.186			0.186	0.186		
6c							0.32			0.19	0.19		
7a	0.07				0.13		0.19				0.35		
7b					0.206		0.172				0.166	0.162	
8a					0.16		0.23		0.11	0.11	0.11	0.11	
8b					0.2		0.19				0.175	0.175	
8c					0.08		0.15		0.17		0.1	0.11	
8d					0.15		0.12		0.12		0.08	0.09	
9		0.06			0.13		0.19				0.18	0.18	
10a		0.05			0.15	0.125	0.125				0.125	0.125	
10b	0.06				0.115		0.19		0.095		0.095	0.19	
10c		0.07			0.13		0.19		0.12		0.12	0.12	
10d		0.1		0.1		0.1	0.1		0.1		0.1	0.1	
11		0.07			0.13		0.19		0.09	0.09	0.09	0.09	
12		0.07			0.065	0.095	0.095		0.0875	0.0875	0.0875	0.0875	
14		0.071		0.071	0.071	0.071	0.071		0.071	0.071	0.071	0.071	
15		0.0325	0.0625	0.0625	0.0625	0.1025	0.1025				0.2	0.18	0.0225
17		0.0305	0.0875	0.0875	0.0875	0.0875	0.0875	0.063	0.063	0.063	0.063	0.063	0.025

Method	H	G	F	E	D	C	B	A	Proposer	Year	Reference
3a			0.14						Burton	1934	[65-68]
3b			0.5					0.25	-	-	[69]
4a			0.15						Newburgh & Spealman	1943	[66, 70]
4b					0.3				Ramana- than	1964	[65, 69, 71-76]
4c	0.16					0.28			ISO	1992	[77, 79]
5a	0.05							0.07	-	-	[80]
5b					0.19		0.07		Houdas	1982	[66, 81]
6a		0.05	0.11				0.14		-	-	[80]
6b					0.107		0.149		Teichner	1958	[65]
6c	0.05		0.11				0.14		Palmer & park	1947	[65, 66]
7a		0.05	0.14					0.07	Hardy & Dubios	1938	[65, 66, 82-90]
7b			0.114		0.082	0.098			-	-	[80]
8a			0.085		0.085				-	-	[80]
8b	0.05		0.07		0.07			0.07	Gagge & Nishi	1977	[60, 66, 86, 91-93]
8c			0.06		0.12			0.21	Nadel	1973	[66, 94]
8d			0.12		0.13			0.19	Crawshaw	1975	[66, 95]

Table 4. (Continued).

Method	H	G	F	E	D	C	B	A	Proposer	Year	Reference
9	0.05		0.07		0.07			0.07	-	-	[80]
10a	0.06		0.07		0.07		0.1		QREC	1943	[65, 66]
10b	0.045		0.06		0.09			0.06	-	-	[80]
10c	0.05		0.06		0.08			0.06	Colin & Houdas	1982	[66, 96-98]
10d	0.1				0.1			0.1	Stolwijk & Hardy	1966	[64, 66, 99]
11	0.05		0.07		0.07			0.06	-	-	[80]
12	0.05		0.14					0.07	Hardy & Dubios	1938	[66, 82]
14	0.071			0.071	0.071	0.071		0.071	ISO	1992	[100]
15	0.0225		0.025		0.035			0.06	-	-	[80]
17	0.025		0.075		0.075		0.037	0.037	-	-	[80, 101]

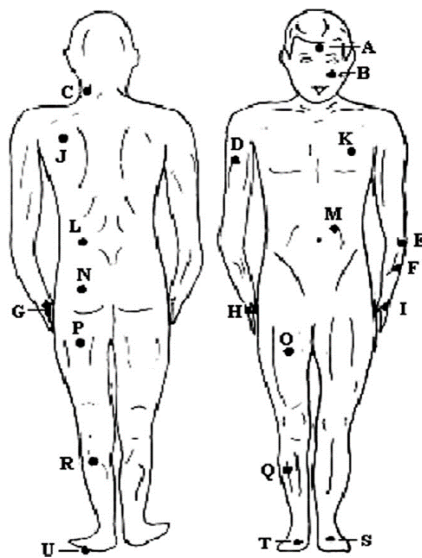


Fig. 10. Measuring sites of skin temperature (A. Forehead, B. Left cheek, C. Left neck, D. Right upper arm, E. Left elbow, F. Left forearm, G. Left palm, H. Right hand, I. Left hand, J. Left back, K. Left chest, L. Left lumbar, M. Left abdomen, N. Left buttocks, O. Anterior thigh, P. Posterior thigh, Q. Anterior calf, R. Posterior calf, S. Left foot, U. Left sole) [59].

the experimental and predicted results, it was confirmed that there is a close relation between skin temperature and thermal comfort. Thus, the skin temperature is an appropriate index for analyzing thermal comfort.

Lan et al. [83] studied a method for measuring skin temperature to investigate the thermal comfort of humans during sleep. They proposed a new three-point measurement system to calculate the mean skin temperature of sleeping subjects. Consequently, it was shown that the skin temperature on the surface of the body was more evenly distributed when a person was sleeping than when awaking. Moreover, the skin temperature of the forehead showed a close relationship with the heat sensation in a long-term measurement. The new three-point method to predict the heat sensation during sleep was

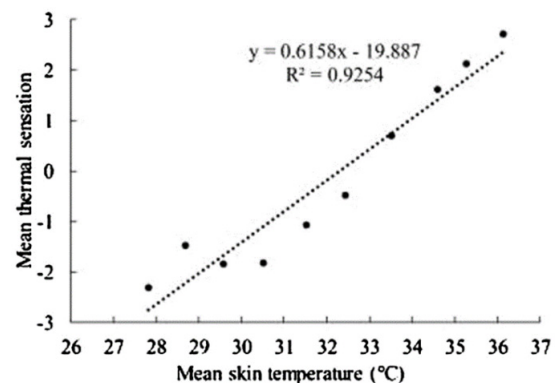


Fig. 11. Relationship between mean skin temperature and average thermal sensation [104].

better than the general seven-point method. Soebarto et al. [78] investigated the differences in thermal sensation, comfort acceptability, and preference between old and young people under the same conditions. Four experiments were conducted at 20 °C and 25 °C, with clothing insulation of 0.72 and 1.06 clo. Thus, it was confirmed that there is no significant difference in thermal comfort and acceptability between older and younger subjects. It was reported that the skin temperature of the hand for both older and younger subjects had a significant correlation with local and global thermal sensation.

3.2 Heart rate variability (photoplethysmography and electrocardiogram)

Humans regulate their body temperature through constriction and relaxation of blood vessels to recover from uncomfortable conditions in the surrounding environment. These changes in blood vessels appear owing to changes in heart rate. Moreover, to observe this variation, photoplethysmography (PPG) or electrocardiogram (ECG) is primarily used. In general, the PPG signal is measured using a pulse oximeter, which measures the difference in the amount of blood flowing into the blood

vessels during the systolic and diastolic states of the heart. The pulse oximeter measures the heart rate by optically detecting the PPG signal through red and infrared wavelengths and is a highly sensitive photodetector [106-108]. The ECG measures the pulse of the heart directly or measures the pulse wave that appears through pulse analysis by using electrodes on the hands and feet. The most commonly used method in HRV analysis is to analyze the RR interval. The RR interval is the difference between the two R-peaks of the heart beat over a time period, as shown in Fig. 12 [109].

HRV analysis can determine human thermal comfort by analyzing the low-frequency (LF) waves of the 0.03-0.15 Hz band related to the sympathetic and parasympathetic nerves of the heart and the high-frequency (HF) waves of the 0.15-0.4 Hz band related to the parasympathetic nerves. Commonly, this is used in the study of human thermal comfort [110-112]. LF/HF ratio is a value to infer sympathetic activity by canceling the parasympathetic nerve of the LF waves with the parasympathetic nerve of the HF waves. In most cases, when a person is not thermally comfortable, the sympathetic nerve, which has a close relation with stress and tension, is activated, and the value of LF/HF increases [113]. Using this variation of LF/HF, the thermal comfort of a person can be analyzed indirectly. In a study related to PPG, Zhu et al. [114] investigated the LF/HF variation with variations in air temperature, relative humidity, and air velocity, and analyzed the relationship between the average LF/HF and thermal comfort. When LF/HF approached a value of 1, the subjects showed satisfaction with the environment, and in particular, it was reported that the air temperature had the greatest effect on the LF/HF changes of the subject. Based on the result of their study, the correlation between LF/HF and the level of thermal sensation and thermal comfort are shown in Fig. 13. In addition, Choi et al. [115] investigated the effect of warm and cold conditions on the heart rate under the same activity level. Heart rate analysis clearly showed a proportional relationship with the metabolic rate based on activity level. Results for all subjects and male groups showed a significantly higher heart rate in a warm chamber than in a cool chamber at an activity level of 2.5 MET. Further, the changes

in heart rate according to activity levels were determined to increase significantly in warm conditions; in particular, this investigation demonstrated significant effects in men and subjects with a body mass index (BMI) of 22 or higher. However, it was also reported that the low BMI group did not show a significant difference between the two thermal conditions.

Jung et al. [116] presented a vision-based approach that uses RGB video images as the only source to infer the temperature control state of the human body in response to changes in the heat state and sensation of the indoor environment. Based on this study, a positive correlation was reported between the vision-based index, skin temperature, and thermal sensation, which showed a high possibility of inferring the thermal sensation of the occupant with sufficient sensitivity, and was confirmed in 10 out of 15 occupants. Nkurikiyeyezu et al. [117] proposed the use of HRV as an alternative indicator of thermal comfort. The experiment was analyzed based on statistics, spectrum, and HRV of 17 subjects who performed minimal office work in cold, neutral, and hot environments. The study confirmed that HRV was distinctly different depending on the thermal environment and could stably predict the thermal state of subjects with an accuracy of 93.7 %. In addition, Chaudhuri et al. [118] proposed a new TCV prediction method through an enhanced predicted thermal state method by detecting the skin temperature of the hand and pulse at air temperatures of 21 °C and 24 °C. It was confirmed that the pulse

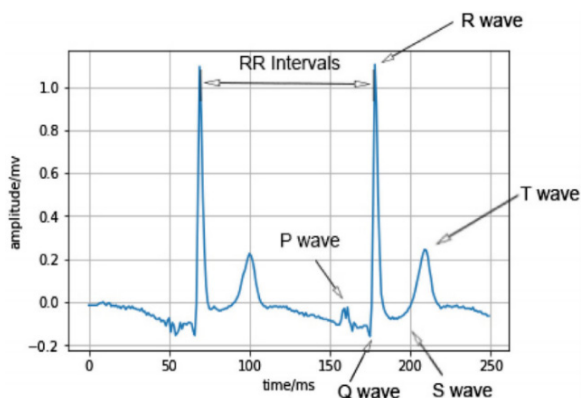
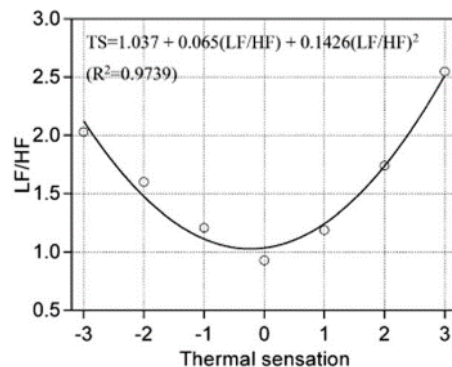
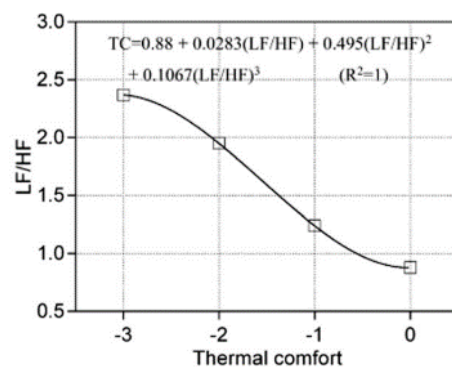


Fig. 12. Sample computation of RR interval from electrocardiogram signal [109].



(a)



(b)

Fig. 13. Relationship between LF/HF: (a) thermal sensation; (b) comfort level [114].

rate had considerable potential in predicting the thermal state of the occupants. Warm sensation caused an increase in heart pulse rates in women and people with low BMI. It was reported that the pulse rate of people with high BMI increased rapidly in warmer environments.

Research related to PPG measurements and thermal comfort was conducted in indoor environments and in various actual environments. Liu et al. [119] developed a model for personal thermal comfort using wearables that can be worn during daily activities. Fourteen models were trained to predict thermal preference using different machine learning algorithms. Consequently, the median predictive power considering all features was determined to increase Cohen's kappa, accuracy, and AUC to 24 %, 78 %, and 0.79, respectively, and the average predictive power achieved the corresponding values of 21 %, 71 %, and 0.7 after 200 subjective votes. It was reported that the personal comfort model showed the highest predictive power when the thermal sensation of the occupant deviated from thermal neutrality. Niu et al. [120] investigated the physiological response and thermal comfort of 54 healthy college students using meteorological measurements, longitudinal surveys, and physiological parameters while performing a variety of physical activities (light, medium, and extreme intensity) on six campus squares. The PET and UTCI were selected as thermal indicators, and blood pressure (BP), heart rate, and skin temperature were measured as physiological evaluation scales. Consequently, the ratio of thermal discomfort increased by 33, 50, and 83 %, corresponding to the increase in activity intensity; moreover, the BP and heart rate were shown according to the level of human activity. The skin temperature accurately represented the physiological response between spaces across activity levels. However, the mean skin temperature did not have any relation with heat detection voting. From weak to severe levels of activity intensity, neutral UTCI decreased by 27.6 °C, 25.6 °C, and 22.0 °C, respectively, and neutral PET decreased by 26.1 °C, 22.1 °C, and 11.9 °C, respectively. Further, it was reported that the shaded outdoor space was more comfortable for outdoor activities than the outdoor space with a low or medium sky view in summer.

3.3 Electroencephalogram

To maintain a constant body temperature under a given condition, a person senses the thermal flux of the ambient atmosphere through the skin and controls the reaction in the brain. The commands of the brain are presented by signals, and these signals are represented as delta, theta, alpha, beta, and gamma bands. The classification of each EEG by frequency band and the related representative states are listed in Table 5.

As a representative study related to brain waves and thermal comfort, Horiba et al. [122] determined whether correlated dimensional analysis of EEG is useful as a method for objectively evaluating the thermal sensation. As a comparative study of simple samples without and with clothing, the experimental results showed that the correlation dimension of EEG signals

Table 5. Classification of electroencephalogram signals based on the frequency and related brain activity [121].

Band type	Frequency (Hz)	Related activity
Delta	~0.5-4	Deep sleep
Theta	~4-8	Normal sleep, sleepy, or meditative state
Alpha	~8-13	Stability, resting, or comfortable state
Beta	~13-30	Tensioned or stressed state
Gamma	~30	Advanced information processing or complex mental activity

without wearing clothes was significantly smaller than that of the EEG signals with wearing clothes. These results showed EEG changes under comfortable conditions with a coat; moreover, the authors reported that expressing thermophysiological comfort with a correlated dimension was a new evaluation method to determine the thermophysiological comfort of clothing.

Kim et al. [123] investigated the effect of thermal sensation on the emotional responses of people. Experiments were performed based on three different temperatures (PMV = -2, 0, and 2), and EEG data of 139 participants were analyzed. Consequently, it was determined that the emotional process according to the room temperature was not important, but it was statistically significant according to the subjective thermal sensation. A positive bias was observed when the participant felt neutral or marginally warm; moreover, a negative bias was observed in all other cases. Accordingly, it was reported that the indoor thermal environment significantly affected the emotions, health, and productivity of tenants. Wu et al. [124] investigated the possibility of continuously mediating the thermal comfort of an individual by using EEG signals in the personal space. The spectral power of the EEG signals of 22 subjects was obtained, and a discriminant model was developed using a linear discriminant analysis or an ensemble learning method with a support vector machine as a sub-classification. It was confirmed that an average identification accuracy of 87.9 % could be obtained within a detection period of 60 s.

Son et al. [125] conducted an experimental study to investigate changes in thermal comfort according to the temperature changes. The changes in brain waves were recorded in various regions, and frequency bands and the results were compared for the various cases. In Fig. 14, the experimental results show the relative theta and beta powers at the positions of the parietal lobe (POz and Cz) and frontal lobe (Fz) in two groups. It was confirmed that the frontal relative theta power increased when the thermal comfort increased by changing the conditions, but the frontal, central, and parietal relative beta powers decreased.

Moreover, the results of thermal comfort evaluation were reported to have a positive correlation with the frontal, central, and parietal midline relative theta powers. Angelova et al. [126] conducted a study on human thermophysiological comfort in cold indoor environments (-1 °C and -11 °C) through EEG

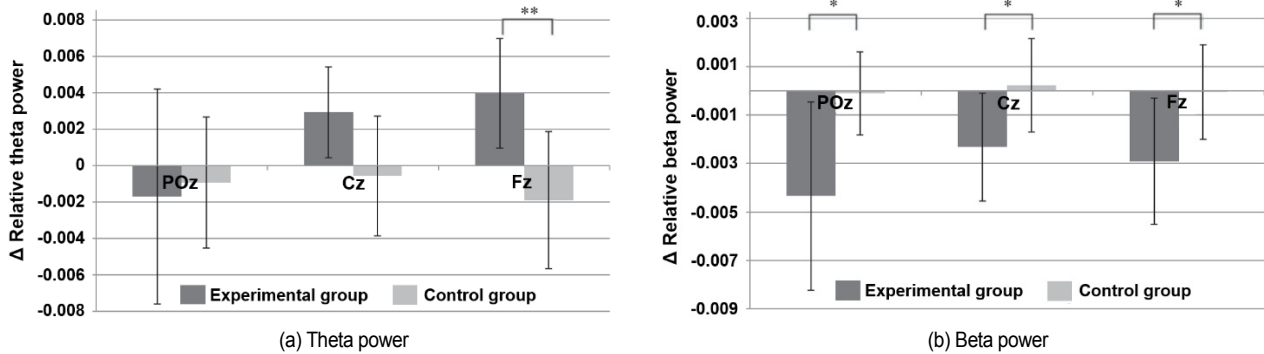


Fig. 14. Relative: (a) theta power; (b) beta power change at the three midline sites for the experimental and control groups [125].

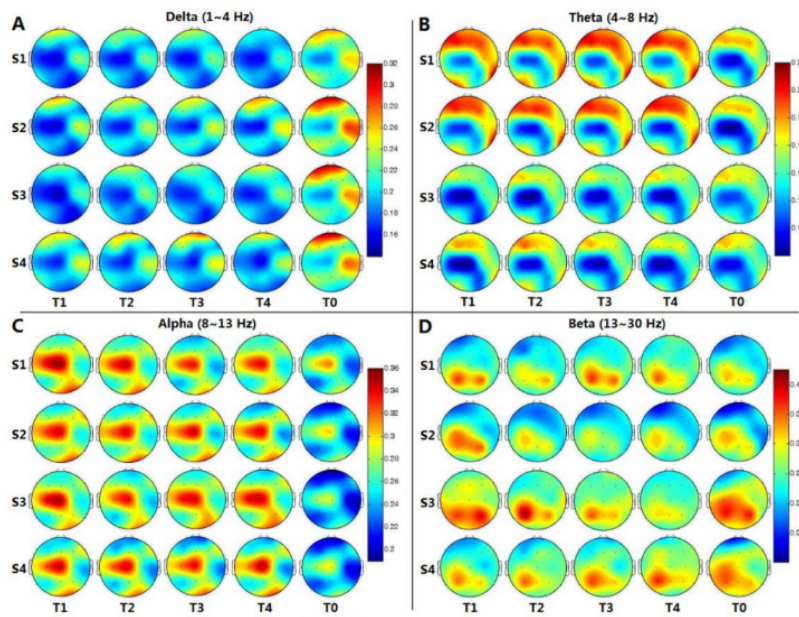


Fig. 15. Topographic patterns of group-averaged relative electroencephalogram (EEG) power in four frequency bands of interest [128].

measurements. Brain activity and brain power were evaluated to investigate thermal comfort. Thus, compared to the brain wave at a temperature of 22 °C as a reference, the delta and theta waves were prominent, and the alpha, beta, and gamma waves also appeared. Moreover, higher brain power was required to complete the same task, and cold environments affected the brain wave activities.

Shan et al. [127] experimentally investigated the correlation between EEG and subjective recognition/task performance, and additional research was conducted on machine learning-based EEG pattern recognition. In general, EEG frontal lobe asymmetric activity is related to subjective questionnaires and objective work performance. The authors reported that the use of EEG frontal asymmetric activity and machine learning-based EEG pattern recognition method as a feedback mechanism for passengers had significant potential to improve human interaction more objectively and holistically. Lv et al. [128] investigated the effects of the stimulation mode and air temperature on the brain response during local thermal stimulation of the hand. Fig.

15 shows the activation positions of each EEG in the four frequency bands in their study. With the visual comparison, the general topographic patterns and their alternation induced by the experimental condition were observed. The theta band activity under metal-based stimulation showed significantly higher EEG relative power throughout the brain than the theta band under water-based stimulation. When compared to stimulation based on water, the EEG relative power of beta band activity was lower during metal-based stimulation in the bilateral frontal and right temporal regions. Therefore, it was confirmed that neurophysiological responses in various EEG frequency bands are sensitive to various influencing factors during local heat stimulation of the hand. Lan et al. [9] experimentally investigated the effect of air temperature on sleep quality and sleep comfort. Sleep quality was assessed through a subjective questionnaire in the morning and an EEG and a subjective assessment of thermal comfort was performed before and after sleep. The analysis of the EEG signals revealed that when the room temperature was not neutral, the subject took a

longer time to fall asleep, and the short-wavelength sleep was presented a shorter duration. In addition, under these circumstances, they reported that subjective sleep quality was the worst.

3.4 Combination research of biosignals

The human body and principles of various operations are significantly complex and are linked to each other. In the evaluation of human thermal comfort, analyzing only one single biosignal, such as skin temperature, HRV, or EEG signals, produces less accurate results while observing human psychological and physical changes. Several studies were conducted through comprehensive analysis using various biosignals simultaneously to improve the accuracy of measuring human psychological and physical changes. First, the studies that analyzed HRV and EEG are introduced in this section. Kum et al. [129] evaluated the proper room temperature by analyzing HRV and EEG according to the rise in temperature. Based on the EEG measurement, it was reported that the increasing rate of LF/HF was 22.9 % as the temperature increased from 24 °C to 25 °C. When the temperature increased from 26 °C to 27 °C, the increasing rate of LF/HF was 10.8 %. By analyzing the physiological response of the human body according to the temperature increase, it was confirmed that the biosignals of HRV and EEG and the subjective questionnaires of TCV and TSV were consistent with each other and could be used as a useful tool for evaluating the thermal comfort of the human body. Yao et al. [111] conducted an experimental study on the variation of HRV and EEG according to the air temperature to investigate thermal comfort. The HRV and EEG of the subjects according to the changes in indoor air temperature based on 20 healthy subjects in their twenties were measured and analyzed. It was determined that the high LF/HF values were observed at environments with a low temperature of 21 °C and high temperature of 29 °C, while low values were observed at relatively comfortable temperatures of 24 °C and 26 °C. The HRV results showed the same tendency as the results of the subjective questionnaire. Besides, in the EEG measurement results, the tendency of the beta band, which occurs primarily in the tension or stress state, and the tendency of the alpha band, which occurs primarily in the rest or comfortable state, showed similar results to those of the subjective evaluation. Fig. 16 shows the relationship between the global relative EEG power of different bands and the thermal comfort sensations. The beta band of occupant was activated and the alpha band of occupant was deactivated in a thermally uncomfortable environment. They confirmed that HRV and EEG are closely related to thermal comfort and are useful tools for evaluating thermal comfort. Zhang et al. [130] conducted a 30 min cognitive performance test and National Aeronautics and Space Administration task load index (NASA-TLX) test at room temperature conditions of 22 °C and 25 °C in summer to investigate a suitable environment for working in a high-temperature office environment. They determined that the cognitive per-

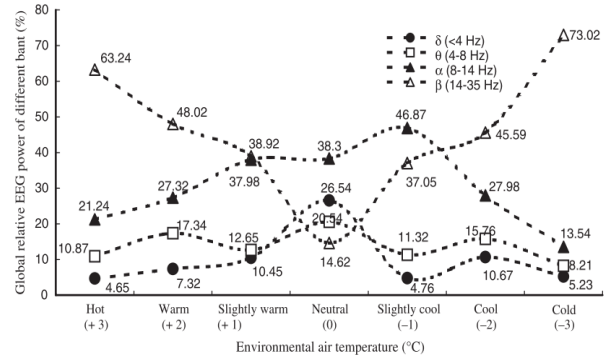


Fig. 16. Relationship between the global relative EEG power of different bands and the thermal comfort sensations [111].

formance test score was not affected by temperature; however, the results of NASA-TLX showed a significant decrease at a high temperature of 25 °C. Further, at temperatures of 22 °C and 25 °C, the measured values of EEG and HRV were not significantly different. That is, there is no large difference in work efficiency while working in an office environment at 22 °C or 25 °C in summer.

Skin temperature, HRV, and EEG signals were also measured and used to evaluate thermal comfort. In the representative studies based on these factors, Yao et al. [111, 131], Lan et al. [132], especially Shin et al. [133], and Kim et al. [134] reported the relationship between thermal comfort and biosignals in a vehicle using an experimental method. Yao et al. [111, 131] investigated the effect of air temperature on skin temperature, ECG, and EEG responses and the potential relationship between these factors and thermal comfort to study thermal comfort from a physiological perspective. When the air temperature increased from 21 °C to 29 °C, the average skin temperature increased; however, the maximum difference between the local skin temperatures decreased and the maximum difference between the average skin temperature and the local skin temperature in the neutral reaction was 5.3 °C at a temperature of 32.1 °C. It was confirmed that useful information on thermal comfort is provided using LF/HF values and EEG signals, and these measurements are sensitive to air temperature and the thermal comfort of subjects.

Lan et al. [132] evaluated the thermal comfort and biosignals during sleep according to three temperature change conditions: constant temperature condition (26 °C), falling-rising condition (28-27-26-27-28 °C), and rising-falling condition (25-26-27-28-27-26 °C). They determined that in the rising-falling conditions, as the skin temperature was low due to the low air temperature, the falling sleep time was longer. The subjective questionnaire also indicated that the sleep condition was poor. There was no change in the quality of sleep or thermal comfort of the subjects under the falling-rising conditions; moreover, it was reported that falling sleep time was delayed when the temperature was low in the early stages of the sleep period. Shin et al. [133] conducted a thermal comfort test in the cooling condition while reducing the cabin and vent discharged air temperature of the

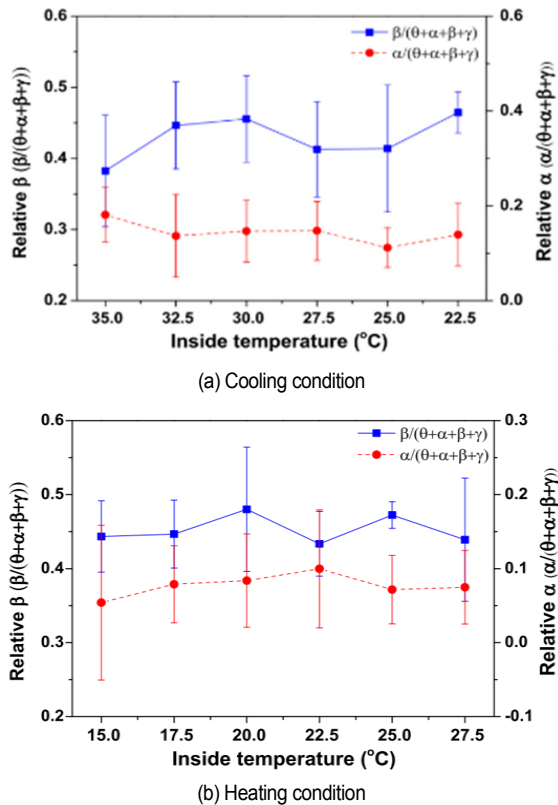


Fig. 17. Variations in relative beta and alpha bands of a driver in (a) cooling; (b) heating conditions [133].

vehicle in the cooling condition. In the heating condition, a test on thermal comfort was also performed while increasing the cabin and vent-discharged air temperature in the vehicle. Fig. 17 shows the relative beta and alpha bands of the driver in the cooling and heating conditions. In cooling condition, it was shown that driving at 25 °C of air temperature was more thermally comfortable than at 35 °C. In heating condition, it was shown that driving at 22.5 °C of air temperature was thermally comfortable than at 15 °C based on analyses of relative alpha and beta bands. When the HVAC system of the vehicle was in a cooling condition, it demonstrated the most effective inactivation of the autonomic nervous system; moreover, the stress of the driver was reduced while driving when the cabin and vent outlet air temperatures were 27 °C and 11 °C, respectively. In addition, this condition was relatively effective in increasing the concentration for driving. Under heating conditions, the cabin and vent outlet air temperatures were 22 °C and 40 °C, respectively, which were most effective in reducing the stress of the driver. The cabin and vent outlet air temperatures of 20 °C and 37 °C were most effective increase the concentration during driving. It was confirmed that the internal environmental conditions of the vehicle were different from those inside the building, and the temperature at the vent outlet had a significant influence on the thermal comfort and concentration of the driver; moreover, the use of PPG and EEG was suitable for the evaluation of concentration, stress, and thermal comfort. Kim et

al. [134] conducted thermal comfort evaluation through subjective surveys and biosignal studies based on EEG and ECG measurements to investigate the comfortable heating mode during indoor heating of passengers in a short time in winter. The subjective survey determined that the subjects showed a more sensitive response to the feeling of comfort than the feeling of warmth, and the seat heating mode was the most preferred. Based on the analysis of EEG and ECG signals, it was confirmed that thermal stress increased after a certain period during hot air heating and the warm air heating mode could be used for a short time to increase the indoor temperature of the initial boarding period of the driver. Moreover, it was determined that when the seat heating mode was actively used, it could help improve the thermal comfort of the driver in winter.

In summary, some representative studies based on skin temperature, HRV, and EEG signals, which are biosignals according to various thermal environments, were introduced and compared in the above paragraphs. Several studies were conducted on the relationship between various biosignals and thermal comfort, and their usefulness was presented. As human skin is insulated by clothes and exposed to the thermal environment, skin temperature is the most important biosignal that changes according to the variation of the thermal environment. Humans sensibly detect changes in skin temperature, and this sensation is transmitted to the brain, which causes physical changes in the body through brain waves. This also results in a change in the HRV. The senses of a person and subjective thoughts that respond to them can determine thermal comfort in a given thermal environment. This implies that biosignals are not independent and have some relationship with each other. Therefore, in the study of thermal comfort, the measurement of biosignals requires comprehensive researches rather than independent research. Moreover, it can be confirmed that biosignals have a meaningful relationship with the subjective feeling of thermal comfort. Thus the use of bio-signal is an effective method to investigate human thermal comfort objectively.

4. Discussion

Many researches of thermal comfort have been conducted based on the experimental conditions, which were discussed in Sec. 2, and these were developed by using bio signals and subjective surveys, which were also discussed in Sec. 3. Thermal comfort has been studied not only indoor of the building but also in other space such as a vehicle, train, and airplane, etc. Because of the constraints of the experimental conditions, most of the researches on thermal comfort has been conducted in the thermal environment chamber or small lab, but these environments are quite different from the actual environments. In previous studies about influencing factors on thermal comfort, some studies on the actual field have been progressed. However, it is not easy to conduct research on thermal comfort by measuring biosignals of the occupant in an actual situation such as driving in a car or traveling by train,

and so on. It is because that attaching various measuring devices to the subject's body in order to measure the thermal comfort under actual conditions can have a great influence on the thermal comfort of subjects as well as the safety during the experiment. Therefore, the evaluation method of thermal comfort in the actual environment is mostly dependent on PMV-PPD calculation.

Since research on the thermal comfort of humans is being carried out to maintain high thermal comfort by providing a comfortable environment to people, the fast or instant evaluation and feedback on the environment of people is absolutely essential. The evaluation of the thermal comfort of the human is possible to perform the measurement of biosignals. Thus, skin temperature, HRV, and EEG were discussed previously in this study. However, it is very difficult to quickly and precisely measure and analyze HRV and EEG because the physical conditions and momentary states of various subjects are different momentarily. Therefore, a solution to solve this problem is also needed in future work. Fortunately, the research on the relation of various biosignals has been in progress continuously, and it can be expected that the correlation between the skin temperature (which is easy to measure and analyze) and HRV and EEG (which are difficult to immediately analyze) will be developed in a soon time. However, if only skin temperature is used to control the thermal environment, it is not possible to satisfy thermal comfort to all people due to differences in human sensitivity under the same environment. Accordingly, it seems that more than two indicators are needed to control the thermal environment. When pulse wave is measured and analyzed using a smartwatch, and its data is analyzed with the measured skin temperature simultaneously, it is expected to develop an algorithm or system that can control the surrounding environment with high thermal comfort.

Because thermal comfort is quite subjective, it is difficult to satisfy everyone's thermal comfort in a space where several people live together (school, office and home, and so on). Therefore, it is necessary to develop a personal thermal environment control device or system that can control individual thermal comfort separately and efficiently. As an example, a local heating or cooling system can be suggested. The local cooling and heating systems are superior in energy savings and higher satisfaction with the thermal environment than a method of integrally controlling the whole thermal environment in an indoor space. Thus, many researches on the development of local cooling and heating systems are actively conducted as a way to realize energy reduction as well as improvement of personal thermal comfort in unpleasant thermal environments.

Although many studies on human thermal comfort have already been conducted, more studies are needed to overcome the various limitations and disadvantages of thermal comfort. In particular, in recent years, since the use of many high technologies can obtain various objective data that could not be obtained before, it is expected that research in connection with these data will be carried out actively. In the present study,

based on the existing studies on human thermal comfort, various studies related to thermal comfort were investigated and introduced to present the direction of future study in this field. This study is expected to be helpful in research for the development of thermal comfort of humans.

5. Conclusion

In this paper, representative factors influencing the thermal comfort of occupants in an indoor space, the evaluation of thermal comfort, and studies on thermal comfort using biosignals were presented and discussed. Because thermal comfort is a state of mind that expresses satisfaction with the thermal environment and is evaluated subjectively, the indicator can be obtained through human investigation or prediction. TSV and TCV are utilized for the evaluation of thermal comfort, and PMV and PPD are methods of predicting thermal comfort through various factors of the thermal environment. There are two types of factors related to thermal comfort: environmental factors as mentioned in ASHRAE, such as air temperature, relative humidity, air velocity, and individual factors such as clothing insulation and metabolic rate. Human thermal comfort is affected by the ambient air temperature, the air velocity, and the rate of increase or decrease in air temperature. Also, it is difficult to calculate the radiant temperature, but it has a great influence on thermal comfort like irradiation of the sun. Relative humidity changes the sensation on the human skin with a combination of air temperature and air velocity. When the relative humidity is low in a hot environment, humans can feel more comfortable than in the high relative humidity. Additionally, when the relative humidity is high in a cold environment, the human can feel more comfortable than in the low relative humidity. The insulation of clothes is a medium between the thermal environment and the human skin and protects the human skin from the thermal environment. It appears more sensitive to children than adults. Maintaining a high metabolic rate through intense exercise in a colder environment is one of the ways to increase thermal comfort. These six factors have a complex effect on the human body and significantly affect thermal comfort.

The thermal comfort of an occupant is expressed through psychological evaluations based on physical reactions caused by changes in the thermal environment. Biosignals, a physical response, are being studied to objectively investigate thermal comfort. The representative measured biosignals are skin temperature, HRV, and EEG signals. Skin temperature, which is first affected by changes in the thermal environment, indicates the beginning of changes in the body. Due to the sense of experiencing changes in the skin temperature, the brain commands changes in body reactions such as changes in heart rate based on changes in brain waves; therefore, thermal comfort can be studied through this biosignal analysis. In HRV studies, LF/HF analysis is mainly used. When the human is exposed to a discomfort environment, the LF/HF index increases. As the LF/HF index is high, the sympathetic nerve is

active, causing tension and arousal. Additionally, human thermal comfort can be confirmed through HRV as a biosignal. In the case of EEG studies, it is possible to check the psychological and physical state according to the frequency band of the brain. For example, the α band indicates a stable state with a frequency range of 8 to 12 Hz, and the β wave implies a tensioned state with a frequency range 16 to 30 Hz. Relative α/β index can be used to determine whether it is a relatively stable or tension state. These interconnected biosignals have a relationship, which was proven by several previous studies. In the study of thermal comfort, biosignals require related and comprehensive research rather than research considering each factor independently. Moreover, it can be confirmed that these factors have a meaningful relationship with the subjective feeling of thermal comfort. However, biosignals are very sensitive and subjective, performing research on biosignals and thermal comfort is difficult, and it is challenging to define objective indicators and conditions. These studies are necessary and must be continuously developed to create a comfortable and proper environment using biosignals for the future.

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Nomenclature

<i>ADPI</i>	: Air diffusion performance index
A_d	: Dunois surface area
<i>AUC</i>	: Area under the receiver operating characteristic curve
<i>BMI</i>	: Body mass index
<i>BP</i>	: Blood pressure
<i>CFD</i>	: Computational fluid dynamics
<i>CPMV</i>	: Corrected PMV
<i>ECG</i>	: Electrocardiogram
<i>EEG</i>	: Electroencephalogram
<i>H</i>	: Height (m)
<i>HF</i>	: High frequency (Hz)
<i>HRV</i>	: Heart rate variability
<i>HVAC</i>	: Heating, ventilation, and air-conditioning
<i>LF</i>	: Low frequency (Hz)
<i>MET</i>	: Metabolic rate
<i>MRT</i>	: Mean radiant temperature
<i>PET</i>	: Physiologically equivalent temperature
<i>PMV</i>	: Predicted mean vote
<i>PPD</i>	: Predicted percentage dissatisfaction
<i>PPG</i>	: Photoplethysmography
Q_{O_2}	: Volumetric rate of oxygen consumption
Q_{CO_2}	: Volumetric rate of carbon dioxide production

<i>RQ</i>	: Respiratory quotient
<i>SCBF</i>	: Skin capillary blood loss
<i>TAV</i>	: Thermal acceptability vote
<i>TCV</i>	: Thermal comfort vote
<i>TCZ</i>	: Thermal comfort zone
<i>TDV</i>	: Traditional displacement ventilation
<i>TEWL</i>	: Transepidermal water loss
<i>TSV</i>	: Thermal sensation vote
<i>UFAD</i>	: Underfloor air distribution
<i>UTCI</i>	: Universal thermal climate index
<i>W</i>	: Weight (kg)

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