Thermal comfort prediction considering thermal adaptation based on facial temperature using thermal images and subjective indexes

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Abstract. The aim of this study is to predict thermal comfort based on a subjective evaluation index of occupants and thermal imaging data, which are physiological signals, while considering thermal adaptation. This study was conducted in an office in the winter, and three subjective evaluation indexes were used. Air temperature data was obtained using a specific equipment, and the facial temperature was recorded using a thermal imaging camera. Based on analysis, thermal adaptation yielded different results at the same facial temperature. In previous studies, a facial temperature of 33 °C before thermal adaptation signified discomfort. However, the same facial temperature of 33 °C after thermal adaptation signified comfort. This implies that simple indexes and physiological signals based on thermal imaging are insufficient to predict the subjective thermal sensation of occupants. Therefore, accuracy of thermal comfort prediction can be improved significantly by considering thermal adaptation using the existing subjective evaluation indexes as well as by considering the results of studies pertaining to facial temperature.

1 Introduction

Thermal comfort is an important factor in controlling the HVAC (heating, ventilation, & air conditioning) system of buildings. A thermally comfortable indoor environment is vital to human health, work productivity, and building sustainability [1, 2]. Therefore, the HVAC system of a building must be controlled by predicting thermal comfort. Accordingly, many relevant studies have been actively conducted.

Prediction models for thermal comfort are based on the principle that physiological signals can be correlated with thermal sensation [3, 4]. The thermal comfort of occupants has been predicted using a subjective evaluation index, i.e., the "ASHRAE 7-point scale," as a conventional method for predicting and evaluating individual thermal sensation [5–7].

Thermal sensation is a subjective feeling of the thermal environment. However, previous studies show that subjective evaluation alone cannot fully reflect the thermal comfort of occupants [3]. Therefore, various studies have been conducted to overcome this limitation. In particular, researchers are interested in predicting thermal comfort based on skin temperature, which is a physiological signal [8–11]. Skin temperature, which responds to various thermal environments, changes the temperature sensed by a skin sensor [6, 7]. Therefore, the skin temperature can be used theoretically as a physiological index to predict thermal sensation.

Recent studies consider human physiological signals to predict thermal comfort, although most focus on prediction models. The relationship between subjective assessment and the physiological response of occupants is rarely investigated. In particular, the human biological variable, "thermal adaptation," is not considered in physiological signals.

Since humans can adapt to their surroundings, the actual range of indoor thermal comfort is in fact wider than the generally defined range [12-14]. Therefore, thermal adaptation should be considered in studies related to thermal comfort.

The aim of this study is to predict thermal comfort based on a subjective evaluation index of occupants and thermal imaging data, which are physiological signals, while considering thermal adaptation.

2 Methods

This study focuses on the relationship between the subjective assessment of thermal comfort before and after thermal adaptation as well as the objective physiological response of occupants.

Recently, the thermal state index (TSI) has been used in many studies as a subjective evaluation index in the field of thermal comfort. TSI, which is simpler than the thermal sensation vote (TSV), has been verified and used as a more appropriate indicator for indoor HVAC systems [2]. The TSI index is categorized into three levels (-1: Cool - discomfort, 0: Comfort, and 1: Warm - discomfort). As shown in Figure 1, the seven levels of TSV can be converted to three levels of the TSI.

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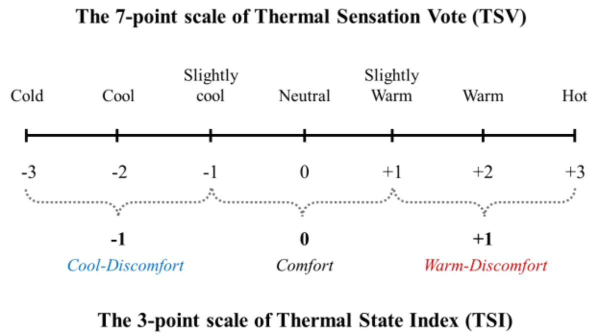

Fig. 1. ASHRAE 7-point thermal sensation scale and corresponding Thermal State Index.

This concept is applied in this study to analyze thermal comfort more comprehensively.

Previous studies confirmed that the skin temperature of the human body is affected more significantly in the winter than in the summer [14]. Physiological signals are crucial, particularly at cold temperatures [15]. In previous studies pertaining to thermal sensation prediction, the temperatures of body parts (arms, legs, neck, face, etc.) were compared with thermal imaging data; the results showed that the facial temperature was predicted with the highest accuracy [5, 8-10]. Additionally, the ideal average temperature of the face was shown to be 33°C (33.0°C to 33.9°C) [16, 17].

Therefore, this study was conducted in an office in the winter, and three subjective evaluation indexes (TCV, TSV and TSI) were used. Air temperature data was obtained using a specific equipment, and the facial temperature was recorded using a thermal imaging camera. Thermal data were obtained by applying the human thermal adaptation time (30 min), which was derived previously [18, 19]. To effectively control temperature changes in body parts other than the face, the amounts of activity and clothing of occupants in an office during the winter were specified based on the ASHRAE standard [5].

3 Experiments

3.1 Experiment Outline

In this study, a field survey was conducted in an actual office in the winter. The HVAC system in the office (the experimental space) was controlled to the recommended winter indoor temperature for Korea (22°C).

To analyze the subjective thermal comfort of occupants, ASHRAE-based evaluation indexes were used, as shown in Table 1 [5]. TSV and TCV data were obtained as subjective evaluation data and analyzed by applying the TSI standard.

Furthermore, as shown in Table 2, the air temperature was measured using a specific equipment, and the facial temperature before and after thermal adaptation was photographed using a thermal imaging camera.

Table 1. Questionnaire survey items.

Thermal Comfort Vote (TCV)						
Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly Comfortable	Comfortable	Very Comfortable
1	2	3	4	5	6	7
Thermal Sensation Vote (TSV)						
Cold	Cool	Slightly cool	Neutral	Slightly Warm	Warm	Hot
-3	-2	-1	0	1	2	3

Table 2. The equipment for the Experiment.

No.	Equipment	Control and measurement	Image
1	Data log	temperature	
2	Thermal imaging camera	facial temperature	

The facial temperature was separately recorded using a camera before and after thermal adaptation. The thermal imaging data obtained immediately after the participants entered the experimental space were defined as the facial temperature values before thermal adaptation. Notably, the participants entered the experimental space simultaneously. At this time, the temperature of the heater was set to 22°C. The thermal imaging data obtained 30 min after seating (when the heater were operating) was defined as the face temperature values after thermal adaptation.

The experiments were conducted at the same location and time for 14 d. Sixty participants (male, 30; female, 30) participated in the experiments, and their average age was 20 to 30. The clothing insulation level (clo) of the participants was limited to 1.0 clo. The amount of activity during the thermal adaptation process (30 min) was limited to “the metabolic rate of a person sitting and typing,” i.e., approximately 1.1 met [20].

All participants were healthy and did take prescription medicines. The participants were instructed to avoid drinking alcohol, smoking, and intensive physical activity for at least 12 h prior to the experiments [21]. All processes including investigation as well as data sharing and storage performed during the experiments were ethically approved by the participants.

3.2 Positioning

The indoor air temperatures during the experimental period were as follows. The average air temperature at

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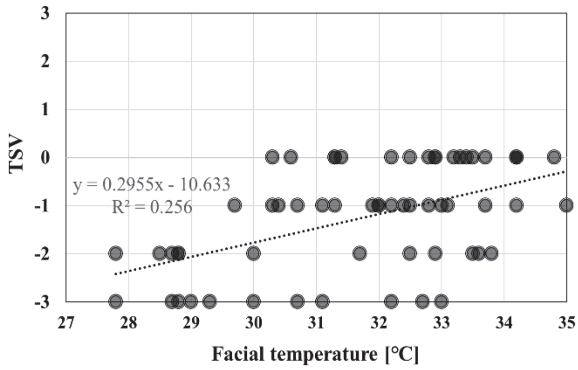
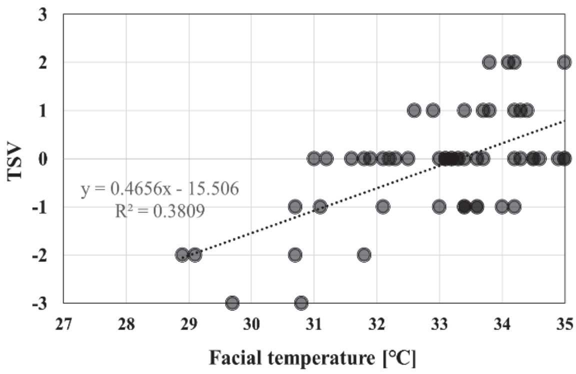
check-in was 19.2°C, and the average air temperature 30 min after check-in was 22.2°C.

The results of the participants' TSV and facial temperatures based on thermal imaging are shown in Figure 2.



(a) Prior to thermal adaptation



(b) After thermal adaptation

Fig. 2. The participants' TSV and facial temperatures based on thermal imaging.

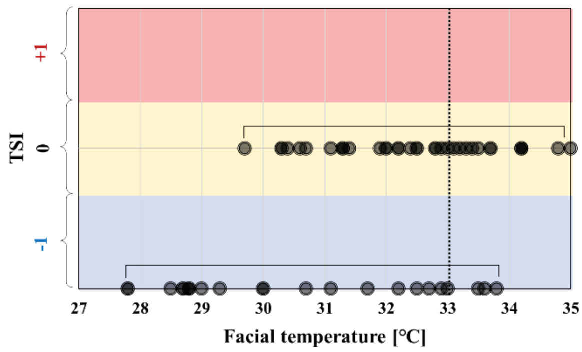
Prior to thermal adaptation (a), the highest TSV value was 0 (neutral), and the facial temperature ranged between 30.3°C and 34.8°C. The lowest TSV value was - 3 (extremely cold), and the facial temperature ranged between 27.8°C and 33.0°C.

After thermal adaptation (b), the highest TSV value was 2 (warm), and the facial temperature ranged between 33.8 °C and 35.0°C, which corresponded to a small temperature range of 1.2°C. The lowest TSV value for (b) was - 3 (extremely cold), which was the same as that for (a). However, the facial temperature ranged from 29.7°C to 30.8°C for (b), which was higher than that for (a). In fact, it was the smallest temperature range recorded, i.e., 1.1°C.

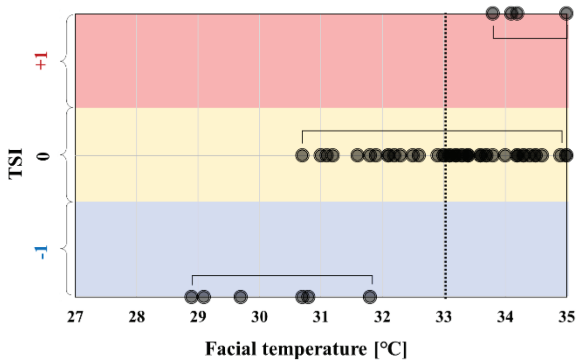
Based on analysis, the lowest and highest facial temperatures for (a) were 27.8°C and 35.0°C, respectively. Meanwhile, the lowest and highest facial temperatures for (b) were 28.7°C and 35.0°C, respectively. For both cases, the highest facial temperature values were the same, whereas the lowest facial temperature values differed by approximately 1°C. This confirmed that the facial temperatures before and after thermal adaptation were different.

4 Discussion

Figure 3 shows the analysis results after applying the TSI. They were mapped based on the TSV, and the relationship was analyzed based on a previous study [22] and the TCV.



(a) Prior to thermal adaptation



(b) After thermal adaptation

Fig. 3. Mapped based on the TSI.

The results show that the participants were more likely to feel comfortable at higher facial temperatures. Since these experiments were conducted in the winter, the participants responded that they felt more comfortable when the environment was warmer [22,23]. In addition, most results (comfortable facial temperature = 33.0°C–33.9°C) from previous studies [16, 17] were included in the "comfort (0)" level of this study. However, some of the results showed the "cool - discomfort (-1)" level of (a), which was 33.0°C, as well as the "warm - discomfort (1)" level of (b) (33.8°C). Therefore, a comprehensive analysis was performed by deriving the probability (%) of thermal comfort before and after thermal adaptation were derived and analyzed.

The sum of probabilities of three levels, i.e., "cool - discomfort (-1)," "comfort (0)," and "warm - discomfort (+1)," was 100%. The results are shown in Figure 4.

For case (a), all occupants (100%) felt uncomfortable at the facial temperature of 28°C or lower. As the facial temperature increased, the probability of feeling uncomfortable increased proportionately. When the facial temperature reached 33°C, approximately 80% of the occupants felt comfortable. When the facial temperature reached 34.0°C, all occupants (100%) reported that they felt comfortable; this was sustained until the next facial temperature.

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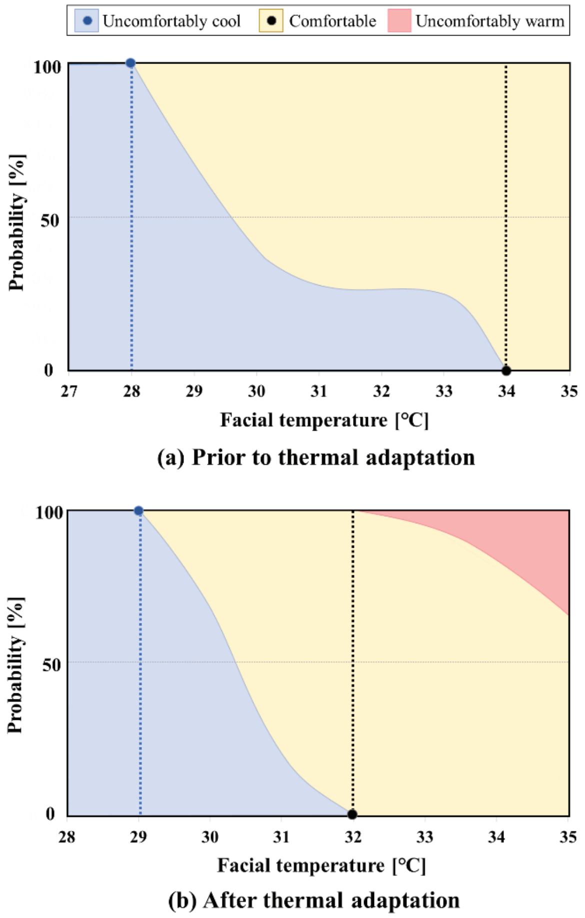

(a) Prior to thermal adaptation

(b) After thermal adaptation

Fig. 4. The probability distribution of TSI.

For case (b), all occupants (100%) felt uncomfortable when the facial temperature was 29.0°C or lower, which was higher than that of case of (a) by approximately 1°C. The probability of feeling comfortable increased with the facial temperature. All occupants (100%) reported that they were comfortable at 32°C, which was lower than the case of (a) by approximately 2°C. This implies that when thermal adaptation is applied to the human body, which is case (b) in this study, a higher level of comfort can be achieved compared with case (a), even if the facial temperature is lower. Additionally, the probability of being uncomfortably warm was indicated, although the probability of feeling comfortable exceeded 50%.

Finally, regression analysis was performed to derive a comfortable facial temperature range before and after thermal adaptation, as shown in Table 3 and Figure 5. The comfort range was compared at 80% and 90% satisfaction.

Table 3. Comfortable facial temperature range before and after thermal adaptation (1).

Comfort Range	Before thermal adaptation (a)	After thermal adaptation (b)
80% satisfaction	30.8 °C–34.2 °C	33.3 °C–35.0 °C
90% satisfaction	31.3 °C–33.5 °C	33.5 °C–35.0 °C

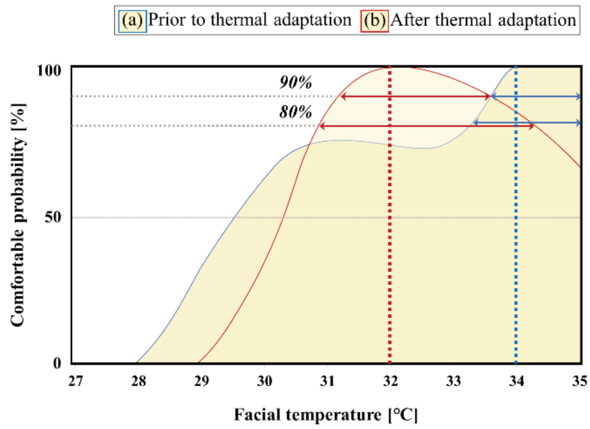

Fig. 5. Comfortable facial temperature range before and after thermal adaptation (2).

When the comfort range was 80%, the comfort ranges of the facial temperature before and after thermal adaptation were 30.8°C–34.2°C and 33.3°C–35.0°C, respectively. When the comfort range was 90%, the comfort ranges of the facial temperature before and after thermal adaptation were 31.3°C–33.5°C and 33.5°C–35.0°C, respectively.

The facial temperatures of the participants before thermal adaptation differed by approximately 1°C, depending on the comfort range. However, the facial temperature of the participants in the comfort range after thermal adaptation began from 33°C in general. This result is comparable to those of previous studies [16, 17].

In general, thermal adaptation yielded different results at the same facial temperature. In previous studies, a facial temperature of 33°C before thermal adaptation signified discomfort. However, the same facial temperature of 33°C after thermal adaptation signified comfort. This implies that simple indexes and physiological signals based on thermal imaging are insufficient to predict the subjective thermal sensation of occupants. Therefore, to improve the accuracy of predicting the thermal comfort of occupants in the future, the thermal adaptation of occupants should be considered in addition to subjective evaluations and physiological signals.

5 Conclusion

In this study, data before and after thermal adaptation were analyzed using subjective evaluation indexes for offices in the winter as well as facial temperatures measured via thermal imaging. The analysis results showed that the facial temperatures before and after thermal adaptation differed significantly. The same facial temperature was interpreted differently depending on thermal adaptation. When the facial temperature of the occupants was 33°C, which is a comfortable level, most of the occupants reported that they were comfortable. However, because some of the occupants reported feelings of discomfort, the results of thermal comfort were analyzed comprehensively based on probability (%) and the regression analysis method.

The results confirmed that the accuracy of thermal comfort prediction can be improved significantly by considering thermal adaptation using the existing subjective evaluation indexes as well as by considering the results of studies pertaining to facial temperature. In the future, variables related to thermal adaptation and seasonal databases should be obtained such that a more accurate thermal comfort prediction model can be established.

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