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**REVIEW**

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# Investigating the Relationship Between Thermal Comfort and Human Psychology: A Review

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**Abstract:** The state of mind is a crucial factor in thermal sensation and should be thoroughly understood in studies of thermal comfort while integrating human psychology into the literature. Fanger's Predicted Mean Vote (PMV) and Percentage of Dissatisfied (PPD) method is a cornerstone in thermal comfort research. On the other hand, the Adaptive Thermal Comfort (ATC) model provides a broader perspective by including behavioral and psychological adjustments, along with the personal and environmental parameters outlined in Fanger's PMV/PPD method. However, literature investigates the ATC model predominantly focuses on behavioral adaptations, neglecting psychological adjustments emphasized by ASHRAE as integral to "the state of mind". Moreover, qualitative approaches dominate the literature, with limited quantitative investigations. Therefore, this paper aims to address the importance of human psychology by systematically reviewing previous field studies to elucidate the magnitude and significance of psychological adjustments to the thermal comfort. Additionally, it introduces the Turhan and Özbey coefficients, derived from a quantitative study, to provide a more comprehensive understanding of the impact of psychological factors on thermal comfort. This work is highlighted the importance of the human psychology to achieve better indoor environmental quality in aspects of thermal comfort.

**Keywords:** Adaptive thermal comfort; Human behavior; Human psychology

## 1. Introduction

One of the key considerations in modern architectural design is thermal comfort[1-4]. Ensuring a comfortable indoor environment, regardless of external weather conditions, is achieved through advanced insulation, ventilation, heating, and cooling systems[5-8]. This focus on thermal comfort highlights the progression from basic survival needs to enhancing the quality of life, demonstrating how architectural buildings integrate both historical principles and modern innovations to meet the diverse needs of contemporary society.

Thermal comfort in indoor environments is a condition that reflects an individual's satisfaction with the surrounding thermal conditions[9-11]. Thermal comfort is affected by personal and environmental adjustments, including air temperature, relative humidity, air movement, radiant temperature, clothing insulation, and the metabolic rate of occupants[9-13]. Achieving thermal comfort means creating an environment where people feel neither too warm nor too cool, promoting comfort and productivity.

Fanger's foundational work, PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) method, providing a quantitative approach to understanding thermal comfort and it is a widely recognized approach for assessing thermal comfort in indoor environments[9-11]. The PMV model is based on heat balance equations and empirical data, taking into account the environmental and personal factors which are air temperature, relative humidity, air movement, radiant temperature, clothing insulation, and the metabolic rate[10]. In addition, the PPD index provides a quantitative measure of the percentage of people likely to be dissatisfied with the thermal environment. It is derived from the PMV value and is used to predict the proportion of occupants who will feel too hot or too cold[10].

In addition to Fanger's PMV/PPD method, the Adaptive Thermal Comfort (ATC) model is another important approach for assessing thermal comfort[13]. This model considers the dynamic relationship between occupants and their environment, considering how people adapt to changes in thermal conditions. The ATC model is incorporated into standards such as ASHRAE 55[10] and EN 15251[14]. The AMV represents the average thermal sensation vote reported by individuals within a group experiencing specific thermal conditions. Thus, unlike the PMV, which is a predictive model, AMV reflects the actual perception and evaluation of thermal comfort by occupants in real-world settings[13].

Thermal comfort is significantly influenced by a combination of physiological and psychological factors, collectively termed physio-psychological aspects. These aspects interact in complex ways to determine an individual's comfort level in a thermal environment. For instance, Lamberti et al.[15] explored the effects of climate on thermal adaptation through experiments in both continental and Mediterranean climates. The study found that although students living in a continental climate engaged in fewer adaptive actions, their neutral temperature was 3.1 °C lower than that of students in a Mediterranean climate, a difference that was statistically significant. The study also compared these findings with the PMV-PPD model, showing that adaptation is influenced by the sub-climate. Neutral temperatures calculated using the PMV model were higher than those obtained from TSV, with this difference being more significant in the colder continental climate. Li et al.[16] was examined the physio-psychological responses to thermal exposure on walking comfort during the summer season. The results revealed that the influence of the thermal exposure variations on pedestrians' overall thermal comfort is related to the skin wettedness. The male subjects have a greater sweating rate and evaporative heat loss than the female subjects and the evaporative heat loss from sweat is dominant, and heat storage takes up 36.0% of the heat produced on average.

There are several adaptive heat balance models which are based on laboratory or field studies, have been thoroughly developed and widely accepted in thermal comfort standards and literature[17-20].

The method named "aPMV" proposed by Yao et al.[17] is an adaptive version of the PMV model, designed to enhance thermal comfort prediction by incorporating adaptability theory into the traditional heat balance model. This model aims to improve the accuracy of thermal sensation prediction by considering the dynamic nature of human responses to thermal discomfort, including physiological, behavioral, and psychological adaptations. By integrating adaptability theory with heat balance theory, the aPMV model introduces the concept of thermal experience into thermal comfort studies, allowing for a more nuanced understanding of occupants' comfort levels[17].

Another method named "nPMV" by Humphreys and Nicol[18] aims to address discrepancies between the PMV predictions and the actual thermal perception of individuals in buildings This new predicted mean vote (nPMV) model proposed by Humphreys and Nicol takes into account the wider thermal comfort range reported by occupants compared to the results obtained from Fanger's studies. The nPMV model is designed to better align thermal comfort predictions with actual experiences of the occupants by considering the broader range of comfort preferences expressed by building occupants[18,21,22].

The Adaptive Thermal Heat Balance (ATHB) framework introduced by Schweiker and Wagner[19] aims to enhance thermal sensation prediction by combining adaptive and heat balance models. This framework postulates individual equations for behavioral, physiological, and psychological adaptation to adjust input values such as basic clothing insulation level and metabolic rate within the thermal comfort models. By incorporating behavioral, physiological, and psychological adaptive mechanisms, the ATHB model offers a more nuanced approach to thermal comfort assessment, taking into account the diverse responses of occupants to varying environmental conditions. This adaptive thermal heat balance model provides a theoretical and data-driven framework that considers the multifaceted nature of human thermal perception and adaptation[19,23,24].

Human psychology, which is considered in the ATC model, is one of the vital parameters which affect the perceived comfort significantly[17-19, 25-35]. Even though the effect of human psychology is mentioned, there are a few data-driven research available to consider the human psychology especially in a quantitative way[25-35]. Furthermore, to the best of the author's knowledge, there are very few review papers examining the effect of human psychology on thermal sensation. However, human psychology, including factors such as mood state and climate adaptation, should be thoroughly considered. Therefore, the aim of this paper is to review studies on the impact of psychological state on thermal comfort. In addition, this study introduces the Turhan and Özbey coefficients, which were developed through a data-driven study to incorporate current mood states into thermal comfort assessments quantitatively and have developed a novel mathematical model.

## 2. Literature Review: State of Mind

The state of mind plays a crucial role in adaptive thermal comfort, influencing how individuals perceive, evaluate, and respond to thermal conditions[10,26,27]. Factors such as past experiences, cultural background, and individual preferences shape comfort perceptions and preferences of occupants[26,28]. One of the measures for the state of mind is mood which refers to a temporary state of mind or emotional condition that can influence an individual's thoughts, behaviors, and perceptions[29,31]. Mood states which can be influenced by various factors, including environmental conditions, physical health, social interactions, and personal experiences, are broadly categorized into two types: positive and negative[28-32].

Positive mood states include feelings such as happiness, cheerful and vigor. Positive moods are often associated with favorable conditions such as a comfortable environment, good physical health, positive social interactions, and enjoyable personal experiences. On the other hand, negative mood states encompass feelings such as hopeless, unhappy and anger. Negative moods can be influenced by adverse factors such as discomfort, poor health, negative social interactions, and stressful experiences[28-32].

Unlike specific emotions, which are often triggered by particular events or situations, moods are more diffuse and can affect overall attitudes and responses to different circumstances, including how one perceives thermal comfort[30-32]. Thus, understanding the interplay between mood and thermal comfort is essential for designing environments that promote well-being and productivity, as mood can influence overall comfort levels and satisfaction with the built environment[28-35].

In the literature, one well-known early study performed by Rohles[36] to analyze the impact of human psychology and psychological adaptation. Occupants were divided three different group during the experiment. For one group, the heaters were activated, and the subjects were notified. They were shown the heater and the red light that signaled it was powered on. For the second group, the heaters were also activated, but the subjects were not informed. The third group had no heaters and received no explanations. The results revealed that both groups with heaters felt warmer compared to the group without heaters. However, the group informed about the active heaters felt significantly and consistently warmer than the group with heaters who were unaware they were operating[36]. The psychological perception is crucial in thermal comfort studies[36-38]. However, this study was focused on the influence of the emotions and mood states on thermal comfort.

Wang and Liu[39] carried out an experiment with 18 college students in China to investigate whether emotion state would have some influence on thermal perception and comfort of the students to examine the role of the positive and negative mood states on thermal comfort. The results demonstrated that bored students reported higher thermal sensation votes than ones neutral and joyful emotional state. Bored students are able to sense warmer than students who reported as neutral and joyful states and get bored may cause an increasing up to 1 scale in 7-point thermal sensation scale[39].

In another study on the relation between mood state and Indoor Environmental Quality (IEQ) was conducted by Zhang et al.[40].The results also support the importance of the mood state not only thermal sensation but also the acceptance of the IEQ. Mood state have significant impact on IEQ acceptance, with negative moods leading to lower acceptance ratings. This mood influence is more substantial in conditions where the thermal quality is poor, even if the other IEQ aspects are satisfactory[40].

When investigating emotional well-being and psychological states, utilizing reliable and validated assessment tools is crucial. Among the widely used instruments in psychological research are the Positive and Negative Affect Schedule (PANAS) and the Profile of Mood States (POMS)[41,42]. These questionnaires provide comprehensive insights into emotional experiences of the individuals by measuring various dimensions of mood states. Thus far, several studies investigating the effect of the mood state on thermal comfort and sensation by using PANAS or POMS questionnaires and found a connection between these aspects[30-35,43-45]. For instance, Ibrahim et al.[43] found a correlation of r=0.3 between anger and thermal sensation. Moreover, Zhang et al.[30] depicted a relationship between thermal sensation and mood state of ashamed with a p-value of 0.001. Özbey et al.[34] showed that thermal sensation is correlated with anxious with a strength of 0.044 p-value.

The study of Ibrahim et al.[43] examines the influence of mood states on human evaluation of the thermal environment using immersive virtual settings by using Virtual Reality (VR) technology. Forty-four university students were participated to the experiments and the mood state were categorized as high medium and low by using PANAS-X which is the expended version PANAS questionnaire. The authors reported that the mood state of the students have significant influence on thermal sensation, with negative moods increasing perceived warmth and positive moods leading to more accurate thermal evaluations. Participants in anger states rated the thermal environment as warmer, while those in happy states gave more neutral ratings[43].

To further examine the role of mood states on thermal sensations of the students, Zhang et al.[30] carried out an experiment with 259 students in a mechanically ventilated university library located in China. The experiments where the PANAS-SF questionnaire (short form of PANAS questionnaire) used, the results shown that negative feeling statements of ‘active’, ‘hostile’, ‘upset’ and ‘afraid’ have a statistically significant relationship between the thermal sensation and satisfaction. Students who indicated ‘hostile’ or ‘upset’ felt significantly warmer than those who did not, whereas students who indicated ‘active’ and ‘afraid’ felt significantly more satisfied with the thermal environments[30].

Turhan and Özbey[44] were one of the first to examine the influence of stress levels on the thermal comfort perception of male and female students through the utilization of the POMS questionnaire. The study utilized a condensed version of the POMS questionnaire and involved 146 male and 70 female students. Participants were divided into experimental and control groups. While the experimental group underwent examinations, the control group spent their time reading preferred books. The findings indicated that students generally experienced heightened stress prior to exams, resulting in a heightened perception of warmth compared to the control group. Furthermore, a noteworthy reduction in the percentage of dissatisfied responses was observed among both male and female students in the experimental group after the examination, reaching approximately 71%[44].

Çeter et al.[31] explored the influence of gender differences on emotional intensity concerning the absolute difference between PMV and AMV (ABS(AMV-PMV)) of the participants. The emotional intensity score (EIS) was calculated with finding the absolute difference between each participant individual score to overall mood score. The findings demonstrated a positive correlation between the ABS(AMV-PMV) and the EIS among male participants across all levels of emotional intensity classifications: very intense, intense, and normal. In contrast, emotional intensity levels did not exhibit statistical significance for female participants[31].

In another investigation, Özbey et al.[32] performed a sensitivity analysis via Monte Carlo Simulation to assess the impact of the current mood states on thermal sensation in a Warm-Mediterranean temperate climate zone. While the subjective data from 281 healthy students were collected using the POMS questionnaire and a 13-point thermal sensation scale the objective data was collected via thermal comfort data logger and different sensors. Six main subscales of the POMS questionnaire (anger, confusion, depression, fatigue, tension and vigor-activity) were analyzed to examine the effects of the ABS(AMV-PMV) of occupants. It has been conclusively shown that the vigor-activity emerged as the most influential subscales on the ABS(AMV-PMV) of students, while confusion was identified as the least effective. Specifically, changes in vigor-activity alone were associated with a difference of up to 0.31 scale, whereas confusion had a comparatively minor effect of 0.11 scale in thermal sensation scale. Furthermore, when considering all subscales collectively, the ABS(AMV-PMV) was found to have the potential to induce a difference of 1.32[32].

Personal and perceived control is also a fundamental aspect of psychological adaptation. For instance, Turhan et al.[45] introduces a novel Thermal Sensation Prediction Model (TSPM) designed to control HVAC systems by considering both physiological and psychological parameters. This model, which incorporates a fuzzy logic model, predicted thermal sensation votes using both psychological and environmental parameters within a Python environment, rather than relying on commercial toolboxes. The model uses two physiological parameters – Mean Radiant Temperature and External Temperature – and one psychological parameter – EIS, which includes vigor-activity, depression, and tension, with a total of 32 subscales. The findings demonstrated that the thermal sensation votes could be accurately predicted by incorporating both types of parameters. Specifically, the developed TSPM achieved an accuracy of 92% in predicting the thermal sensation votes of students. Additionally, the model exhibited better accuracy during the heating season compared to the cooling season.

Özbey and Turhan[33] developed a novel temperature determination model considering human psychology. In this experiment, after the comfort temperature was found via Griffth method, the current mood state of the participants was gathered via the POMS questionnaire. Latter, three comfort temperature equations were developed according to their mood state that categorized as optimistic, pessimistic and neutral. Results have shown that while the students were drifted apart from the neutral zone, the comfort temperatures were decreased. Moreover, this association has been found statistically significant for the students not in neutral mood state[33].

In an investigation into the state of mind on thermal comfort, Özbey et al.[44] analyzed the association between tension level and thermal sensation. This study has confirmed the effectiveness of the tension subscales in POMS questionnaire – tense, shaky, on edge, panicky, relaxed, uneasy, restless, nervous, anxious – to the thermal sensation by considering gender differences. The results demonstrated a consistent association between tension level and thermal sensitivity. While the subscales of “shaky”, “uneasy” and “anxious” statistically affected the thermal sensation of males, only “nervous” and “anxious” subscales were found statistically important for females[44].

(**Table 1**) summarizes the studies in the literature that investigate the impact of human psychology on thermal comfort by considering used psychological test, examining positive and/or negative moods and aim of study.

**Table 1**. Studies investigate the effect of mood states on thermal comfort[30-34,39,40,43-45].

| **Author(s)** | **Used Psychological Test** | **Number of Considering Positive & Negative Statements** | | **Aim of the Study** |
|---|---|---|---|---|
| | | **Positive Mood Statement/s** | **Negative Mood Statement/s** | |
| Wang and Liu[39] | No test used. | 1 | 1 | To find relationship between the thermal sensation votes of the students and emotional state. |

Continuation Table:

| Author(s) | Used Psychological Test | Number of Considering Positive & Negative Statements | | Aim of the Study |
|---|---|---|---|---|
| | | Positive Mood Statement/s | Negative Mood Statement/s | |
| Zhang et al.[40] | Self-designed questionnaire | 1 | 2 | To find the relationship between mood state and IEQ perspective of the occupants. |
| Ibrahim et al.[43] | PANAS-X | 10 | 10 | To examine the influence of mood states on human evaluation of the thermal environment using immersive virtual settings. |
| Zhang et al.[30] | PANAS-SF | 5 | 5 | To investigate the role of mood states on thermal sensations of the students |
| Turhan and Özbey[44] | Shorten POMS Questionnaire | 5 | 35 | To examine the association between the stress level and thermal sensation of the students. |
| Çeter et al.[31] | POMS Questionnaire | 8 | 50 | To investigate the relationship between EIS and the ABS(AMV-PMV) for male and female participants. |
| Özbey et al.[32] | POMS Questionnaire | 8 | 50 | To conduct a sensitivity analysis between ABS(AMV-PMV) and current mood state. Additionally, the effect of the subscales of POMS questionnaire on this difference was investigated. |
| Turhan et al.[45] | POMS Questionnaire | 8 | 50 | To develop a fuzzy logic model – Thermal Sensation Prediction Model – that consider the mood state. |
| Özbey and Turhan[33] | POMS Questionnaire | 8 | 50 | To develop a novel comfort temperature model which consider the human psychology as an additional parameter. |
| Özbey et al.[34] | POMS Questionnaire | 8 | 50 | To investigate the correlation between tension subscales of the POMS questionnaire and thermal sensation. |

Overall, these studies illustrate just how important the state of mind on thermal comfort and highlight the unique relationship between the mood state and the comfort perception. There is a relatively small body of literature that is concerned with effects of the state of mind on thermal comfort. Moreover, what we know about the effects of human psychology on thermal comfort is largely based upon qualitative studies. Thus, a necessity of the mathematical model as quantitative studies is clear to understand the link between the state of mind and thermal comfort.

## 3. A Novel Approach: Turhan and Özbey Coefficients

The one of the major fieldwork study on developing a mathematical model considering human psychology and thermal comfort together was conducted by Turhan et al.[35]. This study has been carried out in a university study hall in Warm-Mediterranean temperate climate zone. A mixed-mode building was selected as a case building and the study was completed with a participation of 419 female and 720 male students in a year period. The objective data were collected via thermal comfort data logger[46] and an environmental data logger which contains DHT-22[47], a mobile application, to gather the subjective data from the students, were developed for the study. 13-point thermal sensation scale[48] was utilized to collect thermal sensation votes, the POMS questionnaire was simultaneously used to evaluate the current mood states of the participants[35].

POMS questionnaire includes 65 statements about six main subscales which are anger, depression, tension, confusion, fatigue and vigor-activity[42]. The POMS questionnaire outcomes are assessed by having participants respond to 65 statements, reflecting on the question, "How are you feeling right now?" For each statement, participants rate their response on a 5-point scale, ranging from "0 – not at all" to "4 – extremely," to indicate the degree to which each statement describes their current feelings. By complication of the questionnaire the total mood disturbance was calculated by subtracting positive feelings from negative feelings. Later, the TMDs were converted to the T-Scores to classify the mood state of the participant. For more detail and utilized formulas please check the references[42,49].

A black box model is an approach where the internal workings of the system are not known or not considered; instead, the focus is on the input and output of the system[17]. The Black Box model used in this study is based on the assumption that the psychological state of an occupant provides continuous feedback (k) to their thermal sensation[35] (**Figure 1**). This model acknowledges the non-linear behavior of thermal comfort and uses the Predicted Mean Vote (PMV) as a dependent variable, influenced by factors such as operative temperature, relative humidity, clothing insulation, and outdoor temperature. The model adjusts the PMV using the Mood State Correction Factors (MSCF), as known as Turhan and Özbey coefficients, to account for changes in thermal sensation due to mood states, resulting in the Actual Mean Vote according to psychological mood changes ($AMV_p$). Turhan and Özbey coefficients are determined using the least square method, minimizing the error between measured AMV and PMV values[35]. It is important to highlight that the derivation of MSCF is similar to study in ref [17] since this model is an adaptive and data-driven model. The novelty of this model is to introduce the coefficients according to current mood states of the occupants by emphasizing the human psychology. More information about the study can be found in reference[35].

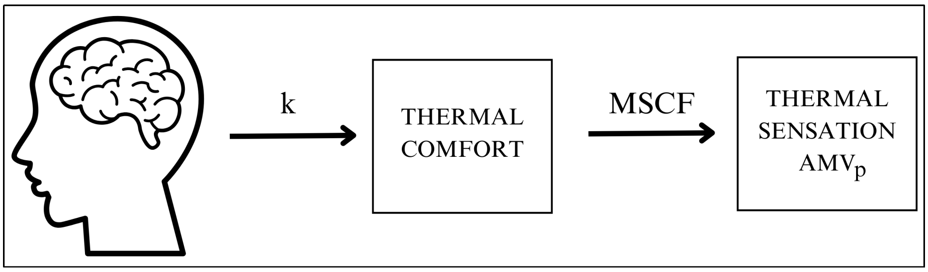

**Figure 1.** The model diagram (psychological feedback is represented with k).

The PMV modelled as a function of the relative humidity (RH), operative temperature ($T_{op}$), basic clothing insulation ($I_{cl}$), and outdoor temperature ($T_{out}$). According to black-box theory the derivation of the $AMV_p$ is generated as given in Equations 3.1 and 3.2. Then, the Equation 3.3 is presented when both sides in equation 3.2 is divided by $AMV_p$. The final equation for the $AMV_p$ and MSCF ($k/\delta$) is given in Equations 3.4 and 3.5, respectively. Moreover, the found coefficients were given in (**Table 2**). Here, the k is the psychological feedback, $\delta$ defines the environmental and personal thermal stimuli that affect thermal comfort.

$$\mathrm{PMV} = \delta \times \left(T_{op}, T_{out}, RH, I_{cl}\right) \tag{3.1}$$

$$\mathrm{AMV}_p = \delta \times \left(T_{op}, T_{out}, RH, I_{cl}\right) - \mathrm{AMV}_p \times k \times \left(T_{op}, T_{out}, RH, I_{cl}\right) \tag{3.2}$$

$$\mathrm{AMV}_p = \frac{\mathrm{PMV}}{1 + \mathrm{MSCF} \times \mathrm{PMV}} \tag{3.3}$$

$$\mathrm{MSCF} = \frac{\sum_i^z \mathrm{PMV} - \mathrm{AMV}_p}{z} \tag{3.4}$$

**Table 2**. Developed MSCF values for the mathematical model[35].

| Classification of Total Mood Distribution | T-Score | Turhan and Özbey Coefficients |
|---|---|---|
| Very Elevated Score—Very Pessimistic<br>(Many more concerns than are typically reported) | ≥ 70 | −0.125 |
| Elevated Score—Pessimistic<br>(More concerns than are typically reported) | 60-69 | −0.075 |

Continuation Table:

| Classification of Total Mood Distribution | T-Score | Turhan and Özbey Coefficients |
|---|---|---|
| Average Score—Neutral<br>(Typical levels of concern) | 40-59 | 0 |
| Low Score—Optimistic<br>(Fewer concerns than are typically reported) | 30-39 | −0.061 |
| Very Low Score—Very Optimistic<br>(Far fewer concerns than are typically reported) | < 30 | −0.114 |

(**Table 3**) illustrates the impact of mood states on thermal sensation using the Turhan and Özbey coefficients with example situations via presenting various PMV values, which represent the predicted mean vote for thermal sensation, and shows how these values are adjusted to the Actual Mean Vote ($AMV_p$) by incorporating the MSCF for different mood states[35].

**Table 3.** Example of the thermal sensation change according to the mood states with different PMV values by using Turhan and Özbey coefficients.

| Mood State | Turhan and Özbey Coefficients | PMV | $AMV_p$ |
|---|---|---|---|
| Very Pessimistic | -0.125 | 0.4 | 0.42 |
| Pessimistic | -0.075 | | 0.41 |
| Neutral | 0 | | 0.40 |
| Optimistic | -0.061 | | 0.41 |
| Very Optimistic | -0.114 | | 0.42 |
| Very Pessimistic | -0.125 | -0.4 | -0.38 |
| Pessimistic | -0.075 | | -0.39 |
| Neutral | 0 | | -0.40 |
| Optimistic | -0.061 | | -0.39 |
| Very Optimistic | -0.114 | | -0.38 |
| Very Pessimistic | -0.125 | 1.2 | 1.41 |
| Pessimistic | -0.075 | | 1.32 |
| Neutral | 0 | | 1.20 |
| Optimistic | -0.061 | | 1.29 |
| Very Optimistic | -0.114 | | 1.39 |
| Very Pessimistic | -0.125 | -1.2 | -1.04 |
| Pessimistic | -0.075 | | -1.10 |
| Neutral | 0 | | -1.20 |
| Optimistic | -0.061 | | -1.12 |
| Very Optimistic | -0.114 | | -1.06 |

In comparison between the mood states, in the same PMV value, the mood states optimistic and pessimistic caused a slight increase in thermal sensation. In example, when the PMV is 1.2, the $AMV_p$ values for the mood states optimistic and pessimistic were found 1.29 and 1.32, respectively. Furthermore, increasing trend in thermal sensation is continued in cases of where the mood state is draft apart from neutral to very optimistic and very pessimistic situations. In case, the PMV is 1.2, the $AMV_p$ varies more significantly from 1.20 (Neutral) to 1.41 (Very Pessimistic), showing a stronger effect of mood state at higher PMV values in comparison to PMV is equal to 0.4. Conversely, in cooler environments where the PMV is smaller than 0, the adjustments also show mood states causing a warmer perception, with $AMV_p$ values being less negative than the PMV values.

## 4. Discussion

The discussion part is split into three sub-bullets including comparison of adaptive heat balance models, limitations, and future works.

### 4.1 Comparison of the Studies

In the literature, various adaptive heat balance models have been developed that incorporate physiological, behavioural, and psychological adaptations[17-20]. These models have significantly contributed to our understanding of thermal comfort by emphasizing the dynamic and adaptive nature of human responses to thermal environments. Physiological adaptations include changes in metabolism, heart rate, and sweat production, while behavioural adaptations involve actions like adjusting clothing or modifying the environment. Psychological adaptations, on the other hand, encompass changes in perception, expectation, and attitude towards the thermal environment.

The adaptive heat balance models typically address psychological adaptations qualitatively and do not delve into quantitative examinations of psychological adjustments. This qualitative approach limits the precision and applicability of the models, especially in diverse and fluctuating real-world settings. The lack of quantitative analysis also hinders the ability to predict individual differences in thermal comfort responses accurately. Furthermore, the existing adaptive heat balance models have not utilized any questionnaires or standardized tools to measure or determine the current mood state of the occupants, which is a critical gap considering the significant influence of mood on thermal comfort perceptions.

In contrast, Turhan et al.[35] introduced a pioneering mathematical model using a black-box approach that integrates current mood states of occupants assessed through the POMS questionnaire, thereby quantitatively considering human psychology. This approach represents a significant advancement as it quantitatively considers human psychology, providing a more holistic and accurate representation of thermal comfort. By incorporating mood states, this model acknowledges that thermal comfort is not solely a physical phenomenon but is also deeply intertwined with psychological well-being. The use of the POMS questionnaire allows for the systematic assessment of mood, capturing both positive and negative states, and their potential impact on thermal comfort perceptions.

### 4.2 Limitations

Although some research has been conducted on the effects of psychological adjustments on thermal comfort and sensation, particularly in a quantitative manner, there are notable limitations in these studies that suggest future research directions.

Firstly, many studies have focused on specific nationalities, which might not account for the variations in cultural experiences and adaptations across different countries[50,51]. Different cultural backgrounds can influence the selection of mood states in the POMS survey and, consequently, the perception of thermal comfort. Therefore, future research should involve participants from multiple nations to comprehensively examine the effects of human psychology on thermal comfort across diverse cultural settings.

Secondly, the experiments conducted so far have often been limited to a single climatic region. This approach does not adequately address the impact of different climatic adaptations on thermal perception by inspecting the state of mind of the individuals. Considering that human psychology and thermal comfort might be influenced by climatic adaptations[52,53], future studies should be carried out in multiple climatic zones to provide a more holistic understanding of these effects.

Another important factor is the age range of participants. Most studies have been conducted with university or college students, which represent a narrow age interval. This demographic limitation may change the results, as the state of mind and its effect on thermal comfort can vary significantly with age[54,55]. Future research should include a broader age range, and specific models should be developed to address the thermal comfort needs of elderly populations.

Finally, integrating the developed models that consider psychological factors into existing HVAC systems can enhance their efficiency and improve overall thermal comfort. This integration could lead to more personalized and adaptive thermal environments in buildings.

### 4.3 Future Works

Future studies should involve diverse nationalities to account for cultural differences, and multiple climatic zones to understand regional adaptations. Additionally, broadening the age range of participants will help develop more inclusive models, particularly for the elderly. Integrating these refined models into existing HVAC systems can lead to enhanced thermal comfort and energy efficiency in buildings. Addressing these areas will advance our understanding and application of psychological factors in thermal comfort research. Incorporating refined models into existing HVAC systems can enhance both thermal comfort and energy efficiency in buildings. Besides, designers and facility managers can leverage insights from these studies to create environments that not only meet physical comfort requirements but also support psychological well-being.

## 5. Conclusion

Studies provide insights into how psychological factors, such as mood states, influence thermal comfort. Understanding these relationships can help design study environments that improve student comfort and wellbeing, highlighting the need to consider psychological components alongside physical environmental factors. In another words, studies suggesting that psychological factors must be integrated into the design and evaluation of indoor spaces to enhance overall comfort and satisfaction.

Studies which consider the state of mind were conducted generally in qualitative way. Besides, a few research available in aspects of quantitative. In one of the major quantitative studies found mood state correction factors as known as Turhan and Özbey[35] coefficients which underscores the importance of considering psychological factors when assessing thermal comfort, as mood states can significantly modify the perceived thermal environment, potentially leading to more personalized and accurate thermal comfort models. The coefficients were determined to be -0.125 and -0.014 for individuals with very pessimistic and very optimistic mood states, respectively. Furthermore, these coefficients approach zero as the mood states of occupants become more neutral. Thus, for individuals experiencing less or more levels of concern, the effect becomes more pronounced[35].

By recognizing and incorporating the complex interplay between mood and thermal comfort, future research and applications can achieve more comprehensive and effective solutions for promoting well-being in built environments.

## Author's Contributions

**Mehmet Furkan ÖZBEY:** Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing.

**Cihan TURHAN:** Supervision, Writing - Review & Editing.

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## Ethics Statement

All protocols were approved by the university's ethics committee (with a number of 422727) and conformed to the guidelines contained within the Declaration of Helsinki.

## Conflict of Interest

All authors have read and agreed to the published version of the manuscript. The authors declare that they have no conflict of interest.

## Informed Consent

All the participants in this study signed informed consent. Additionally, the rights and welfare of the participants were protected and that they were adequately informed about the study procedures, risks, and benefits before agreeing to participate.

## References

[1] Okafor MU, Awuzie BO, Otasowie K, *et al*. Evaluation of Indoor Thermal Comfort Conditions of Residential Traditional and Modern Buildings in a Warm-Humid Climate. *Sustainability*. 2022;14(19): 12138. https://doi.org/10.3390/su141912138

[2] Prianto E and Depecker P. Optimization of architectural design elements in tropical humid region with thermal comfort approach. *Energy and buildings*. 2003;1;35(3): 273-80. https://doi.org/10.1016/S0378-7788(02)00089-0

[3] Ghassan ML, Sari LH and Munir A. An evaluation of the tropical architectural concept on the building design for achieving thermal comfort (Case study: engineering faculty of Syiah Kuala university). *InIOP conference series: materials science and engineering 2021 Feb 1* (Vol. 1087, No. 1, p. 012013). IOP Publishing. https://doi.org/10.1088/1757-899X/1087/1/012013

[4] Honarvar SM, Golabchi M and Ledari MB.

Building circularity as a measure of sustainability in the old and modern architecture: A case study of architecture development in the hot and dry climate. Energy and Buildings. 2022; 275:112469. https://doi.org/10.1016/j.enbuild.2022.112469

[5] Alghamdi S, Tang W, Kanjanabootra S, *et al*. Effect of architectural building design parameters on thermal comfort and energy consumption in higher education buildings. *Buildings*. 2022; 12(3):329. https://doi.org/10.3390/buildings12030329

[6] Prianto E and Depecker P. Optimization of architectural design elements in tropical humid region with thermal comfort approach. *Energy and buildings*. 2003; 35(3):273-80. https://doi.org/10.1016/S0378-7788(02)00089-0

[7] Elshafei G, Vilcekova S, Zelenakova M, *et al*. Towards an adaptation of efficient passive design for thermal comfort buildings. *Sustainability*. 2021; 13(17):9570. https://doi.org/10.3390/su13179570

[8] Nasrollahi N and Shokry E. Parametric analysis of architectural elements on daylight, visual comfort, and electrical energy performance in the study spaces. *Journal of Daylighting*. 2020; 7(1):57-72. https://doi.org/10.15627/jd.2020.5

[9] Fanger PO. Thermal comfort. Analysis and applications in environmental engineering. Danish Technical Press, Denmark, 1970. ISBN: 9788757103410 https://www.cabidigitallibrary.org/doi/full/10.5555/19722700268.

[10] American National Standards Institute. Thermal environmental conditions for human occupancy ASHRAE-55. *American Society of Heating, Refrigerating and Air-Conditioning Engineers*; 2020. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy

[11] Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, *International Organization for Standardization, Geneva*. 2005. https://www.iso.org/standard/39155.html

[12] Özbey MF and Turhan C. The importance of the calculation of angle factors to determine the mean radiant temperature in temperate climate zone: A university office building case. *Indoor and Built Environment*. 2022; 31(4):1004-17. https://doi.org/10.1177/1420326X21104637

[13] De Dear R and Brager GS. Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions*. 1998; 104 (1):145-167. https://escholarship.org/uc/item/4qq2p9c6

[14] Comite'Europe'en de Normalisation CE. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. *EN 15251*. 2007. http://www.cres.gr/greenbuilding/PDF/prend/set4/WI_31_Pre-FV_version_prEN_15251_Indoor_Environment.pdf

[15] Lamberti G, Leccese F, Salvadori G, *et al*. Investigating the effects of climate on thermal adaptation: a comparative field study in naturally ventilated university classrooms. Energy and Buildings. 2023; 294:113227. https://doi.org/10.1016/j.enbuild.2023.113227

[16] Li J, Niu J and Mak CM. Influences of variable thermal exposures on walking thermal comfort in hot summer-Physio-psychological responses. *Building and Environment*. 2023; 239:110346. https://doi.org/10.1016/j.buildenv.2023.110346

[17] Yao R, Li B and Liu J. A theoretical adaptive model of thermal comfort–Adaptive Predicted Mean Vote (aPMV). *Building and Environment*. 2009; 44(10):2089-96. https://doi.org/10.1016/j.buildenv.2009.02.014

[18] Humphreys MA and Nicol JF. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and Buildings*. 2002; 34(6):667-84. https://doi.org/10.1016/S0378-7788(02)00018-X

[19] Schweiker M and Wagner A. A framework for an adaptive thermal heat balance model (ATHB). *Building and Environment*. 2015; 94:252-62. https://doi.org/10.1016/j.buildenv.2015.08.018

[20] Yao R, Zhang S, Du C, *et al*, Toftum J, d'Ambrosio FR, Gebhardt H, Zhou S, Yuan F. Evolution and performance analysis of adaptive thermal comfort models–A comprehensive literature review.

*Building and Environment*. 2022; 217:109020. https://doi.org/10.1016/j.buildenv.2022.109020

[21] Kim JT, Lim JH, Cho SH, *et al*. Development of the adaptive PMV model for improving prediction performances. *Energy and Buildings*. 2015; 98:100-5. https://doi.org/10.1016/j.enbuild.2014.08.051

[22] Cottafava D, Magariello S, Ariano R, *et al*. Crowdsensing for a sustainable comfort and for energy saving. *Energy and Buildings*. 2019; 186:208-20. https://doi.org/10.1016/j.enbuild.2019.01.007

[23] Zhang S and Lin Z. Adaptive-rational thermal comfort model: Adaptive predicted mean vote with variable adaptive coefficient. *Indoor Air*. 2020; 30(5):1052-62. https://doi.org/10.1111/ina.12665

[24] Schweiker M. Combining adaptive and heat balance models for thermal sensation prediction: A new approach towards a theory and data-driven adaptive thermal heat balance model. *Indoor Air*. 2022; 32(3):e13018. https://doi.org/10.1111/ina.13018

[25] Lamberti G, Boghetti R, Kämpf JH, *et al*. Development and comparison of adaptive data-driven models for thermal comfort assessment and control. *Total Environment Research Themes*. 2023; 8:100083. https://doi.org/10.1016/j.totert.2023.100083

[26] Luo M, Cao B, Ji W, *et al*. The underlying linkage between personal control and thermal comfort: psychological or physical effects?. *Energy and Buildings*. 2016;111:56-63. https://doi.org/10.1016/j.enbuild.2015.11.004

[27] Arowoiya VA, Onososen AO, Moehler RC, *et al*. Influence of Thermal Comfort on Energy Consumption for Building Occupants: The Current State of the Art. *Buildings*. 2024 May 7;14(5):1310. https://doi.org/10.3390/buildings14051310

[28] De Dear R, Xiong J, Kim J, *et al*. A review of adaptive thermal comfort research since 1998. *Energy and Buildings*. 2020; 214:109893. https://doi.org/10.1016/j.enbuild.2020.109893

[29] Turhan C, Alkan N, Çeter AE, *et al*. The relation between occupant's mood state and thermal sensation. *REHVA 14th HVAC World Congress (CLIMA 22)*, Rotterdam, 2022. https://doi.org/10.34641/clima.2022.261

[30] Zhang D, Hou H, Tsang TW, *et al*. Predicting students' thermal sensation votes in university libraries taking into account their mood states. *Indoor and Built Environment*. 2024:1420326X231225405. https://doi.org/10.1177/1420326X231225405

[31] Çeter AE, Özbey MF, Turhan C. Gender inequity in thermal sensation based on emotional intensity for participants in a warm mediterranean climate zone. *International Journal of Thermal Sciences*. 2023;185:108089. https://doi.org/10.1016/j.ijthermalsci.2022.108089

[32] Özbey MF, Çeter AE, Örfioğlu Ş, *et al*. Sensitivity analysis of the effect of current mood states on the thermal sensation in educational buildings. *Indoor Air*. 2022; 32(8):e13073. https://doi.org/10.1111/ina.13073

[33] Özbey MF and Turhan C. A novel comfort temperature determination model based on psychology of the participants for educational buildings in a temperate climate zone. *Journal of Building Engineering*. 2023; 76:107415. https://doi.org/10.1016/j.jobe.2023.107415

[34] Özbey MF, Alkan N and Turhan C. Investigation of the Relationship between Tension Level and Thermal Sensation. A Case Study of University Study Hall. *The 11th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings (IAQVEC2023)*, Tokyo, 2023 May 20-23. https://doi.org/10.1051/e3sconf/202339601010

[35] Turhan C, Özbey MF, Çeter AE, *et al*. A novel data-driven model for the effect of mood state on thermal sensation. *Buildings*. 2023; 13(7):1662. https://doi.org/10.3390/buildings13071662

[36] Rohles F. Temperature & Temperament. American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2007:14-9. https://images.finehomebuilding.com/app/uploads/2009/01/27221725/TempxTemperament.pdf

[37] Zhuang L, Huang J, Li F, *et al*. Psychological adaptation to thermal environments and its effects on thermal sensation. *Physiology & Behavior*. 2022; 247:113724. https://doi.org/10.1016/j.physbeh.2022.113724

[38] Wu Y, Liu H, Li B, *et al*. Thermal adaptation of the elderly during summer in a hot humid area: Psychological, behavioral, and physiological responses. *Energy and Buildings*. 2019; 203:109450. https://doi.org/10.1016/j.enbuild.2019.109450

[39] Wang H and Liu L. Experimental investigation about effect of emotion state on people's thermal comfort. *Energy and Buildings*. 2020; 211:109789. https://doi.org/10.1016/j.enbuild.2020.109789

[40] Zhang D, Wong LT and Mui KW. Occupants' mood states in evaluating indoor environmental quality (IEQ) acceptance. *Architectural Science Review*. 2024:1-2. https://doi.org/10.1080/00038628.2024.2329176

[41] Watson D, Clark LA and Tellegen A. Development and validation of brief measures of positive and negative affect: the PANAS scales. *Journal of Personality and Social Psychology*. 1988; 54(6):1063. https://doi.org/10.1037/0022-3514.54.6.1063

[42] McNair DM; Lorr M and Droppleman LF. Manual for the Profile of Mood States; Educational and Industrial Testing Services: San Diego, CA, USA, 1971.

[43] Ibrahim A, Ali H, Zghoul A, *et al*. Mood state and human evaluation of the thermal environment using virtual settings. *Indoor and Built Environment*. 2021; 30(1):70-86. https://doi.org/10.1177/1420326X19880325

[44] Turhan C and Özbey MF. Effect of pre-and post-exam stress levels on thermal sensation of students. *Energy and Buildings*. 2021; 231:110595. https://doi.org/10.1016/j.enbuild.2020.110595

[45] Turhan C, Özbey MF, Lotfi B, *et al*. Integration of psychological parameters into a thermal sensation prediction model for intelligent control of the HVAC systems. *Energy and Buildings*. 2023;296:113404. https://doi.org/10.1016/j.enbuild.2023.113404

[46] Delta OHM Thermal Comfort Data Logger - HD32.3TC - Thermal Microclimate PMV-PPD/WBGT; 2022. Available from: https://environmental.senseca.com/product/hd32-3tc-thermal-microclimate-pmv-ppd-wbgt/ [Last accessed on 8 June 2024]

[47] Aosong Electronics Co.,Ltd, DHT-22 Temprature and Relative Humidity Sensor, Available from: https://www.sparkfun.com/datasheets/Sensors/Temperature/DHT22.pdf [Last accessed on 8 June 2024]

[48] Buratti C, Palladino D and Ricciardi P. Application of a new 13-value thermal comfort scale to moderate environments. *Applied Energy*. 2016; 180:859-66. https://doi.org/10.1016/j.apenergy.2016.08.043

[49] Lin S, Hsiao YY and Wang M. Test review: the profile of mood states 2nd edition. Journal of Psychoeducational Assessment. 2014; 32(3):273-277. https://doi.org/10.1177/0734282913505995

[50] Draganova VY, Yokose H, Tsuzuki K, *et al*. Field study on nationality differences in adaptive thermal comfort of university students in dormitories during summer in Japan. *Atmosphere*. 2021; 12(5):566. https://doi.org/10.3390/atmos12050566

[51] Draganova V, Tsuzuki K and Nabeshima Y. Field study on nationality differences in thermal comfort of university students in dormitories during winter in Japan. Buildings. 2019; 9(10):213. https://doi.org/10.3390/buildings9100213

[52] Amaripadath D, Rahif R, Velickovic M, *et al*. A systematic review on role of humidity as an indoor thermal comfort parameter in humid climates. Journal of Building Engineering. 2023; 68:106039. https://doi.org/10.1016/j.jobe.2023.106039

[53] Tam KP, Leung AK and Clayton S. Research on climate change in social psychology publications: A systematic review. *Asian Journal of Social Psychology*. 2021; 24(2):117-43. https://doi.org/10.1111/ajsp.12477

[54] Baquero MT and Forcada N. Thermal comfort of older people during summer in the continental Mediterranean climate. *Journal of Building Engineering*. 2022;54:104680. https://doi.org/10.1016/j.jobe.2022.104680

[55] Larriva MT, Mendes AS and Forcada N. The effect of climatic conditions on occupants' thermal comfort in naturally ventilated nursing homes. *Building and Environment*. 2022; 214:108930. https://doi.org/10.1016/j.buildenv.2022.108930.