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A Novel Data-Driven Model for the Effect of Mood State on Thermal Sensation

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Abstract: Thermal comfort has an important role in human life, considering that people spend most of their lives in indoor environments. However, the necessity of ensuring the thermal comfort of these people presents an important problem, calculating the thermal comfort accurately. The assessment of thermal comfort has always been problematic, from past to present, and the studies conducted in this field have indicated that there is a gap between thermal comfort and thermal sensation. Although recent studies have shown an effort to take human psychology into account more extensively, these studies just focused on the physiological responses of the human body under psychological disturbances. On the other hand, the mood state of people is one of the most significant parameters of human psychology. Thus, this paper investigated the effect of occupants' mood states on thermal sensation; furthermore, it introduced a novel "Mood State Correction Factor" (MSCF) to the existing thermal comfort model. To this aim, experiments were conducted at a mixed-mode building in a university between 15 August 2021 and 15 August 2022. Actual Mean Vote (AMV) and Profile of Mood States (POMS) were used to examine the effect of mood state on thermal sensation. The outcomes of this study showed that in the mood states of very pessimistic and very optimistic, the occupants felt warmer than the calculated one and the MSCFs are calculated as −0.125 and −0.114 for the very pessimistic and very optimistic mood states, respectively. It is worth our time to note that the experiments in this study were conducted during the COVID-19 Global Pandemic and the results of this study could differ in different cultural backgrounds.

Keywords: adaptive thermal comfort; thermal sensation; psychology; mood states

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1. Introduction

Buildings are responsible for approximately 37% and 40% of the total energy consumption in Turkey and European Union (EU) countries, respectively [1,2]. Moreover, Heating, Ventilating, and Air Conditioning (HVAC) systems are responsible for 50% of the total energy consumed by buildings [3]. Therefore, researchers have focused on decreasing energy consumption and improving the HVAC systems' operational efficiency in their studies [4–6]. On the other hand, the American Society of Heating, Refrigerating, and Air-Condition Engineers (ASHRAE) determines that the most important purpose of HVAC systems is to provide appropriate thermal conditions for occupants [7]. To this aim, the Predicted Mean Vote (PMV)/Predicted Percentage of Dissatisfied (PPD) method, which was presented by Fanger in 1970, is used in air-conditioned buildings to calculate the thermal comfort of the occupants [8]. The method is based on four different environmental and two different personal parameters (air temperature (T_a), relative humidity (RH), air velocity (v_a), mean radiant temperature (T_r), basic clothing insulation (I_{cl}) of occupants, and metabolic rate (M) of occupants, respectively) [7,9].

Accordingly, the calculated PMV value is classified with the 7-point thermal sensation scale (ranging from +3 to −3) developed by Fanger [8]. In this scale, the +3 and −3 values depict hot and cold sensations, respectively. Thermal comfort standards state that the PMV value of the environment should be 0 (neutral), with a tolerance of ±0.5 regarding the PMV [7,9]. Additionally, the PPD depicts the occupants who are dissatisfied with the thermal conditions of the environment. According to the ASHRAE-55 [7], the PPD should not be higher than 10% for a comfortable environment [7–9]. On the other hand, while the PMV is measured for the thermal comfort of a large group, Actual Mean Vote (AMV) is used for the thermal sensation of each occupant.

Numerous studies have shown that the behaviors of the occupants should be also taken into account when assessing thermal comfort [10–13]. Therefore, the notion of Adaptive Thermal Comfort (ATC) was introduced by Brager and de Dear [12], one which could be applied to naturally ventilated and mixed-mode buildings. According to the model, occupants may change the parameters which affect their thermal comfort when they feel thermally uncomfortable. The change in the parameters may be taking on/off clothes, decreasing the activity level, or even opening/closing windows and doors. With these changes, occupants react to reach comfortable conditions; after a time, the psychological adaptation process occurs. However, since the psychology of each person may vary, generally, the measured thermal comfort and thermal sensation are different from each other (Figure 1) [13].

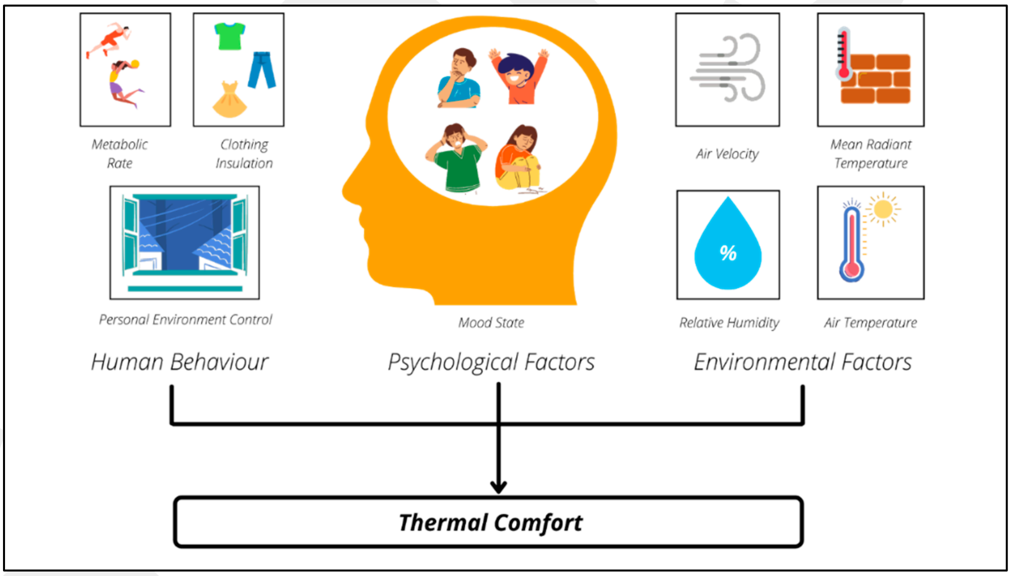

Figure 1. The parameters that affect thermal comfort [8,12–14].

In the literature, thermal comfort studies can be separated into two groups depending on their physiological and psychological parameters [8,13,15–20]. The PMV/PPD method [8], which is commonly applied in thermal comfort studies, was improved based on the study of Gagge et al. [15]. In this study, researchers separated the human body into internal and external parts. While the internal part included the skeleton, muscle, and internal organs, the external part included the skin and the skin's surface. The researchers claimed that a heat transfer process occurs between the internal part and external parts of the human body. Furthermore, a heat transfer process was also observed between the external part of the human body and the thermal environment. Moreover, various parameters, such as face temperature [17], outdoor air temperature (T_{out}) [19], indoor air temperature (T_a) [13], and using both T_a and I_{cl} values [21] in different climatic zones [11,19], were used to develop thermal comfort models.

On the other hand, along with the conducted studies on the physiological parameters, some studies in the literature used the effect of the psychological parameters for the estimation of thermal comfort. The effect of human psychology has a critical role in the estimation of thermal comfort; accelerated studies took human psychology into account in terms of thermal comfort estimation [22–26].

As an example of field tests, Rohles [22] placed two different occupants in two different rooms with architecturally identical features. A heater was placed in only one of the rooms during the experiments but the occupants were informed that there was a heater in both rooms. As a result of the study, both occupants stated that they felt warm and the effect of psychology on thermal comfort was obviously revealed. However, the effect of the psychology on thermal comfort should be investigated with large data sets.

In addition to the field tests, surveys were conducted in the studies. For instance, Nikolopoulou et al. [23] conducted a series of experiments in the spring, summer, and winter seasons with 1431 participants. In the study, the PMV and Actual Sensation Vote (ASV) values of the participants were measured and recorded, respectively, using a 5-point thermal sensation scale. According to the obtained results, the researchers determined that there are critical differences between measured and actual thermal comforts. In another study, Zabetian and Kheyroddin [24], who focused on the outdoor thermal comfort of occupants, carried out a series of experiments in various outdoor environments. In the experiments, the PMV index was used to measure thermal comfort in the summer and winter seasons. According to the results, the researchers revealed that people tend to feel more comfortable in locations where they feel relatively more familiar, more pleased, and freer from disturbances. In another study on outdoor environments, Höppe concluded that people's thermal comfort could vary, even under the same environmental conditions. According to the results, people felt more thermally comfortable in regions where they were relaxed more, such as beaches with a temperature of 40 °C, than they did at the same temperature in urban areas [25]. In a study performed by Zrudlo [26], thermal comfort measurements were taken into account for urban planning purposes. The researchers observed that the thermal comfort of the people living in their own regions was optimal at around the temperature range of 9–11 °C. This situation showed the importance of the psychological adaptations of the human body.

Although there are ongoing studies examining the effect of psychology on thermal comfort, psychological effects were not addressed directly; inferences were merely made on the physical changes caused by the psychological effects of the human body. In these studies, the changes in heart rate and skin temperature caused by the hormones secreted from the hypothalamus of the human brain, which is exposed to psychological effects, were generally used. For instance, in the study presented by Huizenga et al. [27], experiments were performed with 109 participants under different temperature ranges and various conditions. The experiments were conducted in a climate chamber and the researchers observed that temperature change directly affected human psychology and the psychological changes caused significant changes in skin temperature.

In another study conducted in office buildings, the skin temperatures of 430 participants were measured from their fingertips; the PMV values were calculated simultaneously. According to the outcomes of the study, researchers observed that fingertip skin temperature was an important parameter that could be used in thermal comfort calculations [28].

In a similar study performed based on fingertip skin temperature, the effect of psychological changes on the human body was investigated. During the experiments, the participants' PMV values and fingertip temperatures were measured; the determination of the multiple coefficient (R^2) of the linear thermal comfort models was increased from 0.31 to 0.43 by adding the temperature of the fingertip [29].

Yao et al. [30] measured the skin temperatures of participants from various parts of the wrist, forehead, and neck; furthermore, the measurements were repeated under different temperature conditions. According to the results, researchers revealed that forehead skin temperature was an important parameter for thermal comfort calculations, with a confidence level of 99%.

As mentioned in the literature, besides the skin temperature parameter, heart rate was also included as an important parameter of thermal comfort. In experiments conducted by

Liu et al. [31], the heart rate and thermal comfort votes of 33 participants were measured under different air temperature conditions. According to the results, changes in thermal comfort were associated with changes in heart rate.

In another study on the effect of heart rate on thermal comfort, Uemae et al. [32] conducted experiments with 16 participants and measured the heart rates of the participants and various environmental parameters inside the thermo-hygrostat chamber. The relative humidity was kept constant during these measurements and the indoor air temperature was increased or decreased. The 7-point thermal sensation scale was used for the PMV calculation and according to the results, researchers concluded that heart rate was highly related to thermal comfort.

In the study conducted by Ishigaki et al. [33], the relationship between thermal comfort and psychological and physical responses was examined in two children. Experiments were carried out under different indoor-temperature and relative-humidity conditions in the summer and winter periods. The results of the study indicated that there was a difference between the mean skin temperature and the Thermal Sensation Vote (TSV) in the summer and winter periods.

In another comprehensive study performed in the field of thermal comfort by Wu et al. [34], the thermal adaptation of the human body based on psychological, behavioral, and physiological responses was examined. The experiments were performed in hot and humid areas and conducted with 432 young, middle-aged, and elderly participants in a climate chamber with an indoor air temperature set within a range of 18–34 °C. The results of the study revealed that intraoral temperature, blood pressure, and heart rate remained constant in middle-aged and elderly people but skin temperature varied in all age groups.

Ibrahim et al. [35] investigated the relationship between the mood state and the thermal comfort of participants with the help of virtual reality, which was used for creating realistic environments. For this aim, experiments were carried out in an environmental chamber and three different temperature scenarios were used to investigate the relationship between thermal comfort and mood state. Participants were requested to complete the PANAS-X pre-mood state questionnaire before being exposed to VR-based videos, which aimed to expose the different moods of participants, such as anger, and happiness. Afterwards, participants were requested to fill out a thermal sensation vote scale and the outcomes of the study indicated that mood state had a vital effect on thermal comfort and was also affected by the design of the environment.

Another method that has examined the mood states of participants is the Profile of Mood States (POMS) questionnaire, frequently used in the literature as a psychological test developed and standardized by McNair et al. [14]. The POMS questionnaire contains 65 psychological situations and allows participants to express their feelings. The POMS questionnaire was developed over the years and the POMS-2 questionnaire was presented with more accurate results and some additions [36]. The POMS-2 questionnaire includes six different subscales: Tension-Anxiety (TA), Anger-Hostility (AH), Depression-Dejection (DD), Fatigue-Inertia (FI), Confusion-Bewilderment (CB), and Vigor-Activity (VIG). On the other hand, in contrast with POMS, POMS-2 includes a subscale called Friendliness (F) and an overall scale called Total Mood Disturbance (TMD). The aforementioned Total Mood Disturbance (TMD) score is taking into account the six different subscales, except for the Friendliness subscale. The raw scores are obtained from the subscales and converted into T-scores, with a mean and standard deviation of 50 and 10, respectively [37].

In the study presented by Turhan and Özbey [37], the effect of stress level, which is a psychological parameter, on thermal comfort was examined with the participation of female and male students. Experiments were carried out by using the POMS questionnaire to determine the stress level; students were asked to fill out the questionnaire before and after the exam. In addition, the heart rate and skin temperature values of the students were also measured, simultaneously. Experiments were performed with the Pre-test-Post-test Control (PPC) method. According to the obtained results, researchers observed that there were differences between the experimental group and the control group, except for the skin temperature of female students in the pre-test situation.

When the studies which investigate the relationship between thermal comfort and psychology in the literature are examined, the effect of psychology on the human body and thermal comfort is clearly observed. Moreover, the expression "state of mind" used in the definition of thermal comfort by the ASHRAE clearly shows the extent of the relationship between a person's mood state and thermal comfort [7,37].

However, as mentioned, in most of the studies conducted in the field of thermal comfort, physical responses created by psychological effects were taken into account and human psychology was not directly included in the calculations of thermal comfort. In the studies where psychology was aimed at being directly involved, the mood state of the person was not addressed in 65 different mood states. For this reason, this study aims to investigate the effect of the mood states of occupants on their thermal comfort by including all of the aspects (65 different mood states); in addition, it introduces a novel "Mood State Correction Factor (MSCF)" to the existing PMV formula.

2. Materials and Methods

This study aims to develop a mathematical model by examining the effect of mood states on thermal sensation and comfort via a direct determination of the mood state from the POMS-2 questionnaire [36] and thermal sensation votes. The reason for selecting the POMS-2 questionnaire is due to it being a well-known survey in the psychology field that is easy to implement via a basic mobile application compared to the other methods. Additionally, a certain sample size, which is a reliable source to draw conclusions about in reference to the population, is used in this study. To this aim, the diversity of the sample size is also noted for the experiments. The workflow diagram and the methodology of the full study can be seen in Figures 2 and 3.

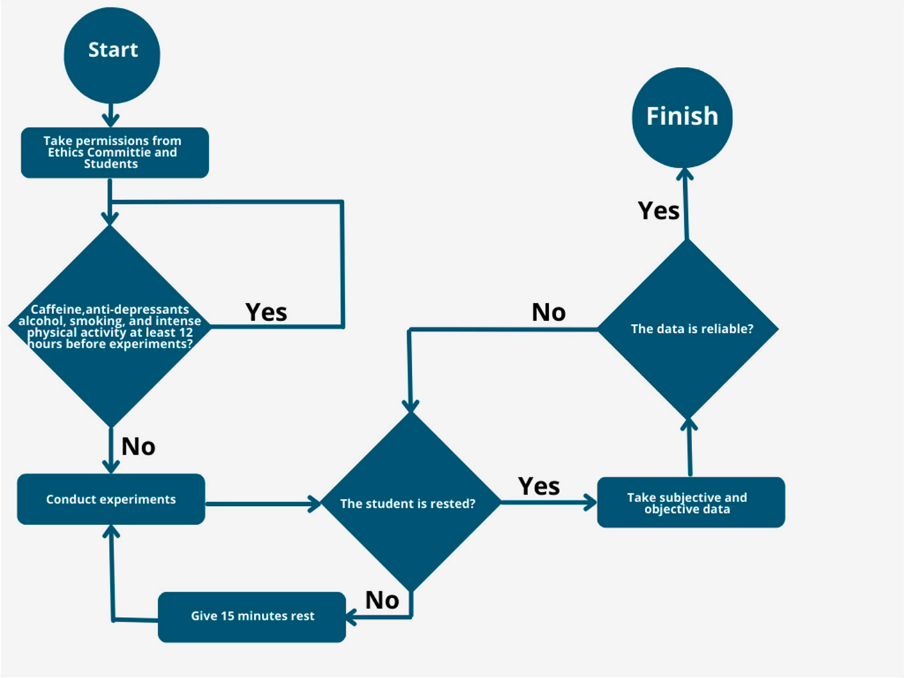

Figure 2. Work-flow diagram of this study.

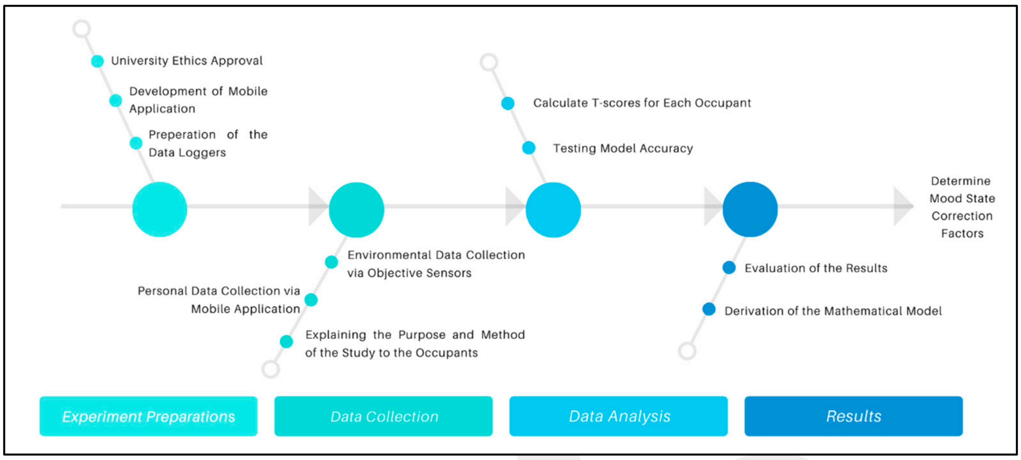

Figure 3. Methodology of this study.

2.1. Design of the Experiments

A university building containing study halls in Ankara/Turkey (39.81° N 32.72° E) was selected as the case building (Figure 4). The city of Ankara is classified as a Csb-type (warm-summer Mediterranean-climate) climate zone, according to the Köppen-Geiger Climate Classification [38]. The average temperature of the winter season (January, February, and December) and summer season (June, July, and August) varies between 0.7 °C and 2.6 °C and 20.3 °C and 23.7 °C, respectively, in Ankara [39].

Figure 4. The location of the case building.

The occupants of the case building (365 m^2) were students (age range: 18–35) and researchers (age range: 35–68). A mixed-mode building, where adaptive thermal comfort models can be applied [20], was selected as the case study. The building has one external wall, a large continuous window facing the north direction, and three internal adiabatic walls. The external wall of the building consists of cement plastering, pumice concrete, and cement screed; meanwhile, the window frames are PVC with double glazing (13 mm air–gap). Moreover, the case building has no mechanical ventilation and the heating of the building is operated by three radiators. In the heating season, the temperature of the building is set to 22 °C to achieve neutral thermal comfort in the indoor environment. Since the aim of this study is to find a relationship between the PMV and AMV and determine the MSCF, large temperature ranges were required. The design of the experiments is depicted simply in Figure 5.

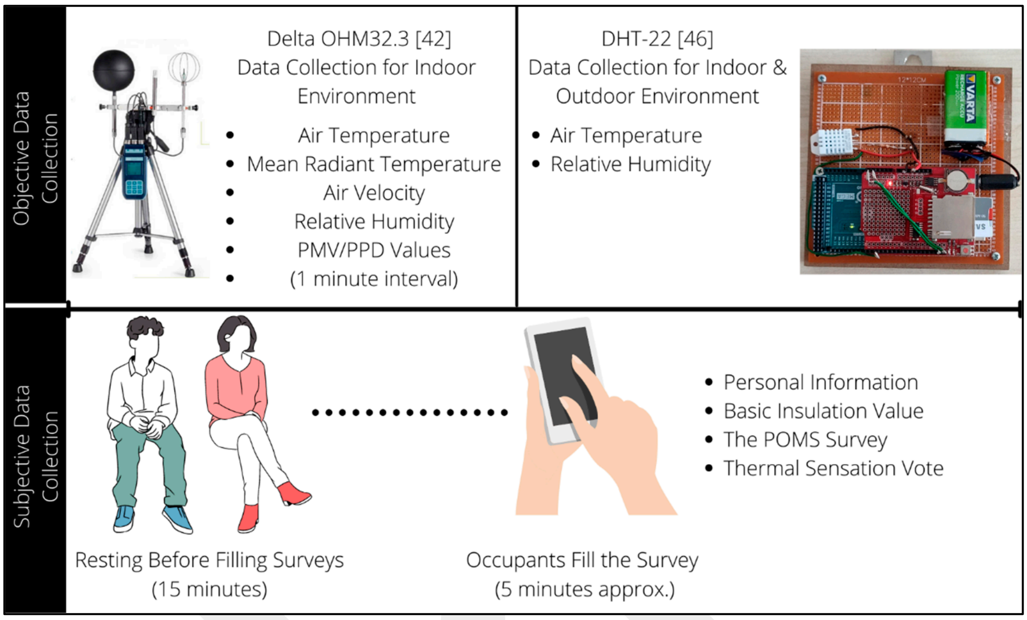

Figure 5. Design of experiments.

Before the experiments, permission was taken from the students and the Ethics Committee of the University to allow for conducting the experiments. Moreover, the occupants were informed about the aim and experimental procedures and they were requested to avoid caffeine, alcohol, smoking, and intense physical activity at least 12 h before the experiments. Moreover, since anti-depressants were proven to affect mood states [40,41], occupants were mainly selected whilst considering who had not used any of them for at least three months. The measurement campaign and surveys were conducted after a 15 min-resting time since the high metabolic rate of students after arriving at the study hall by cycling, running, and walking could affect their thermal sensations and correspondingly mood states.

2.2. Data Collection for Environmental Parameters

The experiments were conducted in an area of 10 m^2 located in the middle of the case building. The reason for selecting the experiment location was to avoid the effect of air velocity caused by opening the door and window, which can affect thermal sensation and mood state. The indoor environmental parameters, which are the PMV, air temperature (T_a), relative humidity (RH), air velocity (v_a), and mean radiant temperature (T_r), were measured every 1 min from a height of 1.1 m, as recommended by the ASHRAE-55 [7]. This took place during office hours (between 09:30 and 16:30) via a Delta Ohm HD 32.3TCA [42] thermal comfort data logger. It is vital to indicate that the Delta Ohm HD 32.3TCA [42] is compatible with ISO 7730 [9], ISO 7726 [43], and ISO 7243 [44] standards. The operative temperature (T_{op}) based on T_a and T_r is calculated by Equation (1) [7,45].

$$T_{op} = A \times T_a + (1 - A) \times T_r \quad (1)$$

If $v_a < 0.2$ m/s, A = 0.5; if $0.2 < v_a < 0.6$ m/s, A = 0.6; $0.6 < v_a < 1.0$ m/s, A = 0.7. The value of A is 0.5 if the v_a is lower than 0.2 m/s; 0.6 if the v_a is between 0.2 and 0.6 m/s; and 0.7 if the v_a is between 0.6 and 1.0 m/s [7,45].

Two DHT-22 [46] temperature and relative-humidity sensors were used to collect temperature and relative-humidity data from outdoors and indoors as a backup of the

Delta Ohm HD32.3TCA measurements. The collected data for the indoor and outdoor environmental parameters were averaged to 5 min, which is the survey-filling time.

An illustration of the case building, with the restricted area for conducting the experiments and the locations of the indoor and outdoor sensors, is presented in Figure 6; the specifications of the sensors are depicted in Table 1. Additionally, an example photo of the area and occupants during the experiments can be seen in Figure 7.

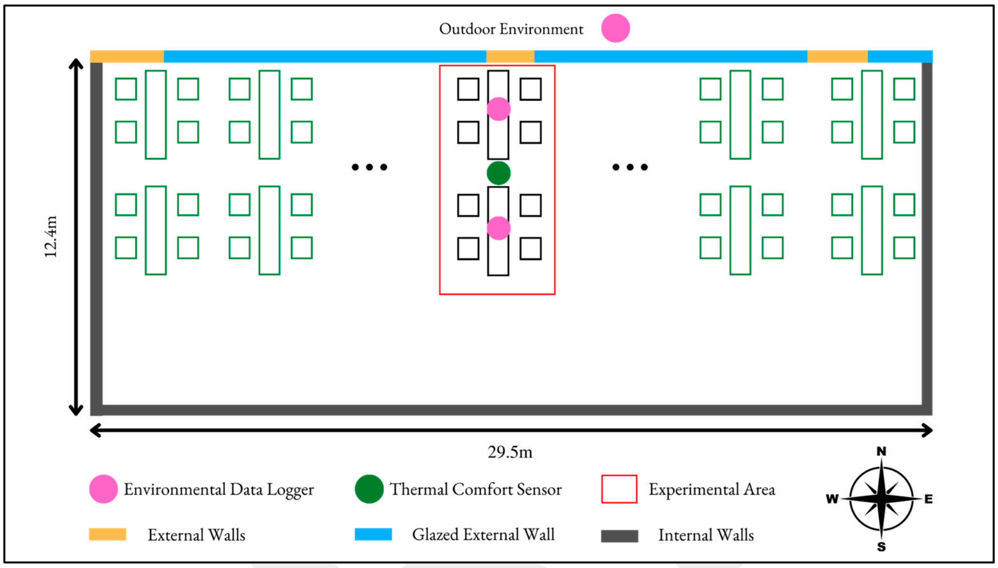

Figure 6. The restricted area used to conduct experiments in the case building with the locations of the used sensors.

Table 1. Measurement devices and specifications.

Temperature and Relative-Humidity Sensor	DHT-22 [46]		RH range Temperature range RH accuracy Temperature accuracy	0–100% −40 to 80 °C ±3% (Max ± 5%) <± 0.5 °C
Thermal Comfort Data Logger	DELTA OHM HD32.3TCA [42]	Globe temperature	Type of probe Measuring range Accuracy Resolution	TP3276.2 probe −10 to 100 °C ±0.1 °C 0.1 °C
		Air velocity	Type of probe Measuring range Accuracy Resolution	AP3203.2 probe 0.02 to 5 m/s ±(0.05 + 5% of the measurement) m/s 0.01 m/s
		Air temperature and Relative humidity	Type of probe Measuring range Accuracy Resolution	HP3217.2R probe Temperature: −40 to 100 °C RH: 0–100% Temperature: ±0.1 °C RH: ±1.5% Temperature: 0.1 °C RH:0.1%

Figure 7. An example photo of the restricted area of the case building and occupants during the experiments.

The authors developed a mobile application to collect subjective measurements, such as AMV and POMS surveys. After filling in personal information, such as nationality, age, gender, height, and weight, the occupants entered information regarding their garments, which included the occupants' underwear, socks, footwear, bottom-wear, top-wear, overalls, jackets, sweaters, etc. Later, the occupants expressed their thermal sensation votes according to a 13-point scale (Figure 8) [47,48]. The reason for using a 13-point scale instead of a traditional 7-point scale was to increase the accuracy of the collected thermal sensation votes in the mathematical model [47,48].

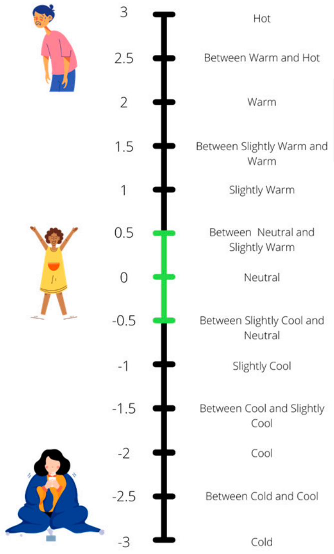

Figure 8. The 13-point thermal sensation scale [47,48].

The POMS-2 questionnaire was also conducted on the developed mobile application. The POMS-2 questionnaire used during the experiments is depicted in Appendix A [12,37] while the survey questions and their representations on subscales of the POMS are given in

Appendix B. The results were collected in a web server, and the Total Mood Disturbance (TMD) was calculated according to Equation (2) [36,49].

$$TMD = Negative\ Feelings - Positive\ Feelings \tag{2}$$

Negative feelings included the sum of the scores of Tension-Anxiety (TA), Anger-Hostility (AH), Depression-Dejection (DD), Fatigue-Inertia (FI), and Confusion-Bewilderment (CB); meanwhile, the positive feelings were only represented by Vigor-Activity (VIG). It is vital to note that the "Friendliness" subscale was excluded from the TMD score since the item significantly includes the interpersonal relationship of the participants. Further details about the POMS-2 questionnaire are given in the reference of [37,38]. After finding the value of the raw scores of the TMD, the raw scores were converted into normalized T-scores [14] with a mean equal to 50 and a standard deviation equal to 10 [37,49], as demonstrated by Equation (3).

$$T - Score = 50 + \frac{10 \times (n - m)}{s} \tag{3}$$

Here, n represents the raw scores, m defines the mean, and s is the standard deviation [14,37]. An increasing T-score indicates a worsening of the mood. The classification of the T-score of the mood state is depicted in Table 2. It is vital to highlight that the other psychological aspects, such as personality traits, attitudes, and thermo-specific self-efficacy, were out of the scope of this paper.

Table 2. Classification of T-Score [37,50].

T-Score	Classification of Mood State
70+	Very Elevated Score—Very Pessimistic (Many more concerns than are typically reported)
60–69	Elevated Score—Pessimistic (More concerns than are typically reported)
40–59	Average Score—Neutral (Typical levels of concern)
30–39	Low Score—Optimistic (Fewer concerns than are typically reported)
<30	Very Low Score—Very Optimistic (Far fewer concerns than are typically reported)

2.3. Mathematical Model Derivation

The regression models are commonly used for thermal comfort studies in different approaches [15,51–53]. In this study, the relationship between the thermal comfort and mood states of the occupants was investigated by deriving a new correlation, called Mood State Correction Factor (MSCF), based on objective and subjective measurements analyzed by using MATLAB [54]. The novel model is based on the "Black-Box Theory". More information about the other model derivations can be seen in [55,56].

In the developed model, the PMV value was selected as a dependent variable while the T_{op}, RH, I_{cl}, and T_{out} values were selected as independent variables. In other words, the PMV value was assumed to be a function of the T_{op}, RH, I_{cl}, and T_{out} values. It is crucial to express that the reason to use the T_{op} is that it comprises T_r, T_a, and v_a, simultaneously [7,57]. Moreover, since this study was conducted in a mixed-mode office building, the T_{out} value was considered in the model. The importance of the T_{out} value in adaptive thermal comfort studies is emphasized in the literature [58,59]; the outdoor environment is vital for the occupants who are required to adjust themselves to achieve thermal comfort. The model diagram of the PMV can be seen in Figure 9.

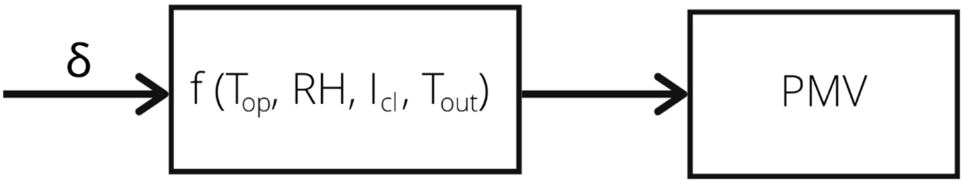

Figure 9. Model diagram of the PMV (δ represents environmental and personal thermal stimuli that affect thermal comfort).

The MSCF is a coefficient that expresses the changes in the thermal sensations of the occupants due to their current mood state. In the mathematical derivation of the model, the black-box model was utilized with an acceptance that the psychology of the occupant gives continuous feedback to the thermal sensation of the occupant, depending on the occupant's current mood (Figure 10).

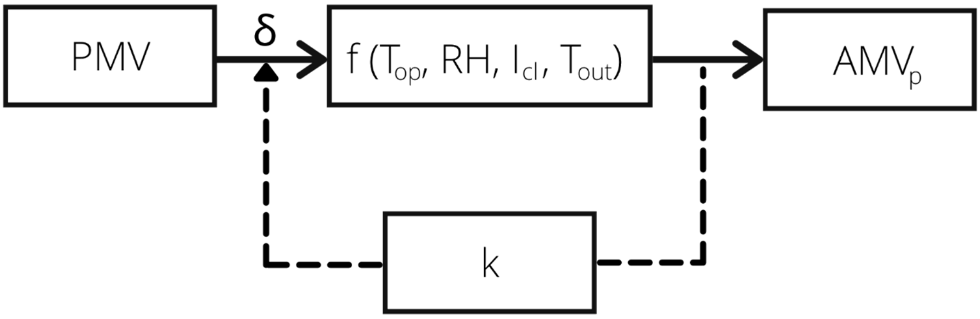

Figure 10. The model diagram (psychological feedback is represented with k).

The system was accepted as a black-box model since the thermal comfort and sensation showed non-linear behavior [60]; the importance weights of the parameters were not known. According to the acceptance of the black-box mathematical model, the thermal sensation always gives feedback via psychological stimuli when the current mood of the occupant is changed momentarily. The output of the system—AMV_p—is the Actual Mean Vote according to psychological mood changes. In other words, it is the real thermal sensation of the occupants.

The PMV value, which represents the occupants' thermal comfort in a given environment, was modeled as a function of the T_{op}, RH, I_{cl}, and T_{out} values and is described with Equation (4).

$$PMV = \delta \times \left(f\left(T_{op}, RH, I_{cl}, T_{out}\right)\right) \quad (4)$$

According to the black-box theory, the derivation of the AMV_p is depicted in Equation (5) [61].

$$AMV_p = \delta \times \left(f\left(T_{op}, RH, I_{cl}, T_{out}\right) - AMV_p \times k \times \left(f\left(T_{op}, RH, I_{cl}, T_{out}\right) \right. \right. \quad (5)$$

By dividing both sides of Equation (5) by AMV_p and combining Equation (4) with Equation (5), Equation (6) is obtained.

$$AMV_p = \frac{PMV}{1 + \left(\frac{k}{\delta}\right) \times PMV} \quad (6)$$

Here, $\frac{k}{\delta}$ represents MSCF. Therefore, the AMV_p equation was modified and is depicted in Equation (7).

$$AMV_p = \frac{PMV}{1 + MSCF \times PMV} \quad (7)$$

The MSCF values were determined by the least square method, which was used to minimize the sum of the error [62]. The MSCF values can be determined by Equation (8) via the least square method. It should be remembered that while the PMV values stemmed from the objective sensor, the AMV_P values stemmed from the mobile application.

$$MSCF = \frac{\sum_i^z PMV - AMV_p}{z} \tag{8}$$

Here, z represents the total data number of each subgroup. After finding the T-scores of the TMD values of the occupants, five different MSCF values were obtained according to occupants' mood states (very pessimistic to very optimistic), as indicated in Section 2.2, Table 2.

3. Results

This section summarizes the measurement and survey results and the MSCF values for all of the mood states of the occupants.

3.1. Measurement Results

In order to obtain the MSCF values, environmental conditions, such as T_{op}, RH, I_{cl}, T_{out}, and PMV were measured for one year between 15 August 2021 and 15 August 2022; the average values and standard deviation of the data are shown in Table 3. The winter season was assumed to be between 4 October and 14 April while the summer season was assumed to be between 15 April and 3 October for Ankara/Turkey [63,64]. In addition, 1.1 met was assumed according to the ASHRAE-55 [7] during the experiments. It is worth noting that 1 met is equal to 65 W/m^2.

Table 3. Data statistics for the winter and summer seasons.

		Winter Season		Summer Season	
		Mean	**Standard Deviation**	**Mean**	**Standard Deviation**
T_{out}	°C	8.8	6.5	22.4	4.6
T_a	°C	21.4	1.1	23.1	1.2
T_r	°C	21.5	0.9	23.0	2.5
RH_i	%	34.1	8.2	38.5	6.5
RH_o	%	66.1	18.3	38.3	13.5
v_a	m/s	<0.01	0.001	<0.01	0.001
PMV	-	−0.48	0.24	−0.11	0.31
AMV	-	0.20	0.89	0.42	1.01
I_{cl}	-	0.95	0.27	0.56	0.21
met	-	1.1	-	1.1	-

Since there exists no mechanical ventilation in the case building, the effect of the v_a was not significant on the thermal sensation of the occupants. The average T_a was measured as 21.4 °C and 23.1 °C for the winter and summer seasons, respectively; although, the set-point temperature of the heating systems was 22 °C. This was the result of internal heat gains, such as the high number of students and personal computers (laptops) in the study hall. The clothing insulation values were measured as 0.95 and 0.56 for the winter and summer seasons, respectively. Most of the students preferred to remove their coats in the study hall during the resting time. It is worth it to note that the study hall was naturally ventilated; however, the v_a values were still below 0.1 since the experimental zone was chosen to be in the middle of the study hall. This means that the students were not affected by the opening of the door and windows.

3.2. Survey Results

A total of 1159 participants, of which 48.4% were female and 51.6% were male, were included in the surveys during one year. The average and the standard deviation of the ages of the participants were 23.4 and 4.2 years, respectively. Additionally, the mean height and weight of the participants were 1.78 m and 76.5 kg, respectively. The mean values and standard deviations (SDs) of the raw scores of the occupants for six subscales are shown in Table 4; meanwhile, Figure 11 depicts the average T-scores of the participants with respect to six subscales of the POMS. It is significant to note that the transformation of the raw scores of the subscales to the T-scores was calculated according to Morgan [65]. The red line in the figure represents the average T-score of the normative forms. It should be emphasized that the table was generated from a mixed-gender sample of participants.

Table 4. The raw score results of the POMS.

	Min–Max *	Mean	SD
Tension-Anxiety (TA)	[0;36]	14.19	5.96
Depression-Dejection (DD)	[0;60]	15.95	9.86
Anger-Hostility (AH)	[0;36]	14.05	8.03
Vigor-Activity (VA)	[0;32]	15.76	5.01
Fatigue-Inertia (FI)	[0;28]	12.39	5.27
Confusion-Bewilderment (CB)	[0;32]	9.78	4.06

* Max–Min values are the values for which a participant can vote a maximum and minimum grade for on the scale.

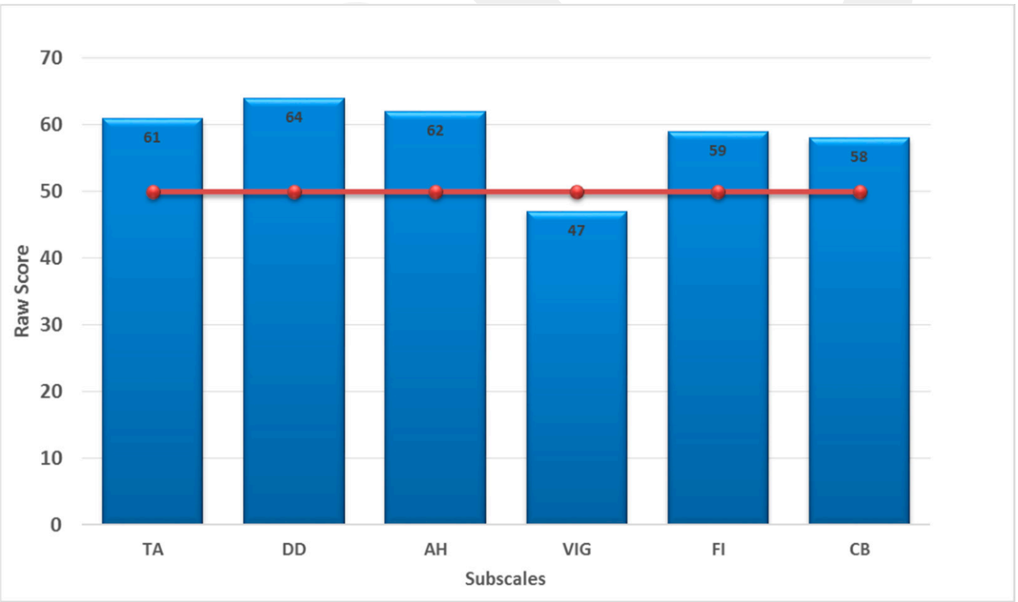

Figure 11. Average subscale T-scores for participants (N = 1011) when plotted against the mean value of normative T-scores.

Considering the mean value of the normative T-scores was 50, the average TA, DD, AH, FI, and CB of the T-scores of the participants were higher than the mean value of the normative T-scores. The reason could be the stress, which affects the mood state of the participants, of studying in the study hall. Similarly, the average T-score of the VIG of the participants was found to be lower than the mean value of normative T-scores. This means that the negative mood state of the participants was higher than the positive mood state. The AMV values were found to be 0.20 and 0.42 for the winter and summer seasons, respectively. The participants felt warmer in the summer season. The reason could be the absence of a cooling system in the building. In winter, radiators were operated; however, in summer there was no system for cooling purposes.

3.3. The MSCF Results

Table 5 depicts the calculated MSCF values for the corresponding T-scores. The MSCF values were calculated according to Equation (8). Since there are five classifications of TMD in the literature, the authors developed five different MSCF values.

Table 5. The developed MSCF values for the model.

Classification of TMD	MSCF Values
Very Elevated Score—Very Pessimistic (Many more concerns than are typically reported)	−0.125
Elevated Score—Pessimistic (More concerns than are typically reported)	−0.075
Average Score—Neutral (Typical levels of concern)	0
Low Score—Optimistic (Fewer concerns than are typically reported)	−0.061
Very Low Score—Very Optimistic (Far fewer concerns than are typically reported)	−0.114

Some of the examples of the effect of mood state on the current PMV calculations obtained by using MSCF values developed by the authors are given below.

In warmer environments;

Example 1: Let us consider that the T-score of the occupant is found to be *neutral* according to the POMS survey (Neutral means that the T-score is between 40 and 59, as given in Table 5). The PMV value is calculated and/or read as 1 from the thermal comfort sensor. According to Table 5, developed by the authors, the MSCF value is 0.

PMV = 1 and T-score is between 40 and 59 (Neutral); MSCF = 0. Then;

$$AMV_p = \frac{PMV}{1 + MSCF \times PMV}$$

$AMV_p = \frac{1}{1+(0)\times 1}$ = 1 (no change on the AMV)

This result means that there is no effect of the current mood state of the occupant on the thermal sensation since the AMV value is the same as the PMV value.

Example 2: For instance, if the PMV is calculated as 1 and the T-score is between 60 and 69 (Pessimistic);

MSCF = −0.075. Then;

$$AMV_p = \frac{PMV}{1 + MSCF \times PMV}$$

$AMV_p = \frac{1}{1+(-0.075)\times 1}$ = 1.08 (feeling warmer)

Example 3: For instance, if the PMV is calculated as 1 and the T-score is <30 (Very Optimistic); MSCF= −0.114. Then;

$$AMV_p = \frac{PMV}{1 + MSCF \times PMV}$$

$AMV_p = \frac{1}{1+(-0.114)\times 1}$ = 1.12 (feeling warmer)

In cooler environments;

Example 4: The PMV= −0.8 and the T-score is above 70 (Very Pessimistic). Then;

MSCF= −0.125

$AMV_p = \frac{-0.8}{1+(-0.125)\times -0.8}$ = −0.72 (feeling warmer)

Special Case: If the PMV = 0, it is obvious that the equation always gives a 0 value in any case of the mood state. To avoid this situation, one can use the value below; the PMV is accepted as +0.01 since the resolution of the PMV data logger is 0.01 and the trend of the thermal sensation is always towards the warmer side.

These equations fit very well within the ±3 range of the PMV values. Figure 12 depicts the difference between the AMV and PMV, according to the mood state of the occupants.

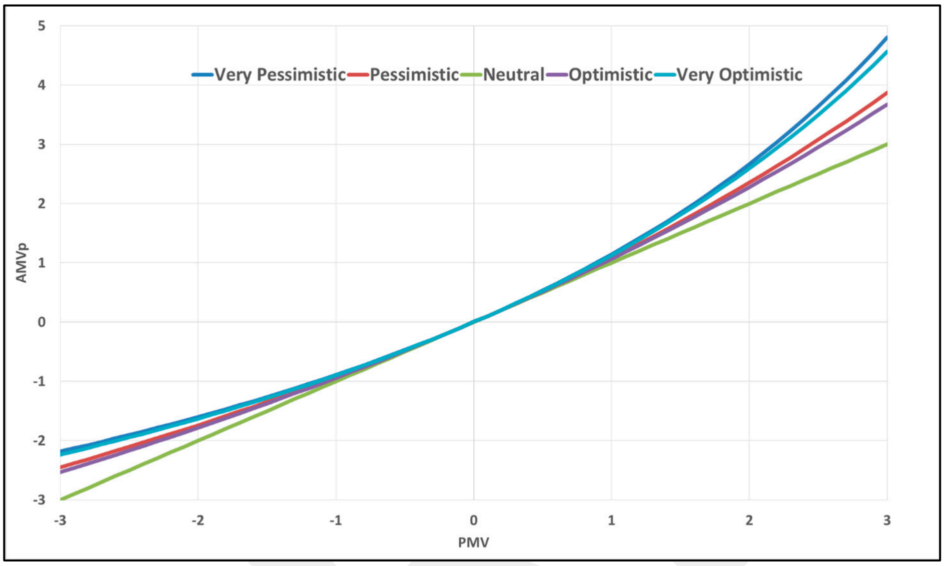

Figure 12. The difference between the AMV and PMV according to the mood state of the occupants.

The figure represents that the difference between the PMV and AMV in the negative mood states is larger than the difference between the PMV and AMV in the positive mood states. This result concludes that negative mood states make the occupant feel warmer than positive mood states. However, the occupants always feel warmer than the calculated PMV value for both negative and positive mood states. At the neutral mood states, the PMV equals the AMV. This result indicates that neutral mood states had no effect on the thermal sensation. Table 6 gives an example of how to change the thermal sensation according to the mood state compared to the measured +0.5 PMV value.

Table 6. An example of the thermal sensation change according to the mood states compared with the measured +0.5 PMV value.

Mood State	MSCF Values	AMVp Values
Very Pessimistic	−0.125	0.537
Pessimistic	−0.075	0.519
Neutral	0	0.5
Optimistic	−0.061	0.515
Very Optimistic	−0.114	0.53

One can say that the difference between thermal sensation and measured thermal comfort is low for the +0.5 PMV value, even for the mood states of very pessimistic and very optimistic. As one can calculate from Table 6, a very pessimistic mood state increases the thermal sensation by 7.4% compared to the neutral mood state. However, for the warmer/cooler environments, this difference is increasing significantly. For example, for the PMV value of 2, the very pessimistic mood state increases thermal sensation by 34% compared to the neutral mood state.

3.4. Limitations

This study was conducted, unfortunately, during the COVID-19 global pandemic. Therefore, the occupants wore masks during the experiments. Even though the effect of the masks could be considered to be very low regarding the clothing insulations, the thermal sensation might have been affected. The authors encourage researchers to investigate the effect of the masks on the thermal sensation and clothing insulation.

Cultural differences should be investigated in detail with further studies. The selections of the mood states in the POMS survey might have been different for occupants from different cultural backgrounds.

4. Conclusions

This study developed a mood state correction factor for the first time in the literature in order to decrease the gap between the actual thermal sensation vote and the predicted mean vote. The model was developed according to the black-box method rules in a mixed-mode building. The experiments were conducted in a living study hall for a year. The selection of this study hall, instead of the lab environments, validated the developed method in a real life setting.

The MSCF values were found to be -0.125, -0.075, 0, -0.061, and -0.114 for the very pessimistic, pessimistic, neutral, optimistic, and very optimistic mood states, respectively. The developed model was valid for both cooler and warmer environmental conditions. The occupants felt warmer in positive and negative mood states while the neutral mood states had no effect on the gap between the AMV and PMV.

The novelty of this study is the addition of a MSCF to the literature via experiments with data-driven models. However, it is worth remembering that the experiments were conducted during the COVID-19 pandemic, which could have affected the mood state of occupants. Further studies should include the effect of the pandemic on the mood state. Moreover, cultural differences should be investigated and included in the results of this study. The authors believe that understanding the gap between the AMV and PMV is sufficient for the energy efficiency of the buildings and the thermal comfort of the occupants. By taking the mood states of the occupants into account, more energy-efficient HVAC systems can be developed. In addition, this study is a starter study in understanding the influence of psychological conditions in the field and highlights that this is deserving of greater attention.

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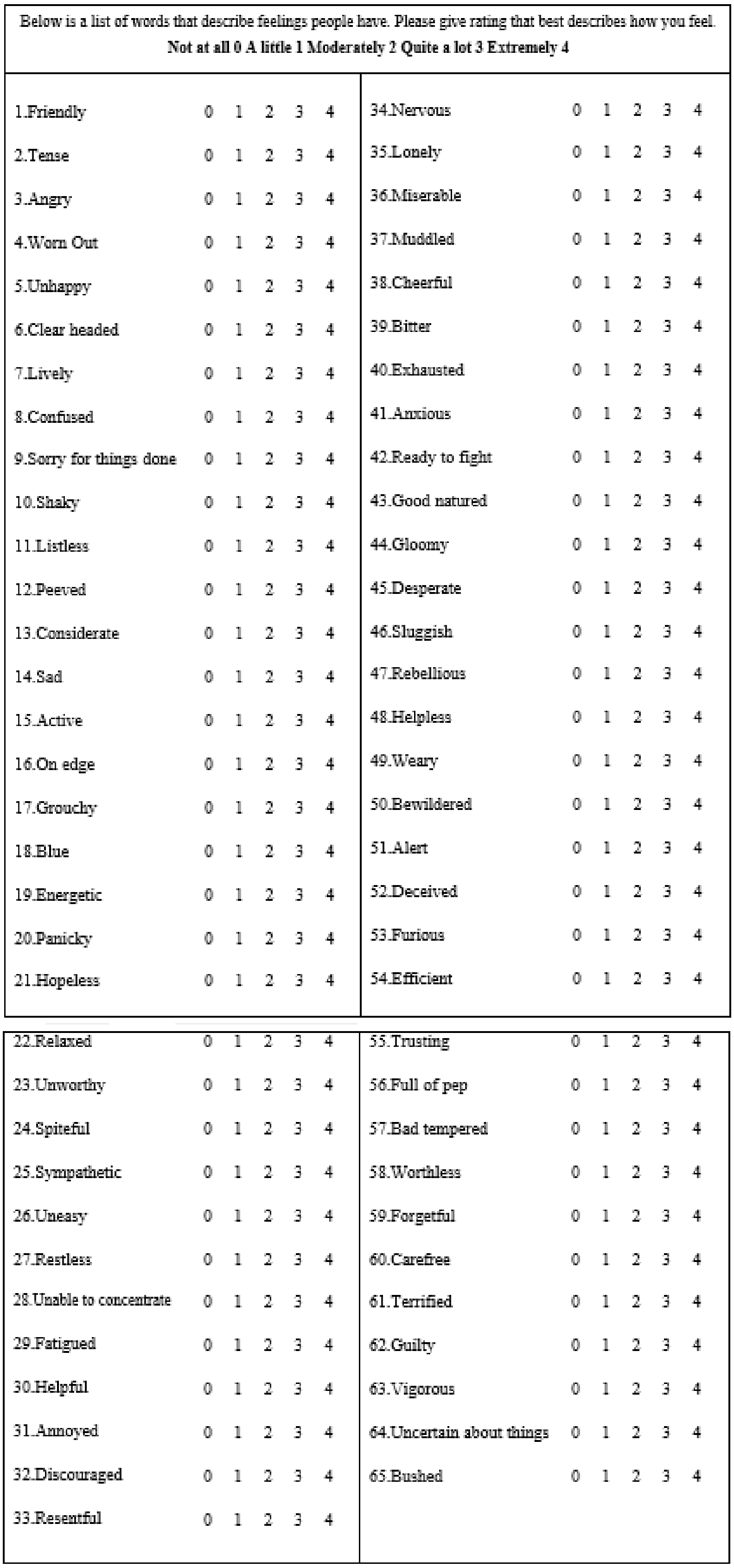
Appendix A



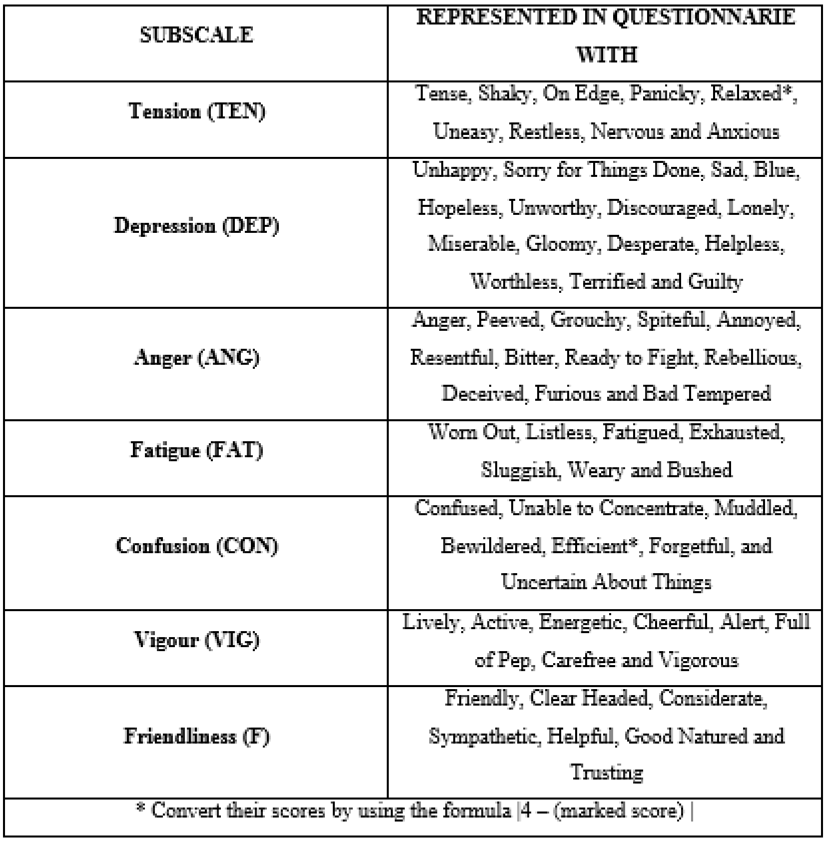
Below is a list of words that describe feelings people have. Please give rating that best describes how you feel.

Not at all 0 A little 1 Moderately 2 Quite a lot 3 Extremely 4

1.Friendly	0	1	2	3	4	34.Nervous	0	1	2	3	4
2.Tense	0	1	2	3	4	35.Lonely	0	1	2	3	4
3.Angry	0	1	2	3	4	36.Miserable	0	1	2	3	4
4.Worn Out	0	1	2	3	4	37.Muddled	0	1	2	3	4
5.Unhappy	0	1	2	3	4	38.Cheerful	0	1	2	3	4
6.Clear headed	0	1	2	3	4	39.Bitter	0	1	2	3	4
7.Lively	0	1	2	3	4	40.Exhausted	0	1	2	3	4
8.Confused	0	1	2	3	4	41.Anxious	0	1	2	3	4
9.Sorry for things done	0	1	2	3	4	42.Ready to fight	0	1	2	3	4
10.Shaky	0	1	2	3	4	43.Good natured	0	1	2	3	4
11.Listless	0	1	2	3	4	44.Gloomy	0	1	2	3	4
12.Peeved	0	1	2	3	4	45.Desperate	0	1	2	3	4
13.Considerate	0	1	2	3	4	46.Sluggish	0	1	2	3	4
14.Sad	0	1	2	3	4	47.Rebellious	0	1	2	3	4
15.Active	0	1	2	3	4	48.Helpless	0	1	2	3	4
16.On edge	0	1	2	3	4	49.Weary	0	1	2	3	4
17.Grouchy	0	1	2	3	4	50.Bewildered	0	1	2	3	4
18.Blue	0	1	2	3	4	51.Alert	0	1	2	3	4
19.Energetic	0	1	2	3	4	52.Deceived	0	1	2	3	4
20.Panicky	0	1	2	3	4	53.Furious	0	1	2	3	4
21.Hopeless	0	1	2	3	4	54.Efficient	0	1	2	3	4
22.Relaxed	0	1	2	3	4	55.Trusting	0	1	2	3	4
23.Unworthy	0	1	2	3	4	56.Full of pep	0	1	2	3	4
24.Spiteful	0	1	2	3	4	57.Bad tempered	0	1	2	3	4
25.Sympathetic	0	1	2	3	4	58.Worthless	0	1	2	3	4
26.Uneasy	0	1	2	3	4	59.Forgetful	0	1	2	3	4
27.Restless	0	1	2	3	4	60.Carefree	0	1	2	3	4
28.Unable to concentrate	0	1	2	3	4	61.Terrified	0	1	2	3	4
29.Fatigued	0	1	2	3	4	62.Guilty	0	1	2	3	4
30.Helpful	0	1	2	3	4	63.Vigorous	0	1	2	3	4
31.Annoyed	0	1	2	3	4	64.Uncertain about things	0	1	2	3	4
32.Discouraged	0	1	2	3	4	65.Bushed	0	1	2	3	4
33.Resentful	0	1	2	3	4						

Figure A1. POMS-2 QUESTIONNAIRE.

Appendix B



SUBSCALE	REPRESENTED IN QUESTIONNARIE WITH
Tension (TEN)	Tense, Shaky, On Edge, Panicky, Relaxed*, Uneasy, Restless, Nervous and Anxious
Depression (DEP)	Unhappy, Sorry for Things Done, Sad, Blue, Hopeless, Unworthy, Discouraged, Lonely, Miserable, Gloomy, Desperate, Helpless, Worthless, Terrified and Guilty
Anger (ANG)	Anger, Peeved, Grouchy, Spiteful, Annoyed, Resentful, Bitter, Ready to Fight, Rebellious, Deceived, Furious and Bad Tempered
Fatigue (FAT)	Worn Out, Listless, Fatigued, Exhausted, Sluggish, Weary and Bushed
Confusion (CON)	Confused, Unable to Concentrate, Muddled, Bewildered, Efficient*, Forgetful, and Uncertain About Things
Vigour (VIG)	Lively, Active, Energetic, Cheerful, Alert, Full of Pep, Carefree and Vigorous
Friendliness (F)	Friendly, Clear Headed, Considerate, Sympathetic, Helpful, Good Natured and Trusting

* Convert their scores by using the formula |4 – (marked score) |

Figure A2. SUBSCALES AND THEIR REPRESENTATIONS IN THE POMS SURVEY.

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