HUMAN BODY HEAT EXCHANGE MECHANISM AND THERMAL COMFORT VIA VISUAL IMPACT

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DEDICATION

To my beloved family and my soulmate…

ABSTRACT

Thermal comfort is a combination of several components and can be described in many ways while for all definitions the precedence is human. In this thesis, thermal comfort is examined through the environmental differences and psychological changes via several experiments performed with human subjects while accounting for metabolic rates and clothing level. For the experimental study, three different test scenarios were considered, to examine if a human subject is feeling hot, cold or comfortable. To track the comfort level of subjects, skin temperatures were measured from four different body segments and TSV (Thermal Sensation Vote) questionnaires were given at certain intervals. To compose the required combinations of environmental parameters of the test room such as, relative humidity, air velocity, air temperature the Fanger Method was used and comfort level of the test rooms were described according to PMV (Predicted Mean Vote) indices. Participant's psychological changes were controlled with emotional stimulating pictures from IAPS (International Affective Picture System) data base. IAPS consists of several colorful images with different levels of stimuli (pleasant, unpleasant and neutral pictures). Each subject attended one of the case conditions randomly and during 15 minute long experiments, watched 3 different blocks of stimuli pictures. Consequently, the direct effects of human emotions on thermal comfort and thermal sensations were assessed throughout the experiments and with this study it is aimed to find a way to decrease energy usage on HVAC systems by controlling human psychology within certain limits.

Keywords: Indoor thermal conditions; thermal comfort; thermal sensation; skin temperature; visual stimuli; energy efficiency

ÖZET

Termal konfor birçok bileşenden oluşur ve farklı yollarla tanımlanabilir fakat her bir tanımın ortak noktası insanı merkeze alarak tanımlamasıdır. Bu tezde, insanlı deneysel çalışmalar yapılarak, termal konforun çevresel ve psikolojik değişimler üzerindeki etkisi incelenmiştir. Deneysel çalışmalar için, termal olarak konforlu, konforsuz sıcak ve konforsuz soğuk olmak üzere üç farklı senaryo oluşturulmuştur. Katılımcıların konfor sevilerini deney boyunca takip edebilmek için deri sıcaklıkları dört farklı noktalardan ölçülmüş ve belirli zaman aralıklarında TSV (termal his oyu) formlarını doldurmaları istenmiştir. Deney odasının çevresel parametrelerini senaryolara uygun ayarlayabilmek için Fanger yöntemi kullanılmış ve odanın konfor seviyesi PMV (ortalama tahmini oy) indeksine göre belirtilmiştir. Katılımcıların psikolojik değişiklikleri için IAPS veri tabanı aracılığıyla duygu uyarıcı resimler kullanılmıştır. IAPS (uluslararası duygu uyarıcı görüntü sistemi) belirli seviyelerde (keyifli, keyifsiz ve nötr) renkli ve uyarıcı resim setlerini içermektedir. Her bir katılımcı rastgele belirlenen bir oda koşulunda 15 dk boyunca 3 blok halinde duygu uyarıcı resimleri izledi. Sonuç olarak, bu çalışma ile insan duygularının termal konfor ve ısıl duyarlılık üzerine olan etkisi incelenmiş ve bina ısıtma ve soğutmaya bağlı enerji tüketimini belirli limitler içinde insanın psikolojik durumunu değiştirerek azaltmayı amaçlamıştır.

Anahtar kelimler: İç mekan termal koşulları; termal konfor; termal duyarlılık; deri sıcaklığı; görsel uyarıcı; enerji verimliliği

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Mom, Dad, I did it!

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ABBREVIATIONS AND ACRONYMS

HVAC	: Heating, ventilation, and air conditioning
PMV	: Predicted mean vote
PPD	: Percent of people dissatisfied
TSV	: Thermal sensation vote
ASHRAE	: American Society of Heating, Refrigerating and Air-Conditioning Engineers
IAPS	: International Affective Picture System
ESP	: Emotion Stimulating Pictures
TC	: Thermal Comfort

NOMENCLATURE

A_{Du}	: Total body area	m^2
A_{Du_m}	: Total body area for male	m^2
A_{Du_f}	: Total body area for female	m^2
$\frac{H}{A_{Du}}$	: Internal heat production per unit body surface area	$\frac{kcal}{m^2-h}$
I_{cl}	: Clothing thermal resistance	clo
T_a	: Air temperature	$°C$
t_{mrt}	: Mean radiant temperature	$°C$
p_a	: Partial water vapor pressure in current air temperature	$mmHg$
v	: Air relative velocity	$\frac{m}{s}$
t_s	: Mean skin temperature	$°C$
$\frac{E_{sw}}{A_{Du}}$	: Heat loss by sweat secretion in unit body surface area	$\frac{kcal}{m^2-h}$
H	: Internal heat production in human body	$\frac{kcal}{h}$
E_d	: Heat loss by water vapor diffusion on the surface of the human skin	$\frac{kcal}{h}$
E_{sw}	: Heat loss by evaporation of sweat	$\frac{kcal}{h}$
E_{re}	: Heat loss by respiration	$\frac{kcal}{h}$
L	: Dry respiration heat loss	$\frac{kcal}{h}$
K	: Conduction heat loss through clothing	$\frac{kcal}{h}$

R	: Radiation heat loss from the body	$\frac{kcal}{h}$
C	: Heat loss by convection	$\frac{kcal}{h}$
A_{Du}	: Total area of the skin	m^2
m_b	: Mass of the body	kg
h_b	: Height of the body	m
M	: Metabolic rate	$\frac{kcal}{h}$
W	: External mechanical power	$\frac{kcal}{h}$
η	: External mechanical efficiency	
$\frac{M}{A_{Du}}$	: Metabolic rate	$\frac{kcal}{h-m^2}$
λ	: Heat of vaporization of water in current environmental air temperature	$\frac{kcal}{kg}$
m	: Human skin permeance coefficient	$\frac{kg}{h-m^2-mmHG}$
p_s	: Saturated water vapor pressure on the surface of the human skin	$mmHg$
V	: Pulmonary ventilation	$\frac{kg}{h}$
W_{ex}	: Expiration air humidity ratio	$\frac{kg\ water}{kg\ dry\ air}$
W_a	: Inspiration air humidity ratio	$\frac{kg\ water}{kg\ dry\ air}$
P	: Atmospheric pressure	$mmHg$
c_p	: Dry air specific heat	$\frac{kcal}{kg\ ℃}$
T_{ex}	: Temperature of the expired air	℃

R_{cl}	: Heat resistance of the cloth	$\frac{m^2-h-℃}{kcal}$
T_{cl}	: Cloth surface temperature	℃
A_{eff}	: Clothed body effective radiation area	m^2
ϵ	: Clothed body outer surface emittance	
σ	: Stefan-Boltzmann constant	$watt/m^2K^4$
T_{mrt}	: Mean radiant temperature	K
f_{eff}	: Factor of the effected radiation area	
f_{cl}	: Clothed body surface area over nude body surface area	
h_{cl}	: Convective heat transfer coefficient	$\frac{kcal}{m^2-℃-h}$

CHAPTER I

INTRODUCTION

1.1. General Background

Sheltering is a natural human habit from ancient times up to today this is because of the thermal interaction between human body and its surroundings and also for protection purposes from danger. Coming up to today's world by increase in population and pace of urbanization, people who lives in urban settings spends 90% of their time in indoor environment. Therefore, the idea behind the primary human need of sheltering has evolved to comfortable living places.

According to ASHRAE-55 (American Society of Heating, Refrigerating and Air Conditioning Engineers), thermal comfort has been stated as the condition of mind which satisfies occupants in current environmental conditions [1]. In this thesis, among other parameters of comfort we only focus on thermal comfort.

The condition of environment varies according to air temperature, mean radiant temperature, air humidity and air relative velocity in a thermal comfort manner. On the other hand, occupant based variables can be counted as activity levels and type of clothing. According to these factors, the thermal comfort is based on several variables as expressed by Fanger [2].

$$\mathbf{F}\left(\frac{H}{A_{Du}}, I_{cl}, T_a, t_{mrt}, p_a, v, t_s, \frac{E_{sw}}{A_{Du}}\right) \qquad (1.)$$

Where the "**F**" represents Fanger's thermal comfort parameters that enables to quantify human thermal comfort. We can list all relevant formulas in Eq. 1.2 and Eq.2.6.

A_{Du}	: Human body surface area by DuBois [3]	m^2
$\frac{H}{A_{Du}}$	: Internal heat production per unit body surface area	$\frac{kcal}{m^2-h}$
I_{cl}	: Clothing thermal resistance	clo
T_a	: Air temperature	$°C$
t_{mrt}	: Mean radiant temperature	℃
p_a	: Water vapor pressure in the current environment	$mmHg$
v	: Air relative velocity	$\frac{m}{s}$
t_s	: Skin temperature	$°C$
$\frac{E_{sw}}{A_{Du}}$	: Heat loss by sweat secretion in unit body surface area	$\frac{kcal}{m^2-h}$

For a specific level of activity, the physiological variables in Eq.1. are mean skin temperature (*ts*) and heat loss by sweat secretion (*Esw*). The sense of thermal comfort depends on the value of these two variables. Also environmental variables can be counted as air temperature (*Ta*), relative humidity, mean radiant temperature (*Tmrt*) and air velocity (*V*). Beside to these factors clothing level (*Icl*) also has considerable impacts on thermal comfort. According to previous studies, it was determined that *ts* and *Esw* values were a function of activity level. In this study experiment room conditions were specified according to Fanger's comfort equations and quantified with PMV indices.

1.1.1. Heat Production Mechanism: Metabolism

Humans are homoeothermic (warm blooded) creatures, hence their body tends to protect inner body temperature in a certain range. The energy production process starts with food gaining into body. By the exchange of energy, food broken down into compounds. Then the energy transfers into heat and mechanical work from various chemical reactions that occurs in several organs by anaerobic and aerobic activities [4]. Body surface area, gender, age, stress level, muscular exercise, illness and time in menstrual cycles are all factors that affects metabolic heat generation. Metabolism express with a special unit "met" and it comes from multiplying by basal metabolism, 1met equals to 58.1 W/m^2.

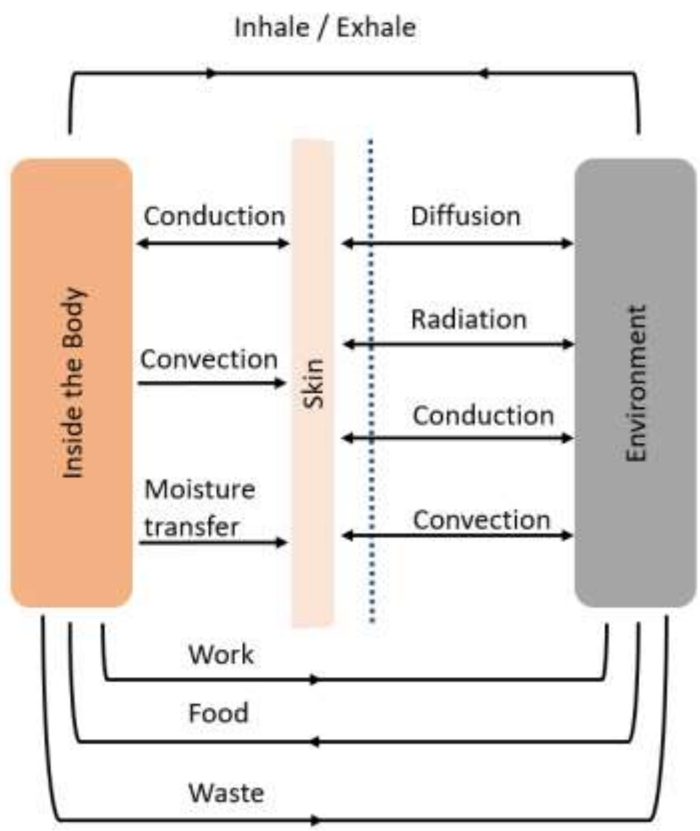

Figure 1. Representation of human body heat exchange and production mechanism.

1.1.2. Heat Balance on Human Body

To maintain the constant internal body temperature (36 - 38 °C), human thermoregulatory system exists [5]. The assumptions are constant environmental temperature and constant metabolic rate. Thus the heat balance equation can be formed according to Fanger (1970) [6] as in the below.

$$H - E_d - E_{sw} - E_{re} - L = K = R + C \tag{1.1}$$

where;

H : Internal heat production in human body

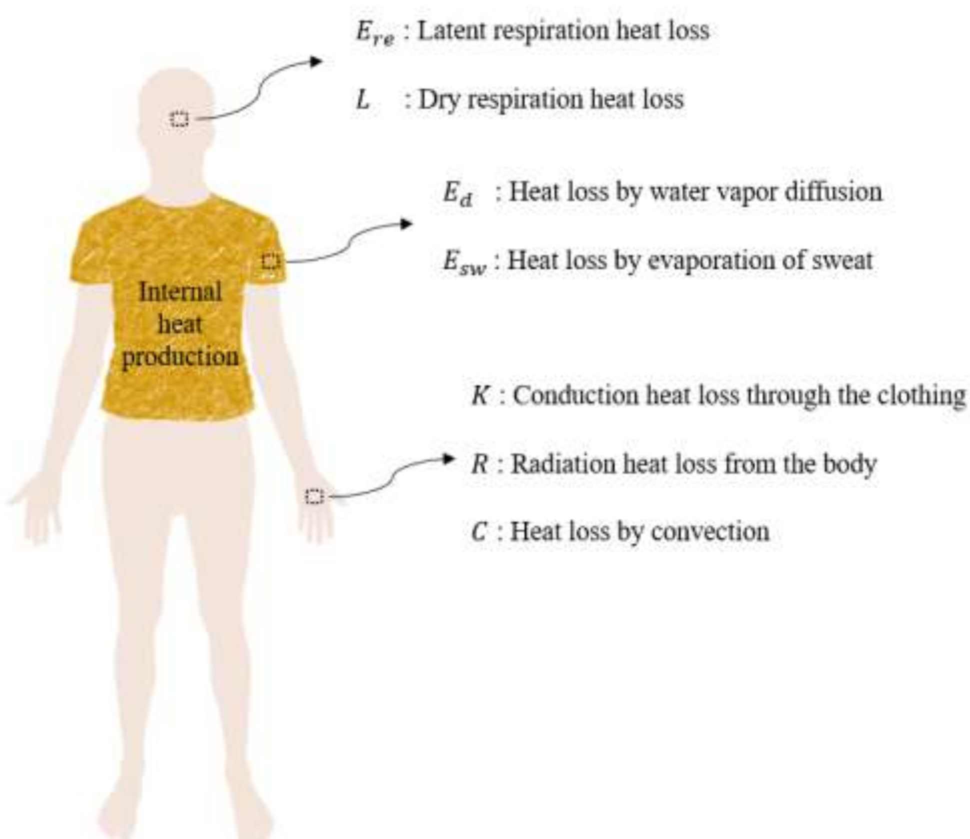

Figure 2. An illustration of a human body heat balance by indicating each heat loss parameter.

The heat balance equation states that; the total heat production in the body (H) equals to the heat loss by respiration ($L + E_{re}$) and heat loss by evaporation ($E_d + E_{sw}$) which is also equals to the heat conduction through the clothing (K) and thereafter heat dissipates from the surface of the clothed area by radiation (R) and convection (C).

1.1.3. Simplified Model of Skin Heat Exchange Mechanism

Since human body is homoeothermic (an organism that self-maintenance of body temperature to a constant level), it needs to keep its core temperature in certain ranges [7]. Skin is the major organ that enables heat and moisture transfer through in and out to the environment. Mainly heat exchange mechanism is divided into two, as latent heat transfer via evaporation of sweat and moisture through the skin surface and also sensible heat transfers via conduction, convection and radiation [8]. Also skin consists of thermal sensors which are involving in the thermoregulatory system as a supporter for thermal comfort and sensation of the human. Figure 3 represents the way heat dissipation from the body with four different way. The heat dissipation through convection, radiation, conduction in the skin structure occurs as vasoconstriction or vasodilation. During the cold exposure body tends to conserve heat and therefore blood vessels are narrow to decrease the heat transfer at the skin level, this process named as vasoconstriction. Similarly, in a hot environment body tends to transfer heat to surrounding and therefore widens the blood vessels through vasodilation. If the body is in thermal balance (while in neutral environment and either no mechanical work included) the thermoregulatory system is not takes an action, therefore heat loss distribution become minimal at the level of, 25% from evaporative heat loss and 75% from sensible heat loss in total [8]. Other than neutral position, during the exercise period, it is possible to observe reverse percentages between sensible and evaporative heat losses.

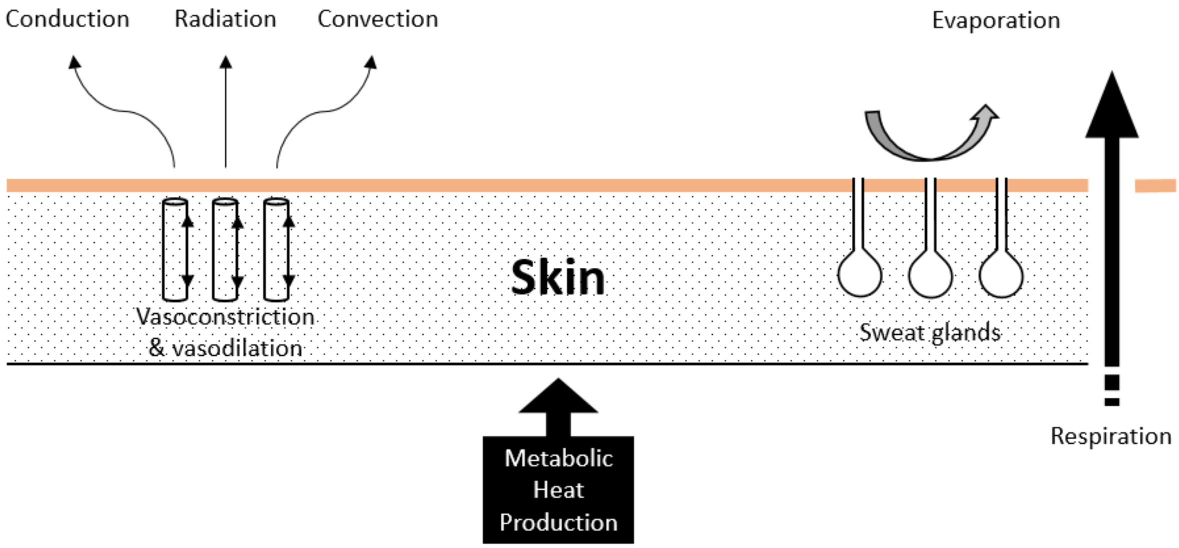

Figure 3. Heat transfer illustration through the skin (adapted from [6]).

1.1.4. Structure of the Skin

Skin is the fundamental organ that responsible for the flow of heat and moisture between the body and surrounding environment. It consists of three layers structure, from deep to the top of the surface, it consist of subcutaneous, dermis and epidermis. In generally, except palms and soles, the thickness of the skin is around 2 *mm*. Epidermis itself is a thin layer and the thickness of it varies between 0.075 *mm* and 0.15 *mm* [9]. The deeper layers of epidermis acts like a barrier for water vapor and prevents significant amount of water vapor diffusion to the environment [10]. Skin itself also consists sweat glands and vascular system that specify conductivity of the skin, according to the demand from thermoregulatory system.

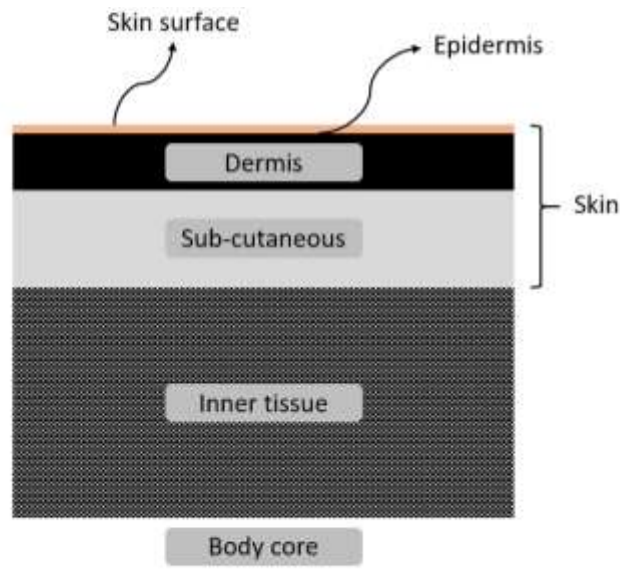

Figure 4. Schematic representation of the three layer human body skin structure (adapted from [11]).

The process of body temperature regulation happens through vasodilation and vasoconstriction which determines the blood flow rate according to warm or cool conditions. During cool conditions, body tends to protect the core temperature and therefore, decreases blood flow rate from core to periphery, this phenomena named as vasoconstriction and throughout that the skin temperature decreases. While in warm conditions, human body makes an effort on removing excess heat. Thus it increases blood flow rate through core to periphery (vasodilation) and therefore skin temperature reduces through evaporation [12].

1.1.5. Thermal Receptors

Temperature sensitive receptors are classified under the head of sensory receptors as the name thermoreceptors [9]. They are taking significant role on human thermoregulatory system and mostly located in the skin structure and the hypothalamus. Thermoreceptors in the skin structure are located within epidermis as free nerve ending. They are also divided into four as cold, hot, cold and hot pain sensitive thermoreceptors. The degree of feelings of hot and cold differs among individuals according to the intensity perceptions [8]. Each thermoreceptors have specific activation range. This means that, low temperatures as perceived painfully cold, cold receptors are inactive and this is also valid for hot and painfully hot receptors.

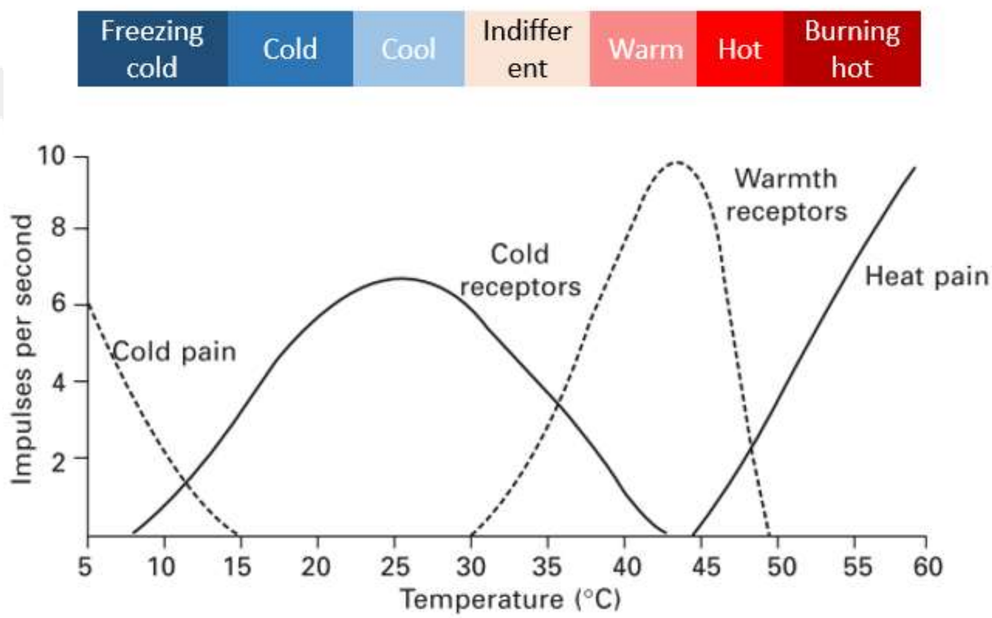

Figure 5. Schematic representation of four different receptors and their activation ranges (adapted from [9]).

When the body's surrounding temperature changes, these receptors sends signals to the brain and conducts thermoregulatory system. Location and quantity of warm and cold receptors differs according to body parts. But cold receptors closely beneath the epidermis, while assessing the experimental results of our study these characteristics are noticed. Back of a hand, forearm and finger dorsal are contains numerous cold spots where are also selected as thermocouple locations in the experiment.

1.1.6. Skin Surface Area

Total body surface area can be calculated from the relationship of body's weight and height, using the general equation that was developed by DuBois [3].

$$A_{Du} = 0.202 {m_b}^{0.425} {h_b}^{0.725} \quad (m^2) \quad (1.2)$$

Surface area of each body segments are differs among individuals. Therefore gender based study on body surface area correlation is determined as in eq. 1.3 and 1.4 [13].

$$A_{Du\_m} = 0.0057h_b + 0.0121m_b + 0.0882 \quad (m^2) \quad (1.3)$$

$$A_{Du\_f} = 0.0073h_b + 0.0121m_b - 0.2106 \quad (m^2) \quad (1.4)$$

where;

A_{Du}	: Total area of the skin	(m^2)
A_{Du_m}	: Total body area for male	(m^2)
A_{Du_f}	: Total body area for female	(m^2)
m_b	: Mass of the body	(kg)
h_b	: Height of the body	(m)

As it is indicated that heat transfer mostly occurs in the skin structure, through that among seven parameters of thermal comfort, five of them (heat loss by evaporation, sweat secretion, conduction, radiation and convection) depends on human body surface area. Details of heat transfer and comfort equations are provided in Chapter II in the title of, one dimensional heat transfer model.

1.2. Scope of the Thesis

In this study the main objectives are to identify the direct effects of human emotions on thermal comfort through the assessment of skin temperature and sensation votes and the impact on energy efficiency. Also it is aimed to examine the relationship between subjective and objective evaluations on thermal comfort and furthermore to analyze that at which comfort scale (-2, 0, +2) emotional evocative pictures place significant role to adjust thermal comfort. Towards this goal, the thermal comfort parameters of rational approach were used while considering the factors of adaptive approach in the manner of human psychology. To investigate the potential effect of visual stimuli pictures on changing the thermal comfort perceptions, skin temperatures on four different body locations were measured and subjective thermal sensations were assessed. Different experimental conditions enabled to analyze the relationship between thermal environment and emotional state. Furthermore, results of local and total thermal sensations were compared. It is found that with the help of visual agents PMV values can be altered from 0.5 to 1 units according to different type of stimuli pictures. This variation is significant, as according to independent experimental studies, every half value of change in PMV value may correspond to roughly 10% energy saving [14]. This means that it could be possible to adjust thermal comfort of occupants via visual impact if different images can be shown to them during a typical day, which results in significantly better energy efficiency measures in built environment.

1.3. Literature Review

There are several studies on the literature for determining thermal comfort. Apparently it is known that to be able to reach that purpose it was significant to understand human body deeply by accounting its thermoregulation system and its interactions with the environment.

By the development of thermometer, studies on thermoregulation first started for clinical purposes. [15]. In 1868, with the mercury in glass thermometer, Wunderlich's experimental studies on mammals started and he described body temperature ranges, daily temperature changes and the effects of exercise on body temperature [16].

In 1911, right after Becquerel and Breschet [64] use of thermoelectricity in 1835, Lefevre [65] enable to measure thermal topography of the body by using thermocouples, likewise he prepared human and whole animal calorimetry which determines metabolic rates.

In 1936, soon after Lefevre, Dubois used his technique to study on fever [66] and in 1959, Benzinger [17] used in his studies on analyzing the control of central core body temperature. In the light of these studies and new methods the threshold on human thermoregulation mechanism is exceeded.

Thermoregulation is a process that enables body to maintain its safe internal temperature within certain boundaries, regardless of the surrounding temperature. Throughout the process, body heat generation occurs mainly in the deep organs particularly the liver, brain, heart and in contraction of skeletal muscles. Therefore, most mammals including human have been able to adapt to divers climates [18], [19].

Thermal comfort depends on sense of an occupant in an environment, thereby it is a subjective term and not easy to define universally. One of the definition states that, if a person would not prefer to be in a different environment then it can be accepted that in the current environment occupant is thermally comfortable [20]. On the other hand, ASHRAE defines thermal comfort as "optimal" point of view and indicates that TC is both related with psychological and physical states of group and accepts preferences of majority [21].

TC is a combination of all factors that influence heat exchange to and from human body and environment. Body heat balance, hence the thermal comfort depends on two different set of factors which are human body depended factors includes weight, height, gender, age, metabolic rate, level of activity, clothing preferences and environmental factors like air velocity, air temperature, mean radiant temperature, relative humidity, water vapor pressure [68], [22]. In human thermoregulatory system the body permanently produces and transfers heat to ensure the balance of thermal equilibrium. In the below representation human thermoregulatory system is schematically expressed by Hensen [23]. This complex system is a combination of behavioral and autonomic thermoregulation, both contains several feedback loops, many internal and external sensors and outputs.

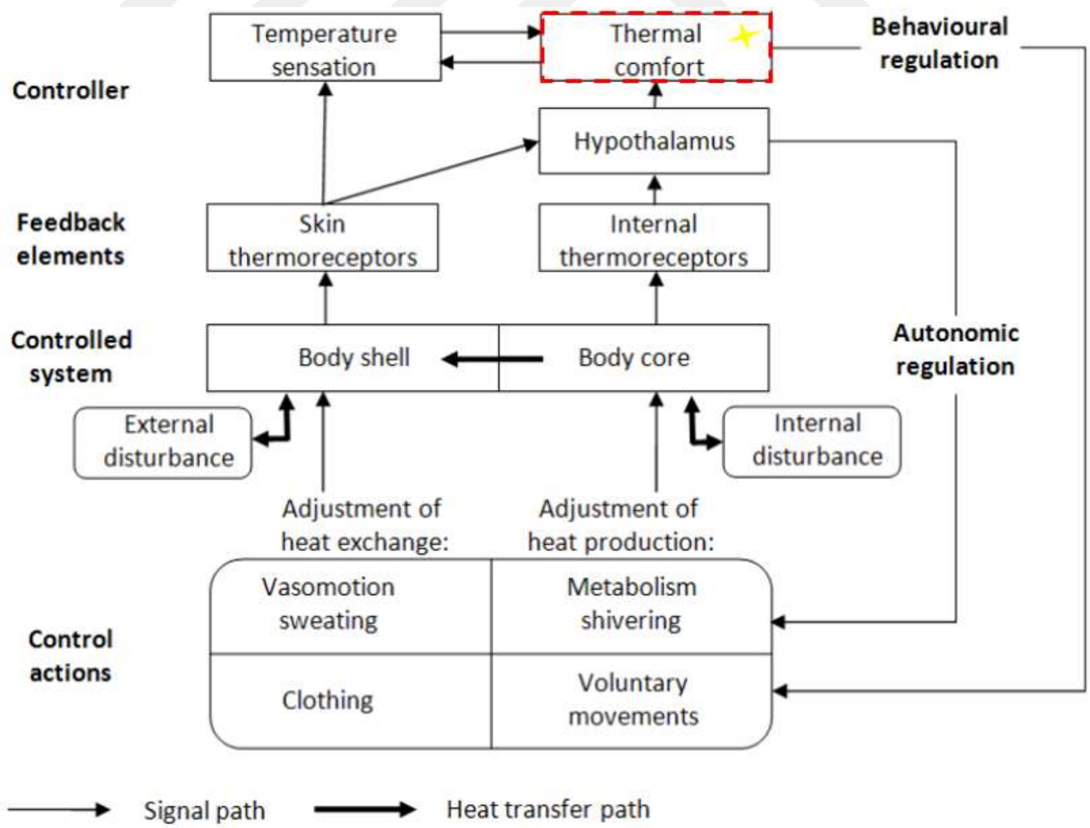

Figure 6. Human thermoregulatory system, from Hensen [23].

The approaches on TC exists in two different point of views. One approach basis on the fundamentals of heat balance and the other named as adaptive approach [24]. The heat balance approach so called rational approach drives its studies in climate chamber whereas the adaptive approach runs field studies with real case conditions in buildings [25].

In 1970, rational approach relied on Fanger's study [69]. He conducted an experiment in a climate chamber, while accounting steady state heat transfer model, with 1296 young college students. In the study subject's clothing and activity levels are settled as equal but they experienced different thermal conditions. Throughout the study participants assessed their thermal sensations by filling 7 point PMV thermal sensation indices that ranging between hot to cold. This PMV method also constituted the fundamentals of ASHRAE 55 and ISO 7730 standards. Throughout his study Fanger combined environment's physical parameters, human body physiological parameters and thermal perception of comfort [26].

In 1971, Givoni and Goldman studied on an empirical, one-node human thermal model. The equations relies on the experimental results and accordingly designed for predicting thermal responses in hot conditions. In the model human body assumes as an unit and the thermoregulation system is not counted in the equations [70], [26], [27].

In 1972, Gagge model also called "Core and Shell model" is revealed by Gagge et al [28]. It analysis human body into two concentric layers as core and skin. Therefore in the model heat transfer mechanism occurs in two sections, firstly; in between core and skin and secondly; between skin and environment. In 1986, Gagge et al. were made an improvement on the model [29]. In 1988, According to Doherty and Arens evaluations on these models it was proven that models are giving accurate results in steady state conditions while in sedentary activity level [24].

The acceptableness of a present thermal environment in the manner of occupant expectation was determined through the studies of adaptive approach [30]. The approach of adaptive thermal comfort which take into account not only purely physiological factors but also include psychological and behavioral factors. The issue of adaptive comfort addressed in the ANSI/ASHRAE [31]. The idea behind adaptive approach is suitable for non-air conditioned places or when the system is turned off and where the thermal conditions of the space are regulated primarily by the occupants through freely opening and closing windows.

In this study the thermal comfort parameters of rational approach were used while considering the factors of adaptive approach in the manner of psychology and the energy efficiency. It is aimed to express the effect of human psychology on thermal comfort and sensation. For that IAPS (International Affective Picture System) were used to change occupant's mood in a certain time interval.

CHAPTER II

ONE DIMENSIONAL HEAT TRANSFER MODEL

2.1. Internal Heat Production (H)

Body internal heat production is mostly occurs in the brain, liver, heart and the skeletal muscles throughout the exercise.

Human body is a homoeothermic organism, so that it is able to regulate its internal body temperature between wide ranges of environmental conditions. Heat production is a function of metabolism which enables to transform food with fats, carbohydrates and proteins to produce energy by oxidation [5].

After the oxidation process the released energy in the human body per unit time which is metabolic rate (M) is mostly converted to internal body heat (H) and partially external mechanical power (W). Then the equation can be written as;

$$H = M - W \qquad \left(\frac{kcal}{h}\right) \tag{2.1}$$

The external mechanical power is depending on the activity level. And the external mechanical efficiency is a ratio of external mechanical power and metabolic rate. Higher the work from the physical point of view, like walking uphill, higher the external mechanical efficiency. Most of the activities external mechanical efficiency assumed to be zero including office work, shopping, during sting or standing still positions. For the high activity levels the external mechanical efficiency calculation is given in eq. (2.2).

$$\eta = \frac{W}{M} \tag{2.2}$$

Inserting eq. (2.2) into eq. (2.1) then it forms as;

$$H = M(1 - \eta) \qquad (\frac{kcal}{h}) \tag{2.3}$$

After dividing this expression to body surface area (eq. (1.3)), it yields;

$$\frac{H}{A_{Du}} = \frac{M}{A_{Du}}(1 - \eta) \qquad (\frac{kcal}{h}) \tag{2.4}$$

In eq. (2.4), $\frac{M}{A_{Du}}$ represents the metabolic rate which is vital for the calculations of heat loss by evaporation.

As a result of several experiments that Fanger studied on, human metabolic rates at different activity levels are determined as in Table 2. Metabolic rate represents the heat production (*H*) for a specified activity levels, through that it can be directly written to the thermal comfort equations. Mechanical efficiency (η) is only counted for upgrade walking and relative air velocity is also given for different walking levels.

Table 1. Metabolic rate at different activities (adapted from [2]).

Activity		Metabolic Rate $kcal/hm^2$	Mechanical Efficiency η	Air Velocity m/s
Resting				
Sleeping		35	0	0
Reclining		40	0	0
Seated		50	0	0
Standing		60	0	0
Walking				
On the level	km/h			
	3.2	100	0	0.9
	4.0	120	0	1.1
	4.8	130	0	1.3
	5.6	160	0	1.6
	6.4	190	0	1.8
	8.0	290	0	2.2
Up a Grade				
Grade %	km/h			
5	1.6	120	0.07	0.6
5	3.2	150	0.10	0.9
5	4.8	200	0.11	1.3
5	6.4	305	0.10	1.8
15	1.6	145	0.15	0.4
15	3.2	230	0.19	0.9
15	4.8	350	0.19	1.3
25	1.6	180	0.20	0.4
25	3.2	335	0.21	0.9

2.3. Heat Loss by Evaporation

The evaporative heat losses occurs on the skin surface regardless from thermoregulatory system. Heat loss through diffusion of water vapor (E_d) and sweat evaporation (E_{sw}) are classified under the title of evaporative heat loss (see, 2.3.1 and 2.3.2).

2.3.1. Heat Loss by Water Vapor Diffusion (E_d)

To be able to regulate internal body heat, water vapor diffusion (E_d) occurs on the surface of the human skin regardless from the thermoregulation process. This is defined as an insensible perspiration [6]. It is the magnitude of the water vapor diffusion per unit body surface area depending on the difference between saturated water vapor pressure (p_s) on the skin surface and partial water vapor pressure (p_a) in the current environment. Heat loss by water vapor diffusion is also proportional to the heat of vaporization of water (λ) which is related to ambient air temperature, skin permeance coefficient (m) and human body surface area (A_{Du}). For the calculation of heat loss by water vapor diffusion;

$$E_d = \lambda \, \mathrm{m} \, A_{Du}(p_s - p_a) \qquad (\frac{kcal}{h}) \qquad (2.5)$$

The permeance magnitude of the skin has been determined as $6.1 \cdot 10^{-4} \; \frac{kg}{h} m^2 mmHg$ from Fanger's analysis according to data from Inouye et al [6].

Saturated water vapor pressure on skin surface (p_s) is constituted by Fanger [2] as a function of skin temperature (T_s) based on steam table [32] and it is only valid while the skin temperature T_s is in between 27°C - 37°C.

$$p_s = 1.92 T_s - 25.3 \qquad (mmHg) \qquad (2.6)$$

Substituting the values of heat of vaporization (λ), human skin permeance coefficient (m) and saturated water vapor pressure (p_s) into the equation (2.5) gives:

$$E_d = 0.35 \, A_{Du}(1.92 \, T_s - 25.3 - p_a) \qquad (\frac{kcal}{h}) \qquad (2.7)$$

where;

E_d	: Heat loss by water vapor diffusion on the surface of the human skin	$(\frac{kcal}{h})$
λ	: Heat of vaporization of water, $575\ (\frac{kcal}{kg})$ (at 35℃)	$(\frac{kcal}{kg})$
m	: Human skin permeance coefficient, $6.1 \cdot 10^{-4}$	$(\frac{kg}{m^2-mmHg})$
A_{Du}	: Total body area	(m^2)
p_s	: saturated water vapor pressure on the surface of the human skin	$(mmHg)$
p_a	: Partial water vapor pressure in current air temperature	$(mmHg)$
T_s	: Skin temperature	$(°C)$

By that skin exchanges the heat through water vapor diffusion on the surface of the skin structure where sweat and clothing are assumed as uniformly distributed.

2.3.2. Heat Loss by Evaporation of Sweat (E_{sw})

The only physiological variable that effects thermal comfort under steady state conditions is heat loss by sweat secretion which is a function of skin temperature and metabolic rate. Unless the sedentary activity ($\frac{H}{A_{Du}} \sim 50 \frac{kcal}{m^2-h}$) in a thermally comfortable environment, the sweat secretion can exist.

The relationship between mean skin temperature and activity level studied experimentally by Fanger. The results of the study maintains the thermally comfortable environment for different metabolic activities of human. In the graphical representation shown in Figure 5. the change in metabolic rate stated with the mean skin temperature from the assessment of several college age female and male human subjects.

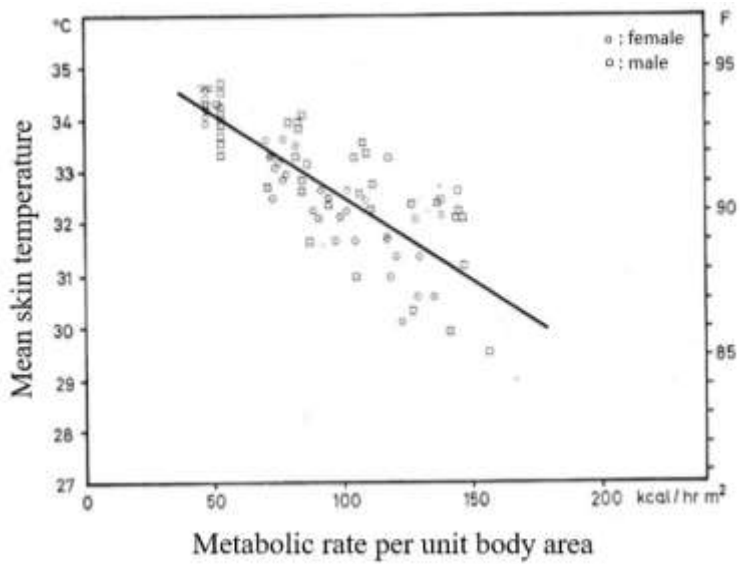

Figure 7. In steady state ambient temperature, relationship between metabolic rate per unit body area and mean skin temperature (adapted from [2]).

According to the results, the equation for skin temperature is represented in eq. 2.8.

$$T_s = 35.7 - 0.032\frac{H}{A_{Du}} \quad (°C) \tag{2.8}$$

where;

T_s : Mean skin temperature ($°C$)

$\frac{H}{A_{Du}}$: Metabolic rate ($\frac{kcal}{m^2-h}$)

From the equation (eq. 2.9), it is possible to say that, when the ambient temperature is steady state, change in activity level effects as oppose to mean skin temperature. Accordingly, the sweat rate graph represented as Figure 7, which is constituted from the results that are collected from several female and male human subjects.

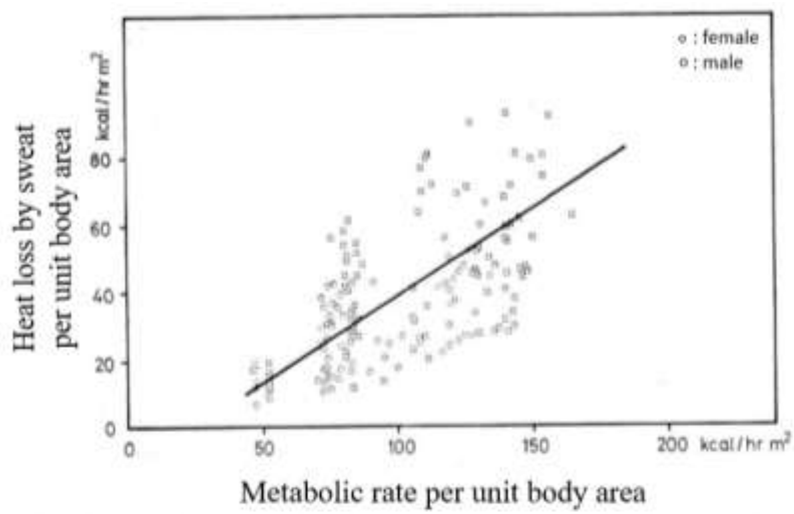

Figure 8. In steady state ambient temperature, change in heat loss by evaporation of water from the surface of the skin with metabolic rate (adapted from [2]).

Sweat secretion depending on metabolic rate and activity level so that it is assumed to be zero for sedentary activities ($\frac{H}{A_{Du}} \sim 50 \frac{kcal}{m^2-h}$) at thermal comfort level.

$$E_{sw} = 0.42\ A_{Du}(H - 50) \qquad \left(\frac{kcal}{h}\right) \qquad (2.9)$$

where;

E_{sw} : Heat loss by evaporation of sweat $\left(\frac{kcal}{h}\right)$

A_{Du} : Total area of the skin (m^2)

H : Internal heat production $\left(\frac{kcal}{h}\right)$

2.4. *Heat Loss by Latent Respiration* (E_{re})

Respiration is a form of evaporative heat loss. While breathing the ambient air gets in the body and reaches to alveoli and transfers back to the ambient from nose. During this permanent breathing action approximately 10% of total heat loss from the body both in the form of latent and dry heat loss [33]. In a closed environment human breath causes increase in temperature and humidity of the current environment. Calculation of heat loss by latent respiration, E_{re} depending on ventilation of pulmonary and the differences between humidity ratio of expired and inspired air.

$$E_{re} = V(W_{ex} - W_a)\lambda \qquad \left(\frac{kcal}{h}\right) \qquad (2.10)$$

The pulmonary ventilation is a mechanical action and it occurs because of the pressure differences in between alveoli of the lungs and ambient air [34]. The relationship between pulmonary ventilation (*V*) and metabolic rate (*M*) for any activity level is given in Equation 2.12 according to Fanger's analysis.

$$V = 0.0060\ M \qquad \left(\frac{kg}{h}\right) \qquad (2.11)$$

Also according to the study of McCuthan and Taylor that Fanger stated, the differences of inspired and expired air humidity ratio can be written as a function of ambient air temperature and inspired air humidity ratio.

$$W_{ex} - W_a = 0.0277 + 0.000065 \quad {}_a - 0.80\ W_a$$

$$\cong 0.029 - 0.80\ W_a \qquad \left(\frac{kg\ water}{kg\ dry\ air}\right) \qquad (2.12)$$

Substituting; $W_a = 0.622 \frac{p_a}{P-p_a} \cong 0.00083\, p_a$ into the equation (2.13) it gives;

$$W_{ex} - W_a = 0.029 - 0.00066\, p_a \qquad (\frac{kg\ water}{kg\ dry\ air}) \qquad (2.13)$$

Then substituting the values of pulmonary ventilation (V) and $W_{ex} - W_a$ into the equation (2.11), so the overall heat loss by respiration becomes;

$$E_{re} = 0.0023M(44 - p_a) \qquad \left(\frac{kcal}{h}\right) \qquad (2.14)$$

where;

E_{re}	: Heat loss by respiration	$\left(\frac{kcal}{h}\right)$
V	: Pulmonary ventilation	$\left(\frac{kg}{h}\right)$
W_{ex}	: Expiration air humidity ratio	$(\frac{kg\ water}{kg\ dry\ air})$
W_a	: Inspiration air humidity ratio	$(\frac{kg\ water}{kg\ dry\ air})$
λ	: Heat of vaporization of water, $575\ (\frac{kcal}{kg})\ (at\ 35°C)$	$(\frac{kcal}{kg})$
p_a	: Partial water vapor pressure in current air temperature	$(mmHg)$
P	: Atmospheric pressure (at Sea level, 760 $(mmHg)$)	$(mmHg)$

In the study the experiment room assumed at sea level and correspondingly atmospheric pressure (*P*) taken as 760 *mmHg* and also the value of *Pa* is provided from temperature vs saturation vapor pressure table according to the current air temperature.

2.5. *Dry Respiration Heat Loss* (L)

The heat loss during respiration, depending on the differences between inspired and expired air temperature.

$$L = V c_p (T_{ex} - T_a) \qquad \left(\frac{kcal}{h}\right) \qquad (2.15)$$

c_p is representing the specific heat capacity of dry air at constant temperature. The value of c_p is; $0.24\ kcal/kg\ °C$. To be able to calculate an exact value of T_{ex}, the following formula (eq. 2.13) was constructed by McCuthan and Taylor [35].

$$T_{ex} = 32.6 + 0.066 T_a + 32\ W_a \qquad (°C) \qquad (2.16)$$

Since the effect of dry respiration heat loss is too small comparing with other heat loss parameters, it is counted as constant average value in the overall heat balance equation. $T_{ex} = 34\ °C$

When we rewrite the equation of dry respiration heat loss (L) by placing the constants, it becomes;

$$L = 0.0014 M (34 - T_a) \qquad \left(\frac{kcal}{h}\right) \qquad (2.17)$$

where;

L	: Dry respiration heat loss	$(\frac{kcal}{h})$
V	: Pulmonary ventilation	$(\frac{kg}{h})$
c_p	: Dry air specific heat, $0.24\ kcal/kg\ °C$	$(\frac{kcal}{kg-°C})$
T_{ex}	: Temperature of the expired air	(°C)

T_a : Air temperature $(°C)$

W_a : Inspiration air humidity ratio $(\frac{kg\ water}{kg\ dry\ air})$

Trough that when the expired air temperature (*Tex*) kept constant the equation of dry respiration heat loss depends on activity level (metabolic rate, *M*) and air temperature.

2.6. *Conduction Heat Loss through Clothing* $(\boldsymbol{K})$

Clothed body heat conduction is quiet complicated. The air between skin and cloth causes the internal heat convection and radiation and also conduction of cloth itself is need to be considered to calculate total conduction heat loss. Instead of these complicated calculations, Gagge et al. [36] derived the term I_{cl} (equation 2.15), which is the clothing resistance. It is a non-dimensional representation of overall thermal resistance with a most accepted unit clo. To be able to translate in *clo* units, *Rcl* (clothing resistance) divided into 0.18 which is equal to 1 *clo.*

$$I_{cl} = \frac{R_{cl}}{0.18} \qquad (clo) \qquad (2.18)$$

The unit clo and tog are the most accepted units for clothing resistance and to be able to calculate in conduction equation it needs to be used as a unit of $\frac{℃-m^2-h}{kcal}$.

$$1\ clo = 1.55\ tog = 0.18\ \frac{℃-m^2-h}{kcal}$$

The overall clothed body heat conduction equation expressed in Eq. 2.16. In the equation the unit of *Rcl* written in $\frac{℃-m^2-h}{kcal}$ then the unit of temperature and skin area simplified, it becomes $\left(\frac{kcal}{h}\right)$.

$$K = A_{Du} \frac{(T_s - T_{cl})}{R_{cl}} \qquad \left(\frac{kcal}{h}\right) \qquad (2.19)$$

where;

K	: Dry respiration heat loss	$(\frac{kcal}{h})$
I_{cl}	: Clothing thermal resistance	(clo)
R_{cl}	: Clothing thermal resistance	$(\frac{m^2-h-℃}{kcal})$
T_s	: Mean skin temperature	(℃)
T_{cl}	: Cloth temperature	(℃)
A_{Du}	: Total area of the skin	(m^2)

In this study according to the experiment results, the mean skin temperature (*Ts*) calculated from four different body segments, detailed information are provided in Chapter III.

2.7. Radiation Heat Loss $(\boldsymbol{R})$

Heat loss by radiation occurs between surface of the human body and its surroundings. It is expressed by the Stefan-Boltzmann's law as given in equation (2.17).

$$R = A_{eff}\, \varepsilon\, \sigma\, [(T_{cl} + 273)^4 - (T_{mrt} + 273)^4] \qquad \left(\frac{kcal}{h}\right) \qquad (2.20)$$

The emittances (ε) of clothed body is mostly selecting in between 0.95-1.0 [11]. Since the shape of the human body is irregular, we can use the following equation (Eq. 2.18) for to be able to calculate the effected radiation area (A_{eff}).

$$A_{eff} = f_{eff} f_{cl} A_{Du} \qquad (m^2) \qquad (2.21)$$

where;

R	: Radiation heat loss from the body	$(\frac{kcal}{h})$
A_{eff}	: Clothed body effective radiation area	(m^2)
ε	: Clothed body outer surface emittance	
σ	: Stefan-Boltzmann constant $(4.96 \cdot 10^{-8})$	$(\frac{kcal}{m^2-h-K^4})$
T_{cl}	: Cloth temperature	(℃)
T_{mrt}	: Mean radiant temperature	(℃)
f_{eff}	: Effective radiation area factor	

The effective radiation area of a clothed body (A_{eff}) is constituted from multiplication of, factor of effected radiation area (f_{eff}) which is a ratio of effective radiation area of clothed body over total body surface area, ratio of a clothed body over total body surface area (f_{cl}) and total body surface area (A_{Du}). The value of F_{eff} is calculated in between 0.696 – 0.725, the exact value of F_{eff} depends on age, gender, body type, weight of a body and body position (seated or standing) [69].

Thermal resistance of clothes (I_{cl}) differs according to its characteristics and size. Based on general clothing types, resistance values are given in Table 2 [69].

Table 2. Clothing options and their clothing resistance and the ratio of clothed body to total body surface area adapted from [69].

Clothing Options	I_{cl} (clo)	f_{cl}
No Clothes	0.0	1.0
Shorts	0.1	1.0
Typical Light Clothing: Shorts, open-neck shirt, light socks and sandals	0.3-0.4	1.1
Light summer clothing: Long light-weight trousers, open-neck shirt with short sleeves	0.5	1.1
Typical business suit	1.0	1.2
Typical business suit & cotton coat	1.5	1.2

where;

I_{cl} : Clothing thermal resistance (clo)

f_{cl} : Clothed body surface area over nude body surface area

Then substituting all the parameters into the eq.2.17;

$$R = 3.4 \cdot 10^{-8}\, f_{cl}\, A_{Du}\, [(T_{cl} + 273)^4 - (T_{mrt} + 273)^4] \quad \left(\frac{kcal}{h}\right) \tag{2.22}$$

In the final version of the equation (Eq 2.19) several parameters assumed as constant these are, surface emittance of a clothed body (ε) taken as 0.97, effective radiation area factor (f_{eff}) taken as 0.7 and also surface area ratio of clothed body over nude body (f_{cl}) taken as 1.1 according to light clothing value.

2.8. *Heat Loss by Convection* (C)

Convective heat loss occurs on the clothed body outer surface and depends on body surface area, clothing factor, ambient air and cloth temperature. It is given as;

$$C = A_{Du}\, f_{cl}\, h_c\, (T_{cl} - T_a) \qquad \left(\frac{kcal}{h}\right) \tag{2.23}$$

In the equation 2.18, h_c represents the convection coefficient and the value differs according to low velocities (natural convection) and high velocities (forced convection).

For natural convection or still air, convective coefficient (*hc*) is a function of air temperature (*Ta*) and clothing temperature (*Tcl*). The formula (Eq. 2.19) was obtained from the experimental study of Nielsen and Pedersen which is both valid for the positions of seated and standing [2].

$$h_c = 2.05(T_{cl} - T_a)^{0.25} \qquad \left(\frac{kcal}{m^2 - h - ℃}\right) \tag{2.24}$$

The equation (Eq. 2.19) is in compliance with laminar boundary layer with free convection formula (Eq. 2.20) where *Nu* represents Nusselt number, *Gr* is Grashof number and *Pr* stands for Prandl number.

$$Nu = Const.(GrPr)^{0.25} \tag{2.25}$$

For forced convection the convective heat transfer coefficient (*hc*) is a function of air velocity (*v*). According to Winslow, Gagge and Herrington's study [2], the force convection coefficient for semi reclining subjects where the velocity downwardly applied, was yield as;

$$h_c = 10.4\sqrt{v} \qquad \left(\frac{kcal}{m^2 - h - ℃}\right) \tag{2.26}$$

$$Nu = Const.Re^m Pr^n \tag{2.27}$$

For the cases where air velocity is below 0.10 m/s, natural convection coefficient formula (Eq. 2.19) is used for convection heat transfer formula (Eq. 2.18) and for velocities above 0.10 m/s, forced convection coefficient is considered with Eq. 2.21. Consequently, it is possible to represent both cases as in Equation 2.23, it is yield as;

$$h_c = \begin{Bmatrix} 2.05(T_{cl} - T_a)^{0.25} & for\ 2.05(T_{cl} - T_a)^{0.25} > 10.4\sqrt{v} \\ 10.4\sqrt{v} & for\ 2.05(T_{cl} - T_a)^{0.25} < 10.4\sqrt{v} \end{Bmatrix} \quad (2.28)$$

where;

C	: Convective heat transfer	$(\frac{kcal}{h})$
A_{Du}	: Total area of the skin	(m^2)
f_{cl}	: Clothed body surface area over nude body surface area	
h_{cl}	: Convective heat transfer coefficient	$\frac{kcal}{m^2-°C-h}$
T_{cl}	: Cloth temperature	(℃)
T_a	: Air temperature	(℃)
h_c	: Convective heat transfer coefficient	$(\frac{kcal}{m^2-h-°C})$
v	: Air velocity	$\left(\frac{m}{s}\right)$

In this study air velocity assumed as 0 m/s and natural convection formula was obtained, details are given in experimental protocol part (Chapter III).

2.9. Heat Balance Equation

Thermoregulation plays a significant role about maintaining the internal temperature in human body. The heat that is produced in the body is in balance with heat loss from the body. Under this circumstances the double sided heat balance equation yields as;

$$H - E_d - E_{sw} - E_{re} - L = K = R + C \tag{2.29}$$

This is determined from the conservation of energy equation in one dimensional system. where;

H	: Internal heat production in human body	$(kcal/h)$
E_d	: Heat loss by water vapor diffusion on the surface of the human skin	$(kcal/h)$
E_{sw}	: Heat loss by evaporation of sweat	$(kcal/h)$
E_{re}	: Heat loss by respiration	$(kcal/h)$
L	: Dry respiration heat loss	$(kcal/h)$
K	: Conduction heat loss through clothing	$(kcal/h)$
R	: Radiation heat loss from the body	$(kcal/h)$
C	: Heat loss by convection	$(kcal/h)$

Substituting metabolic heat production and all heat loss parameters as; respiratory heat losses ($L + E_{re}$), evaporative heat losses ($E_d + E_{sw}$) and heat loss by conduction, convection, radiation into the equation (1.2), then equation (2.5) derives.

$$\underbrace{M(1-\eta)}_{H}-[\lambda\, \mathrm{m}\, \underbrace{A_{Du}\,(p_s-p_a)}_{Ed}]-[0.42\, \underbrace{A_{Du}\,(H_{in}-50)}_{Esw}]-[V\, \underbrace{(W_{ex}-W_a)}_{Ere}\,\lambda$$

$$-\,[V\underbrace{c_p\,(T_{ex}-T_a)}_{L}]=\underbrace{A_{Du}\frac{(T_s-T_{cl})}{0.18 I_{cl}}}_{K}=A_{eff}\,\varepsilon\,\sigma\,[\underbrace{(T_{ex}-T_a)^4}_{R}-(T_{ex}-T_a)^4] \tag{2.30}$$

$$+\,A_{Du}\,\underbrace{f_{cl}\,h_{cl}\,(T_{ex}-T_a)}_{C}$$

2.10. Thermal Comfort

While body produces heat through metabolic activities it also loses and gains heat in several ways as described in previous sections, through the combination of these heat balance equations, thermal comfort can be quantified and written in terms of PMV parameter (section 2.10.1).

When the heat balance equation is rewritten while inserting the constant values into; internal heat production (eq. 2.3), heat loss by water vapor diffusion (eq. 2.5), heat loss by evaporation of sweat (eq. 2.10), heat loss by latent respiration (eq. 2.11), heat loss through conduction (eq. 2.16), radiative heat loss (eq. 2.17), heat loss by convection (eq. 2.18) equations, then put those equations into the raw heat balance equation (eq. 2.5) and dividing by body surface area (A_{Du}), thermal comfort equation (Eq. 2.6) yields as;

$$\frac{M}{A_{Du}}(1-\eta)-0.35\left[43-0.061\frac{M}{A_{Du}}(1-\eta)-P_a\right]-0.42\left[\frac{M}{A_{Du}}(1-\eta)-50\right]-$$

$$0.0023\frac{M}{A_{Du}}(44-P_a)-0.0014(34-T_a)$$

$$=3.4\cdot 10^{-8} f_{cl}[(T_{cl}+273)^4+(T_{mrt}+273)^4]+f_{cl}h_c(T_{cl}-T_a) \tag{2.31}$$

Solving the left side of this double sided equation (eq. 2.6) gives clothing temperature (T_{cl}) (eq.2.7)

$$T_{cl} = 35.7 - 0.032\frac{M}{A_{Du}}(1-\eta) - 0.18 I_{cl}[\frac{M}{A_{Du}}(1-\eta)$$
$$-0.35\left[43 - 0.061\frac{M}{A_{Du}}(1-\eta) - P_a\right] - 0.42\left[\frac{M}{A_{Du}}(1-\eta) - 50\right] \quad (2.32)$$
$$-0.0023\frac{M}{A_{Du}}(44 - P_a) - 0.0014\frac{M}{A_{Du}}(34 - T_a)] \ (°C)$$

2.10.1. PMV (Predicted Mean Vote)

The term PMV (predicted mean vote) indicates thermal comfort or discomfort level in terms of its own indices. It was first generated with large group of people who were giving their personal thermal sensations to 7 point scale thermal sensation indices where it ranges between -3 and +3 as indicates too cold and too hot (Figure 9.) in a specified thermal environment. In the PMV index all minuses (-) represents cold sensations and all plus signs (+) indicates warm sensations and from any point the distance between neutral (0) zone is proportional to discomfort level.

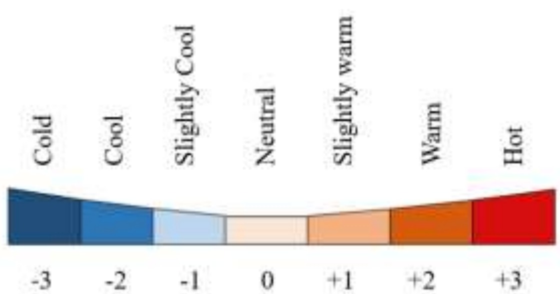

Figure 9. ASHRAE 7 point thermal sensation indices [21].

According to some personal data (weight, height, current metabolic activity level, current clothing level) of subjects and environmental (air temperature, humidity, air velocity, radiation) information, the given PMV equation (eq. 2.33) was formed. The PMV equation was a combination of individual heat gain and loss equations.

$$PMV = \left(0.352e^{-0.042\left(\frac{M}{A_{Du}}\right)}\right)\left[43 - 0.061\ \frac{M}{A_{Du}}(1-\eta) - \ P_a\right] - 0.42\left[\frac{M}{A_{Du}}(1-\eta) - 50\right]$$

$$-0.0023\frac{M}{A_{Du}}(44 - P_a) - 0.0014\frac{M}{A_{Du}}(34 - T_a)$$

$$-3.4 \cdot 10^{-8} f_{cl}[(T_{cl} + 273)^4 + (T_{mrt} + 273)^4] - f_{cl}h_c(T_{cl} - T_a) \qquad (2.33)$$

2.10.2. PPD (Predicted Percent Dissatisfied)

The term PPD (predicted percent dissatisfied) was first revealed by Fanger. It express the percent of thermally dissatisfied people in a particular environment according to specific thermal sensation indices. The PPD equation was formed from PMV index and expressed as in the given (eq. 2.34).

$$PPD = 100 - 95e^{-\left(0.03353PMV^4 + 0.2179PMV^2\right)} \qquad (2.34)$$

From the equation of PPD, the graph shapes as in the given (see Figure 10). In the original Fanger's PPD graph it contains whole 7 point scales but for this study we only focused -2 to +2. The graph states that no thermal environment will satisfied everyone in a group. Even in neutral (PMV = 0) environment at least 5% will be dissatisfied. Therefore individual characteristics and preferences takes significant role to please more people in a particular environment.

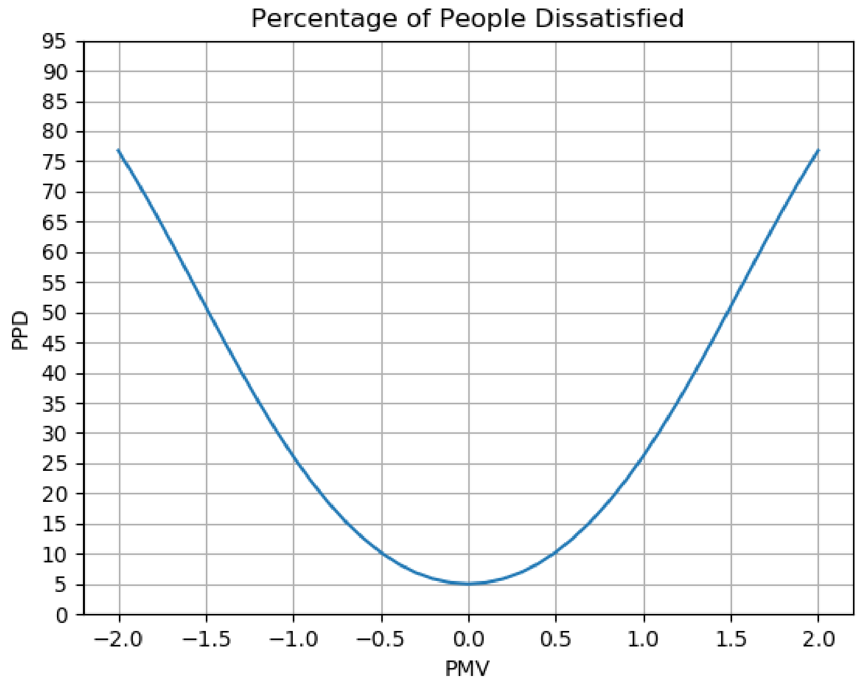

Figure 10. Percent of people dissatisfied graph according to PMV index.

Now we have all the required parameters for determining comfort, we can test them in an experimental study which is given in the next Chapter.

CHAPTER III

EXPERIMENTAL STUDY

Thermal comfort is depending up on two components. Firstly the physical condition like the environmental fluctuations (temperature, relative humidity, and air motion etc.), metabolic activity level and clothing preferences should be specified. Second, psychological state of the occupant thereby subjective thermal sensations need to be determined [37]. Since the human body changes its thermal appearance frequently, depending upon on metabolic rate, it is essential to consider the heat transfer at the skin by accounting for radiation, convection, conduction heat transfer to assess the current thermal comfort level.

Forming a thermally comfortable environment also depends on human feelings. The fluctuations on emotions happen according to the blood flow rate changes which transports heat to the skin. Therefore skin temperature can be correlated with individual thermal sensation assessments. Accordingly, this experiment aims to identify the direct effects of human emotions on thermal comfort. Throughout the experiments we will try a way to decrease energy usage on HVAC systems by controlling human psychology within certain limits.

To change the subject's psychological states, visual stimuli method is used with IAPS data. In the literature the predominantly effective emotion stimuli method for all kind of emotions was proved as visual stimuli methods. In parallel with the previous studies visual stimuli pictures have an impact on cerebral blood flow rate changes [38]. Also several researches justifies that anger and happiness related visual stimuli also has an impact on physiological changes like increase in blood pressure and respiration also anger related visual stimuli causes increases in heart rate [39], [40]. These impacts also affect to thermal sensation in the current environment [41].

Moreover, it is aimed to identify the best thermal comfort assessing point on human body both in the manner of user friendly location and meaningful data collection. In addition, it is aimed to observe in which thermal environment the IAPS (International affective picture system) effects most on occupants and changes their thermal sensations.

In order to explore the possibility of reaching these targets, 3 different test conditions set as cold, hot and neutral thermal environments. The level of cold and hot specified according to the Fanger's thermal comfort equations and represented in terms of PMV. For this python codes were written to express the relations between heat loss parameters. Those codes are given in Appendix C. With 33 volunteer human subjects each experiment was conducted as 15 minutes preconditioning and 15 minutes experiment. Each subject attended the experiment for once only and participate individually. During the experiment in each thermal environment, subjects watched an ESP video that consist IAPS pictures with pleasant, non-pleasant and non-emotional stimulus. Throughout the experiment skin temperature data are collected from 4 different body parts (hand middle finger, hand top, wrist, ankle). Beside to that at the very first moment in the experiment (0^{th}min.) and after each 5^{th} min. subjects fill TSV questionnaire which consist of 3 different questions (detailed information are given in experimental protocol part).

3.1. Experiment Room

Experiments took place in Özyeğin University, Engineering Faculty Building (EF), Living Laboratory, No 113. Experiments run in July and April 2019. During the experiments Istanbul outdoor temperature changed between 23 and 28℃ and average relative humidity was 64% [42], [43]. Dimensions of the room is given in Figure 8 as, width 6 m, length 4.15 m and height 2.8 m. The HVAC (heating ventilation, and air conditioning) system locates at the ceilings and it has one local controllable inlet and one outlet. Humidifier locates in front of the experiment desk as 0.8 m distance. To form hot conditions additional heaters are used for the experiment. With these devices, room conditions can be adjust according to needs and can be fix during the tests.

Air temperature of the test room is adjust by mentioned local controllable AC. To regulate relative humidity of the test room, Sinbo Sah-6107 Ultrasonic Humidifier [44] is used. With these equipment, air temperature and relative humidity are recorded during the experiments by Testo 635-2 temperature and moisture meter device. The oscillations are saved for temperature is ±0.2 ℃ and for relative humidity is ±2.4%.

The preparation room locates in front of the experiment room and air temperature, humidity and air velocity values are settled by central HVAC system as comfortable living area (PMV 0).

The experiment case conditions (see Table 3.) are specified according to Fanger's PMV indices and in accordance with thermal comfort equations. For all conditions, air velocity assumed as lower than 0.1 m/s.

Table 3. Three different case conditions with the corresponding temperature and relative humidity data.

Case Condition	**Air Temperature (℃)**	**Relative Humidity (%)**
Cold (PMV -2)	20±0.2	65±2.4
Neutral (PMV 0)	24±0.2	65±2.4
Hot (PMV +2)	30±0.2	75±2.4

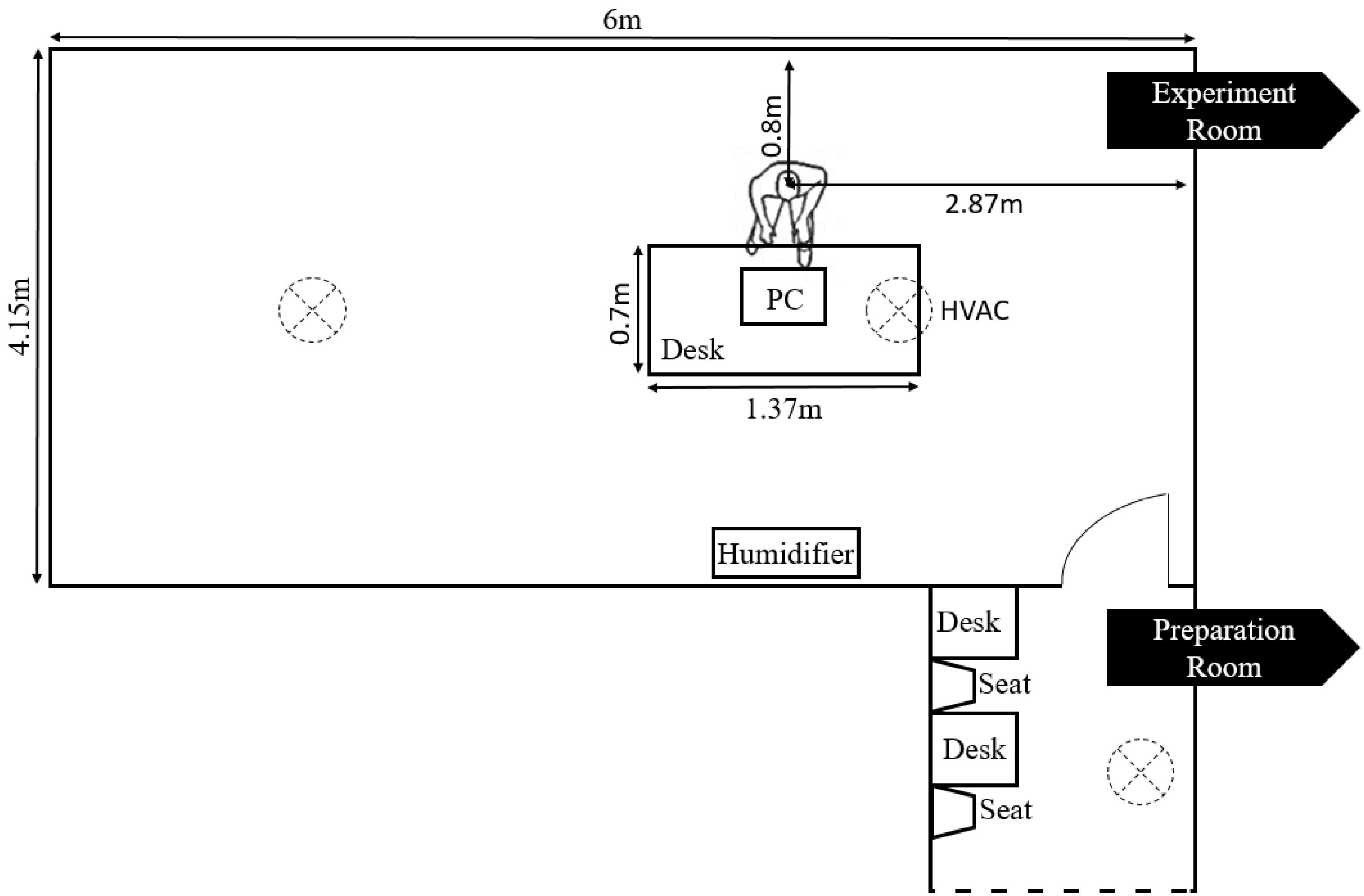

Figure 11. Top view of the experimental facility.

3.2. Human Subjects

The present study was conducted with a permission of Özyeğin University Research Ethics Committee (REC). The permission is shown in Appendix F.

The experiment performed with the participation of 33 mentally and physically healthy adults who are aged between 23 and 50. The sample size for the experiment was justified by previous relevant studies who were worked on similar sample sizes; by Zhang's [45], Ghahramani's [46], Liu's [47], Dai's [48], Chaudhuri's [49] and Atmaca's [50] were referring 17, 15, 22, 11, 20, 25 human subjects. According to Parson's experimental study [51], gender differences in response to thermal comfort while in same clothing and activity level is low. Therefore the present study conducted with 16 female and 17 male subjects who have been residing at least for past 2 years in Istanbul and certainly adopted to the climate. It was carefully fallowed up that, from the experiment group no participants have a neuropsychiatric disease or using physcatric medications, addiction to alcohol, epilepsy or have an attention disorder.

2 days before the experiment it was asked to all attendees to sleep well at the night before the experiment and not drinking too much alcohol. Participants were randomly placed one of the experiment cases (neutral, hot and cold conditions) and they were not informed about the room conditions before they get in. All participants be prepared at the preparation room and their heart rates were measured from finger with pulse oximeter which shows pulse rate and oxygen level of the body system.

All participants consist of Ozyeğin University grad and undergrad students and they all voluntarily attended. At the beginning of the each experiment, the informative and compulsory "experiment procedure" paper (see Appendix A-1) is given to subjects and written assent was obtained from participants.

In this study personal information was not required or used in any academic publication. All participants' data were collected in a pool and no individual data selected. It was stated to all participants that any time, without any permission subjects have a right to withdraw the experiment. As stated participants are randomly assigned one of the experiment conditions (cold; PMV-2, hot; PMV+2, neutral; PMV0), and it was not announced before the test. The experiment schedule and detailed information are given in below (Table 3). For each day maximum two different room conditions are set. Experiment days are selected according to weekly weather forecasts [67] to have similar outdoor conditions during experiment days. Detailed information about room conditions are given in experimental protocol (section 3.4.)

Table 4. "Thermal Comfort" Experiment schedule, all dates at 2019.

Date	Case	Conditions	Subjects	Total Number of Subjects
22-Jul	PMV -2 PMV +2	20°C, 65% RH, <0.1m/s 30°C, 65% RH, <0.1m/s	2 6	8
23-Jul	PMV -2	20°C, 65% RH, <0.1m/s	5	5
24-Jul	PMV +2 PMV 0	30°C, 65% RH, <0.1m/s 40°C, 65% RH, <0.1m/s	5 3	8
26-Jul	PMV 0	24°C, 65% RH, <0.1m/s	7	7
01-Aug	PMV -2	20°C, 65% RH, <0.1m/s	2	2
05-Aug	PMV -2 PMV 0	20°C, 65% RH, <0.1m/s 24°C, 65% RH, <0.1m/s	1 2	3

3.2.1. Clothing Level and Temperature Sensor Placement

Clothing level has a significant impact on thermal comfort and thermal sensation therefore it is vital to standardize clothing level for all participants. During the experiments all participants wore their own cloths but before the experiment day it was asked them to wear 0.55 clo (level of clothing insulation, $1clo$ = 0.155 $m^2{}^{\circ}C/W$) [52] which corresponds to typical summer indoor clothing (long light-weight trousers, open-neck shirt with short sleeves, standard underwear, short socks and sneakers). For female participants who have long hair, it was asked to tie up their hair. Also any jewelry include watch were not allowed to wear, during the experiment. In addition, in case of smart phones heating up problems and cause conduction on human body therefore might ruin the experiments, it was asked to be turned off and put away from the participants.

Sensors were placed on four different body locations of each participant. Three of them were attached on three different location on non-dominant hand and one sensor attached on left side ankle. Hand sensors were located as, dorsal side of the hand, palmar side of middle finger tip and palmar side of wrist. Number of body locations were decided according to previous studies on relationship between local skin temperatures and thermal sensation [53], [54], [49]. The reason of selecting wrist and top of a hand is that ulnar and radial arteries passes through from there and therefore heat loss mostly occurs at these locations. Also, finger and hand are places on body where most AVA (arteriovenous anastomoses) are locates which determines the state of vasoconstriction or vasodilation according to signals from hypothalamus [12]. Additionally, some naturally intrusive locations such as back, chest, chin and abdomen where specifically disclaimed.

Thermocouples are attached to skin with 2 different tapes, for the first layer of tape which touches directly to the skin surface was medical tape and the second layer tape was chosen as aluminum. Aluminum tape is used because of the round tip of sensors that not fully touches to surface of the skin therefore insulating tape was chosen to disconnect the interaction between ambient temperature.

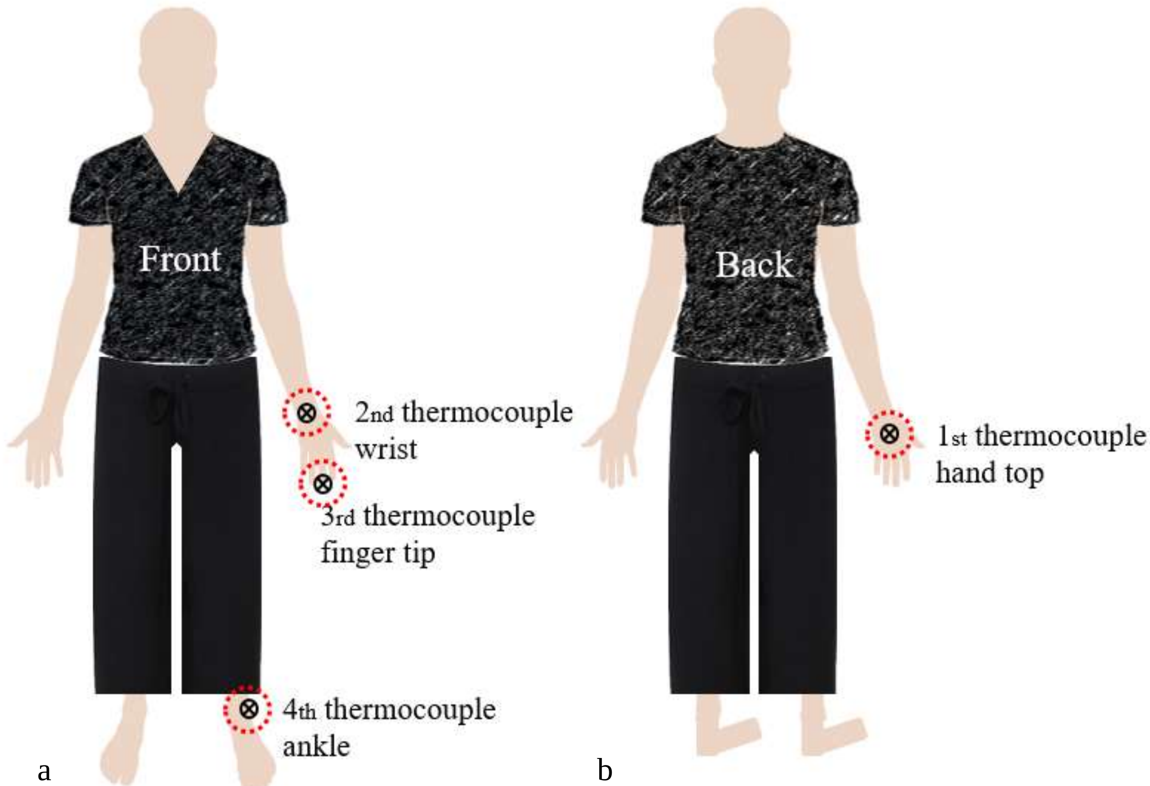

Figure 12. Illustration of participant's clothing level. Black labels on four different body parts are the locations of the skin temperature sensors. a. and b. are front and back views for thermocouple placements.

Anthropometric characteristics and general thermal comfort satisfaction information of subjects are outline in Table 5.

Table 5. Anthropometric characteristics and general thermal comfort information of subjects.

Subject No	Age	Weight (kg)	Height (m)	DuBois Body Surface Area (m^2)	Gender	General Comfort Satisfaction
1	26	68	1.76	1.9	M	YES**
2	27	90	1.82	2.1	M	NO
3	28	88	1.81	2.1	M	YES
4	26	60	1.68	1.7	W	YES
5	26	59	1.70	1.7	W	NO
6	27	84	1.87	2.1	M	NO
7	24	82	1.86	2.1	M	NO
8	25	90	1.93	2.2	M	YES
9	25	57	1.60	1.6	W	NO
10	29	75	1.75	1.9	M	NO
11	28	50	1.61	1.5	W	NO
12	27	62	1.70	1.7	W	YES**
13	28	53	1.66	1.6	W	YES
14	25	90	1.78	2.1	M	YES**
15	28	105	1.72	2.2	M	YES
16	26	64	1.79	1.8	M	YES
17	29	71	1.83	1.9	M	YES
18	35	63	1.62	1.7	W	YES
19	28	90	1.82	2.1	M	YES
20	26	88	1.85	2.1	M	YES
21	28	50	1.72	1.6	W	NO
22	23	62	1.65	1.7	W	YES**
23	23	50	1.59	1.5	W	YES
24	26	103	1.83	2.3	M	NO
25	48	53	1.63	1.6	W	YES*
26	29	56	1.60	1.6	W	YES
27	27	79	1.80	2.0	M	YES**
28	27	84	1.87	2.1	M	NO
29	26	52	1.61	1.5	W	NO
30	50	63	1.58	1.7	W	NO*
31	27	86	1.86	2.1	M	YES**
32	28	85	1.81	2.1	M	YES
33	24	57	1.72	1.7	W	YES

* Participants who are age above the population
** Participants who were signed their general thermal comfort level as “comfortable” but also they are signed their general thermal sensations as cold or hot.

3.3. Measuring Devices

During the experiments air temperature and relative humidity of the test room and skin temperature of the participants are continuously recorded. To regulate the test room according to required conditions air velocity measured with anemometer at 5cm close to each velocity inlet also temperature and relative humidity are measured with Testo 635-2 at four different heights.

- **Skin temperature sensors (T-type thermocouples)**

Figure 13. T-type double insulated skin thermocouple [55].

In this experiment, T type 36 gauge, double insulated, thermocouple wire is used. Thermocouples tips are soldered with 9mm copper wire. To contact thermocouple tips on human body, porous medical tape and aluminum tape are used.

- **DAQ System**

Figure 14. Data acquisition hardware, USB-1808 series [56].

Signals are transferred through data acquisition with USB-1808 Series DAQ that has 8 channels and for software DAQami™ v3.0 is used.

- **Pulse Oximeter**

Figure 15. Beurer PO 60 Blutooth pulse oximeter [57].

Before each experiment while participants were in preparation room, their heart rates are measured regularly with Beurer PO 60 Bluetooth® pulse oximeter until to see calm and stable pulses.

- **Anemometer**

Figure 16. Testo 417 rotating vane anemometer [58].

To measure air velocity Testo 417 – Rotating vane anemometer is used. Measurements are done at 5cm close to velocity inlet. Technical information for anemometer is given as;

Measuring range is +0.3 to +20 m/s

Accuracy is ± (0.1 m/s + 1.5 % of mv)

Resolution is 0.01 m/s

- **Thermometer & Moisture meter**

Before and during the experiments temperature and moisture gauged with Testo 635-2 temperature and moisture meter. All data are recorded through Testo comfort software (ComSoft Basic 5.0). Technical data for temperature measurement is given as;

Figure 17. Testo 635-2 temperature and moisture meter [59].

Measuring range is -40 to +150 °C

Accuracy is ±0.2 °C (-25 to +74.9 °C)

Resolution is 0.1 °F

Technical information for moisture meter is given as;

Measuring range is 0 to +100 %rH

Resolution is 0.1 %rH

During the experiments change in local temperature and relative humidity values in test room are determined as negligible. Also the test room was not receiving direct sunlight at any time of the day, therefore the difference between wall and ambient temperatures were negligible. Accordingly average radiation temperature accepted as equal to ambient temperature.

3.3.1. Repeatability and Reliability Tests for Thermocouples

T-type of thermocouples used in this tests (technical information about thermocouples given in section 3.3). For DAQ system software, DAQami version 3.0 – Data Acquisition Software is used [60].

The given picture (see Figure 18.) represents the test setup for thermocouples repeatability and reliability tests. In the system all couple tips are put in a nested box to disconnect air flow on tips, thereafter increase the box temperature and collected temperature data via DAQ. During the tests the box temperature keep tracked with Testo 635-2. The test duration is set 20 minutes for each because, it is significant to be able to observe skin temperature changes in short time period while noticeable temperature differences happening. Therefore the test duration specified with respect to actual experiment time (15 min.) with additional 5 minutes for extreme minimum and maximum temperatures. The initial and final box temperatures were also determined according to actual experiment temperature limits. Since in the actual experiment all thermocouples to be connected to human skin, the extreme minimum and maximum temperature limits would be 25℃ and 36℃. Therefore initial box temperature set as 22℃ and final box temperature set as 38℃. To increase the temperature inside the box electrical heater was used. The test is repeated 5 times and results are shown in section 3.3.1.1 and 3.3.1.2.

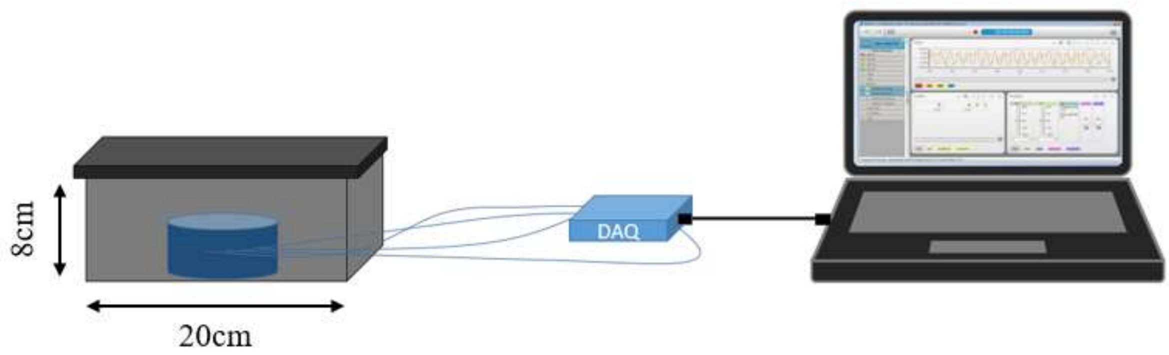

Figure 18. Demonstration of system setup for repeatability and reliability tests.

As it is shown in graphs (Figure 24a&b, 25a&b, 26a&b, 27a&b) there is a difference between temperature measured by different thermocouples for different parts of the body, but in the second part of the graphs (Figure 19, 20, 21, 22, 23) shows a proper repeatability for each thermocouples in five different experiments.

In order to have a quantitative observation of repeatability of thermocouples the standard deviation of each thermocouples for five experiments are calculated individually with the given standard deviation (STD) formula (eq. 3.1).

$$SD = \sqrt{\frac{\sum|x-\mu|^2}{N}} \tag{3.1}$$

From the equation (eq. 3.1) STD’s are calculated for all 4 thermocouples individually and the results shows that; for hand, foot, wrist thermocouple’s standard deviations are lower than 3% and for finger thermocouple’s standard deviation is lower than 4% which is acceptable for this experiment.

3.3.1.1. Test Results

The results of five repeatability and reliability tests are given in below graphs. Each graph consists four thermocouples and shows off their time vs temperature changes during 20 minutes heating up tests. The results are shown with two different representations as it is indicated. Firstly, for each tests all thermocouples were analyzed in the same graph and secondly each sensor assessed with itself. In the first representations, it is seen from graphs (Figure 20, 21, 22, 23, 24) that at first 10 minute of each tests, all sensors acts parallel to each other and indicates increase in temperature for 6℃. But in the second part of the graphs (last 10 minutes of the tests) “T_hand” coded sensor reaches 38℃ few minutes before other sensors and therefore a distinction occurs between “T_hand” and other sensors. Also in test

1, 3 and 5 small temperature differences are seen between sensors. The reason of this different feedback from different thermocouples in high heating rates can be related to different soldering quality of thermocouple tips, difference in length of each wire and connection errors to DAQ devices.

Four thermocouples high heating rate repeatability and reliability tests are given in Figure 19, 20, 21, 22, 23. Each test duration is 20min. and all test are performed with the same procedure. Thermocouples are named according to the places in actual experiment.

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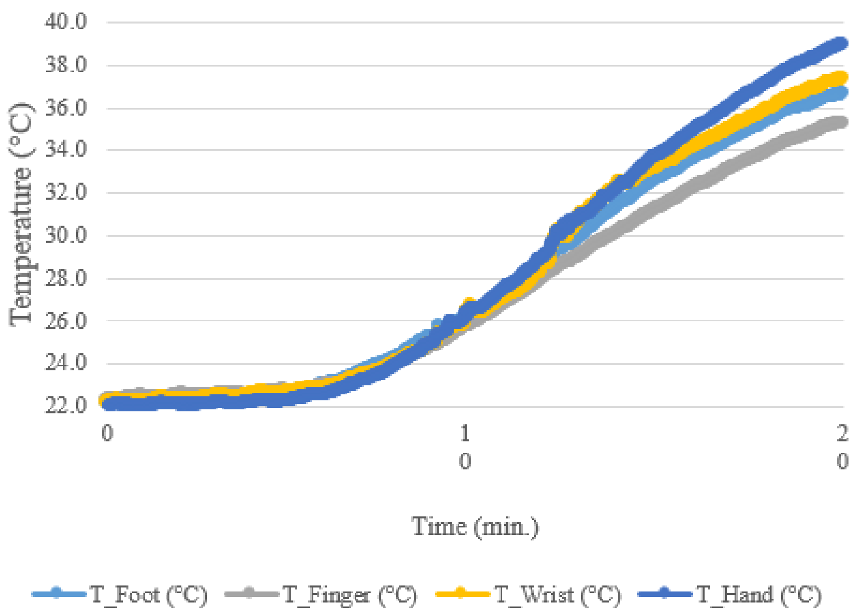

Figure 19. Test 1 results.

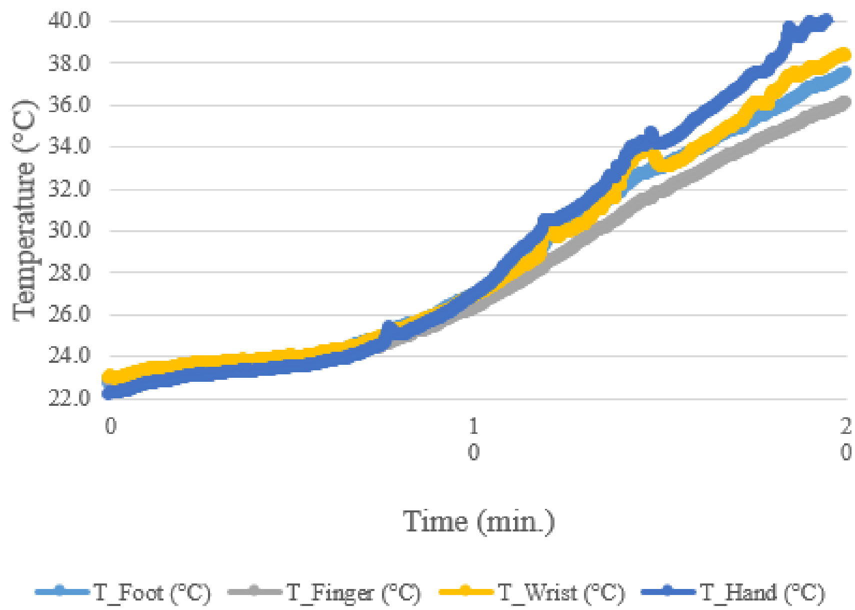

Figure 20. Test 2 results.

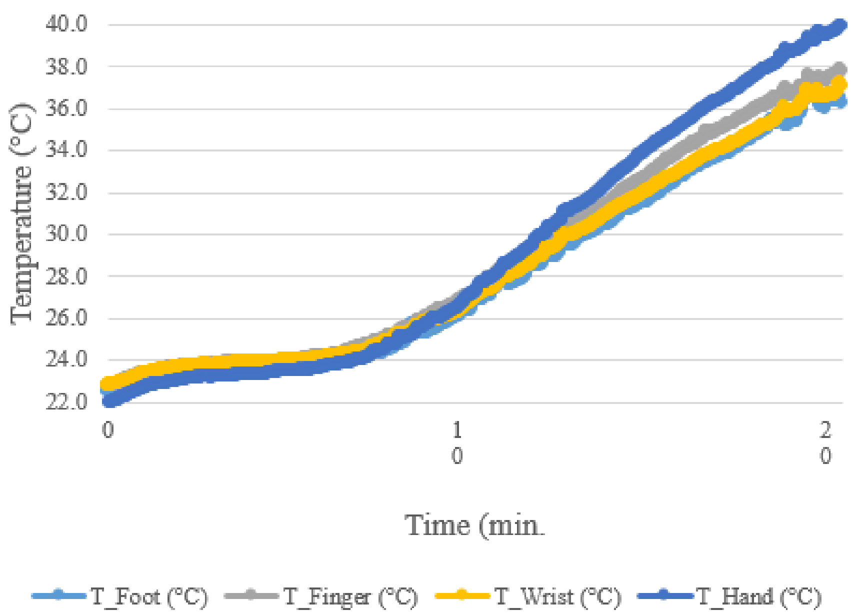

Figure 21. Test 3 results.

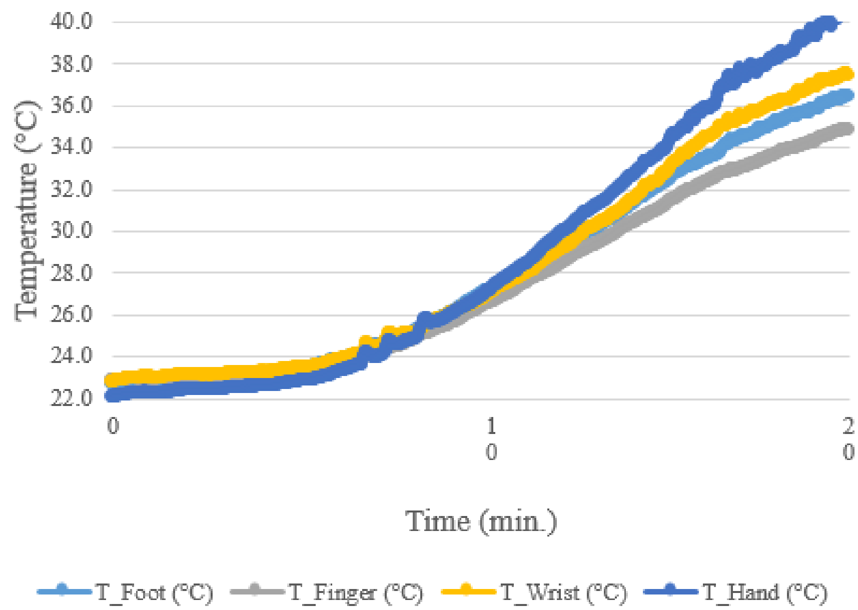

Figure 22. Test 4 results.

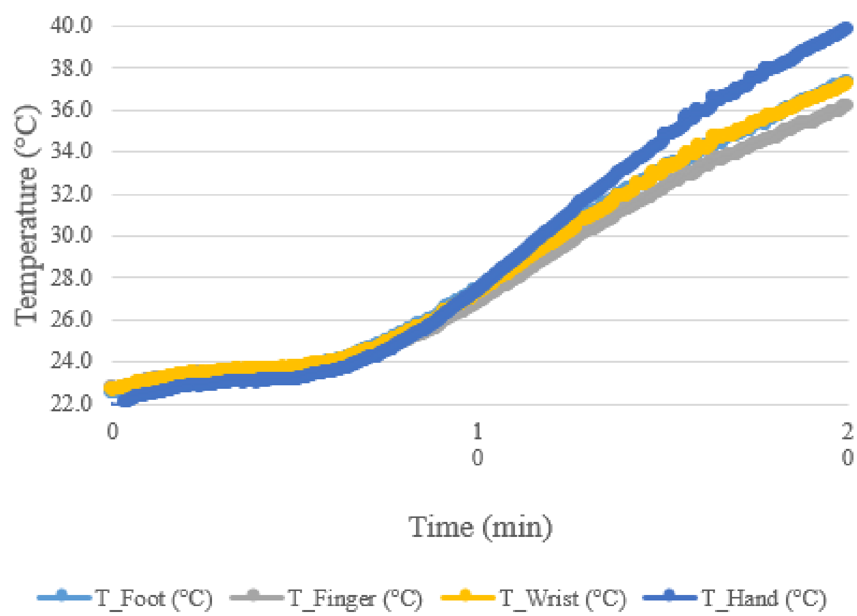

Figure 23. Test 5 results.

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3.3.1.2. Individual Test Results of Thermocouples

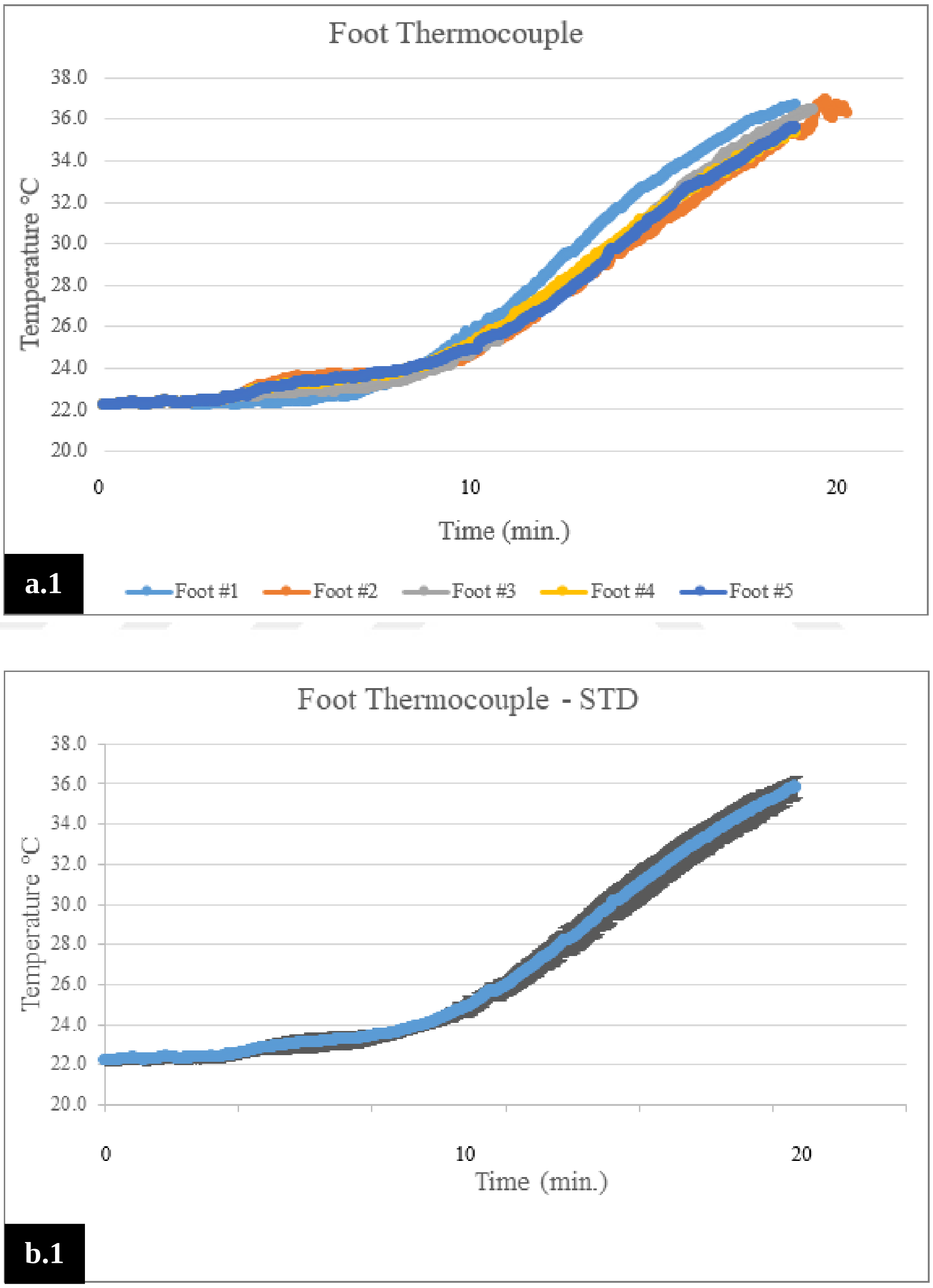
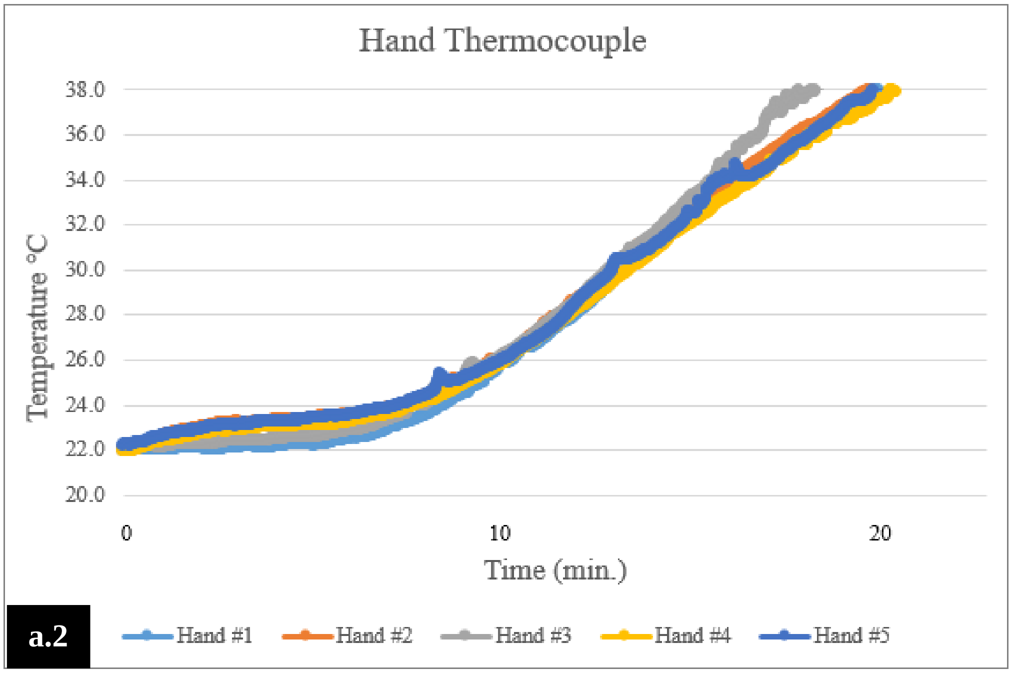


Figure 24. a.1. Time vs temperature changes of the "Foot" coded thermocouple in five times repeated heat up tests. b.1. The average of five test results and error bars are given. "Foot" coded sensor's standard deviation is lower than 3%.



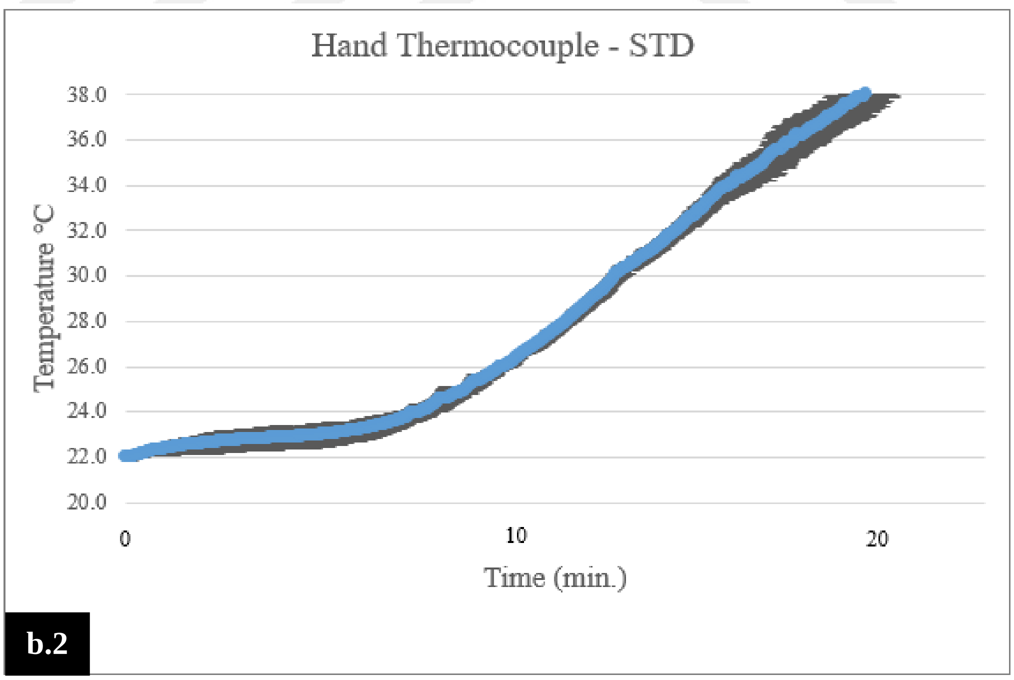
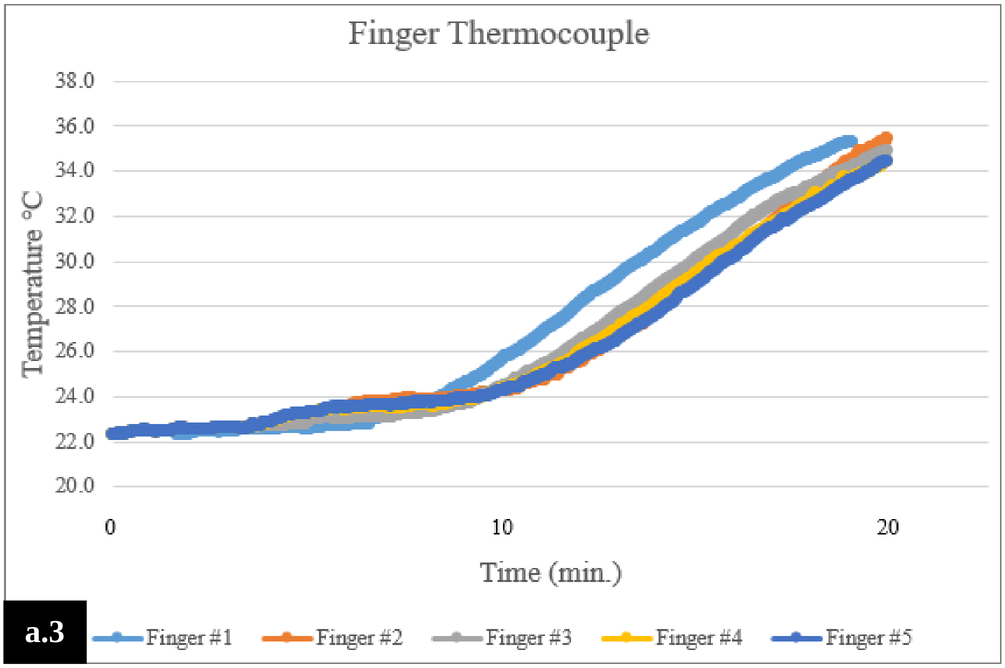


Figure 25. a.2. Time vs temperature changes of the "Hand" coded thermocouple in five times repeated heat up tests. b.2. The average of five test results and error bars are given. "Hand" coded sensor's standard deviation is lower than 3%.



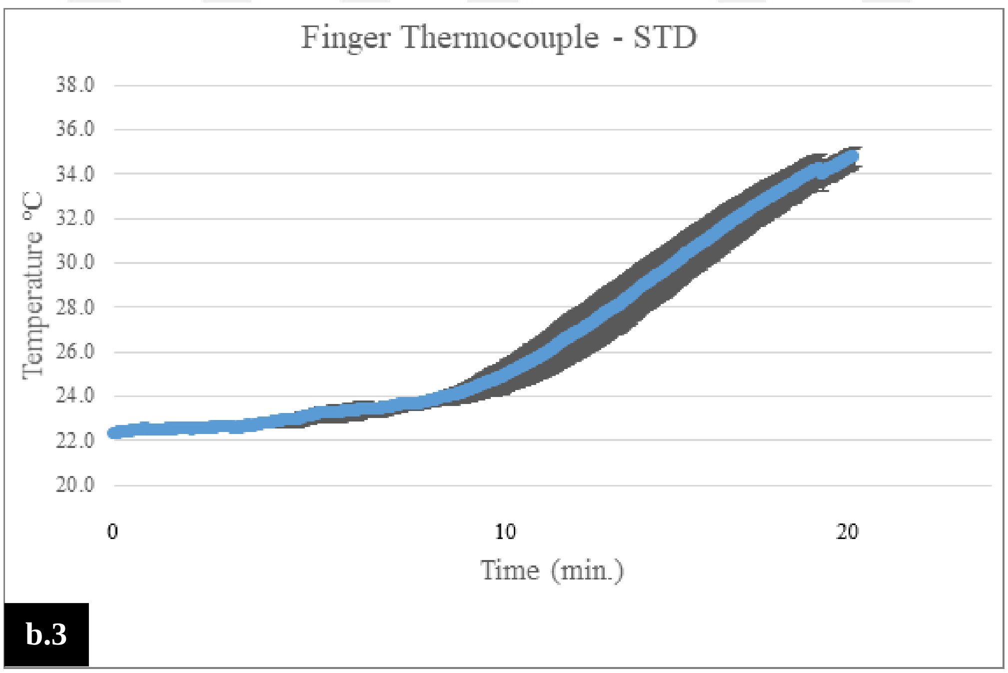


Figure 26. a.3. Time vs temperature changes of the "Finger" coded thermocouple in five times repeated heat up tests. b.3. The average of five test results and error bars are given. "Finger" coded sensor's standard deviation is lower than 4%.

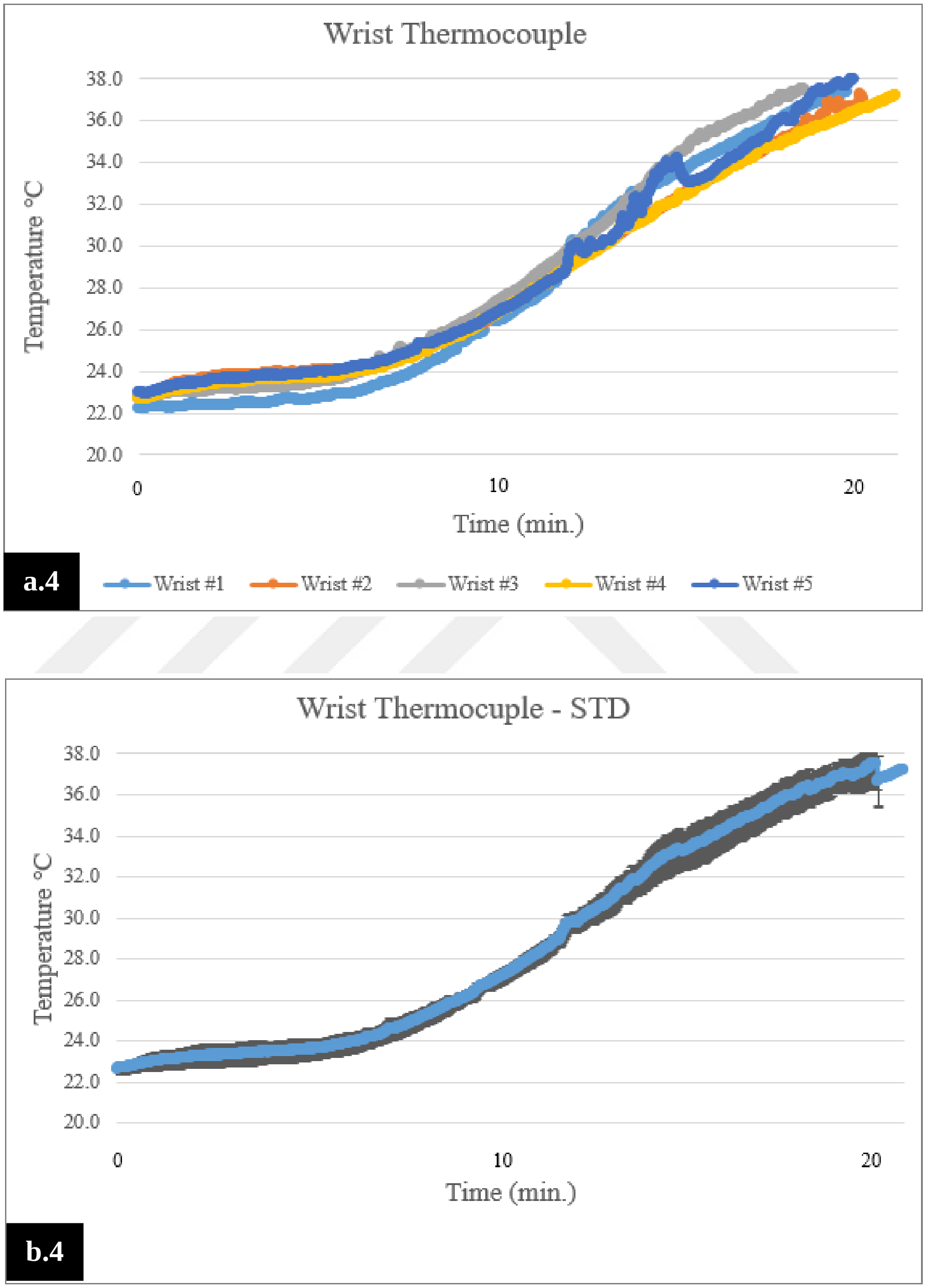


Figure 27. a.4. Time vs temperature changes of the "Wrist" coded thermocouple in five times repeated heat up tests. b.4. The average of five test results and error bars are given. "Wrist" coded sensor's standard deviation is lower than 3%.

3.4. Experimental Protocol

Subjects were assigned one of the three different experiment cases (see Appendix A-2), each case represents different combinations of thermal parameters. Case 1 participants consisting of four female and five male were experienced uncomfortably cold indoor environment. Case 2 subjects consisting of five female and six male were exposed to uncomfortably hot indoor environment. And for group 3 (six female and seven male), neutral (comfortable) thermal environment was designed. Before the experiment, participants are only informed about possible case conditions, but their individual exposure parameters were not declared.

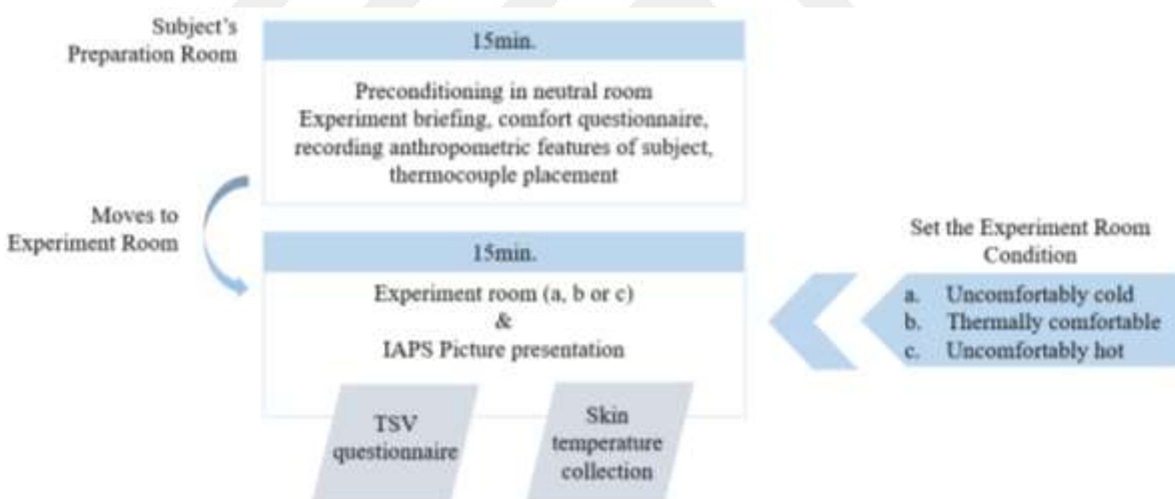


Figure 28. The protocol follow for the experiment.

The experiment consist of two parts; firstly, participants were pre-conditioned in a thermally neutral environment for 15 minutes to prevent any bias due to recently exposed climate. Also waited participants to calm down her/his heart rate and relatedly decrease current metabolic rate that can effect on thermal sensation vote.

In the course of experiment, the participant was informed about experiment procedure and her/his anthropometric characteristics are noted.

Also a short questionnaire (see Appendix B-3.a.) was given for subject's general thermal comfort assessment. During this period, thermocouples are attached on subject's skin as shown in Figure 29. and tested for 3 minutes.

Figure 29. Thermocouple's locations on dorsal and palmar sides of a hand (a &b) and ankle (c).

After pre-conditioning, subject is invited to test room (see 3.1). When participant indicate with her/his raising hand that she/he is ready, then clicks on screen and emotional stimulating video starts and simultaneously thermocouples activates and starts to record skin temperatures. The participant remained in sedentary seated position during the experiment and continuously engaged in watching ESP video. In consequence of sedentary seated position subject's activity level selected as 1.0 metabolic rate (Met).

Each 5 minute intervals video stops for 40 seconds and asks subjects to fill TSV form in accordance to 7 point ASHRAE thermal sensation indices (Figure 8). A period of 5 minute determined by the content of the ESP video as in earlier studies, therefore end of the each picture block TSV form is given [41]. The TSV form is appended in Appendix (Appendix B-3b).

During the experiment, air temperature, relative humidity and skin temperatures were recorded per second. Air velocity is also maintained to less than 0.1 m/s and velocity inlet flaps adjusted to minimum gap. Measurements of environment were taken from two different locations as, on top of the subject’s desk and from a height of 1.2 m.

The tests are conducted while glass façade blinds were lowered and artificial lights (450 - 500 lux) were turned on. Position of subject and orientations of thermometer, moisture meter and DAQ device are shown in Figure 30. Door of the test room was transparent, therefore to prevent any distraction from outside, a large cover is put. IAPS pictures were displayed on 17in (43cm) monitor, positioned 0.6 m away from the subject.

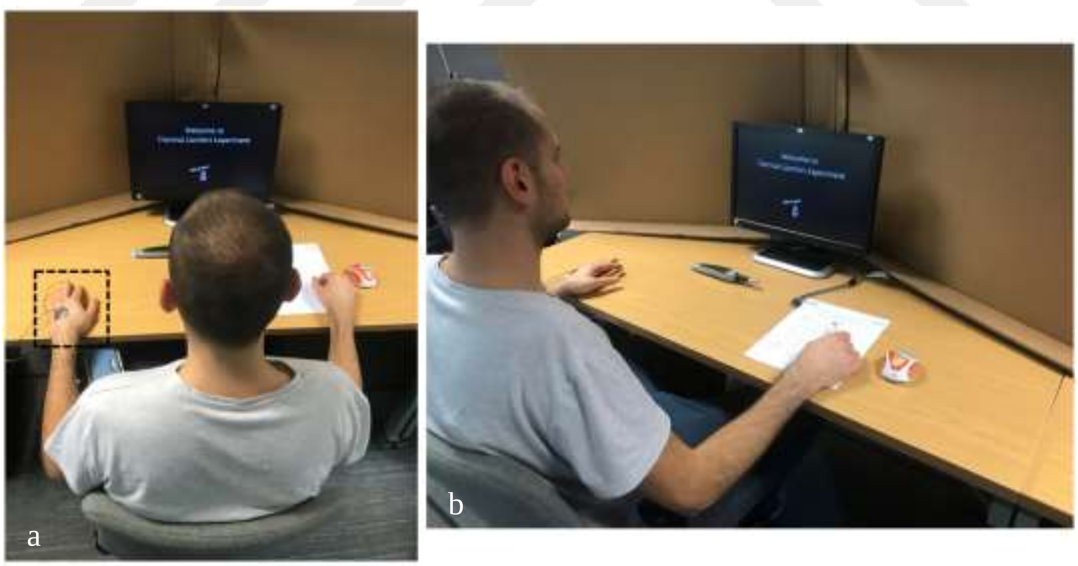


Figure 30. a. A typical operation of the experimental setup, back side view. A participant sits right across the screen. b. The experimental setup is shown at the right. Temperature sensors are located on three different places both on dorsal and palmar sides of a non-dominant hand and one on ankle as indicated. (Photographs are taken and used with a permission of the volunteer. These photos are only representative pictures, they were not taken during an experiment).

The standardized emotional pictures were taken and used with a permission of The Center for the Study of Emotion and Attention (University of Florida). The IAPS data base consist of 956 colorful images with different valence and arousal scores which have been rated on nine-point scale. During the experiment the set of emotionally evocative pictures are presented in the order of pleasant, neutral and unpleasant. Pictures were selected according to their valance numbers, higher number of valence refers to positive emotions likewise low valance numbers are considering as negative emotion stimulating pictures.

The valance scores of IAPS varies roughly from 1 to 9 and in the present study, for pleasant pictures 7.50 and above valence scores were selected and for unpleasant pictures it was selected in between 2.40 and 3.85. The neutral pictures (non-emotional) valence scores were in between 4.50 and 5.25. Justifying by the recent studies the negative emotion stimulating pictures were limited at certain valence scores for not to cause psychological discomfort on subjects [41].

The protocol of picture presentation and emotion stimulus are given in Figure 32. Each block consist of 47 pictures and the duration of each picture settled as 6 second. The interval of 6 sec. justified by previous studies, as indicated that more than 6sec. screening, subject exhausted by the current stimulus or changed to different emotions [61]. sec. justified by previous studies, as indicated that more than 6sec. screening, subject exhausted by the current stimulus or changed to different emotions [61].

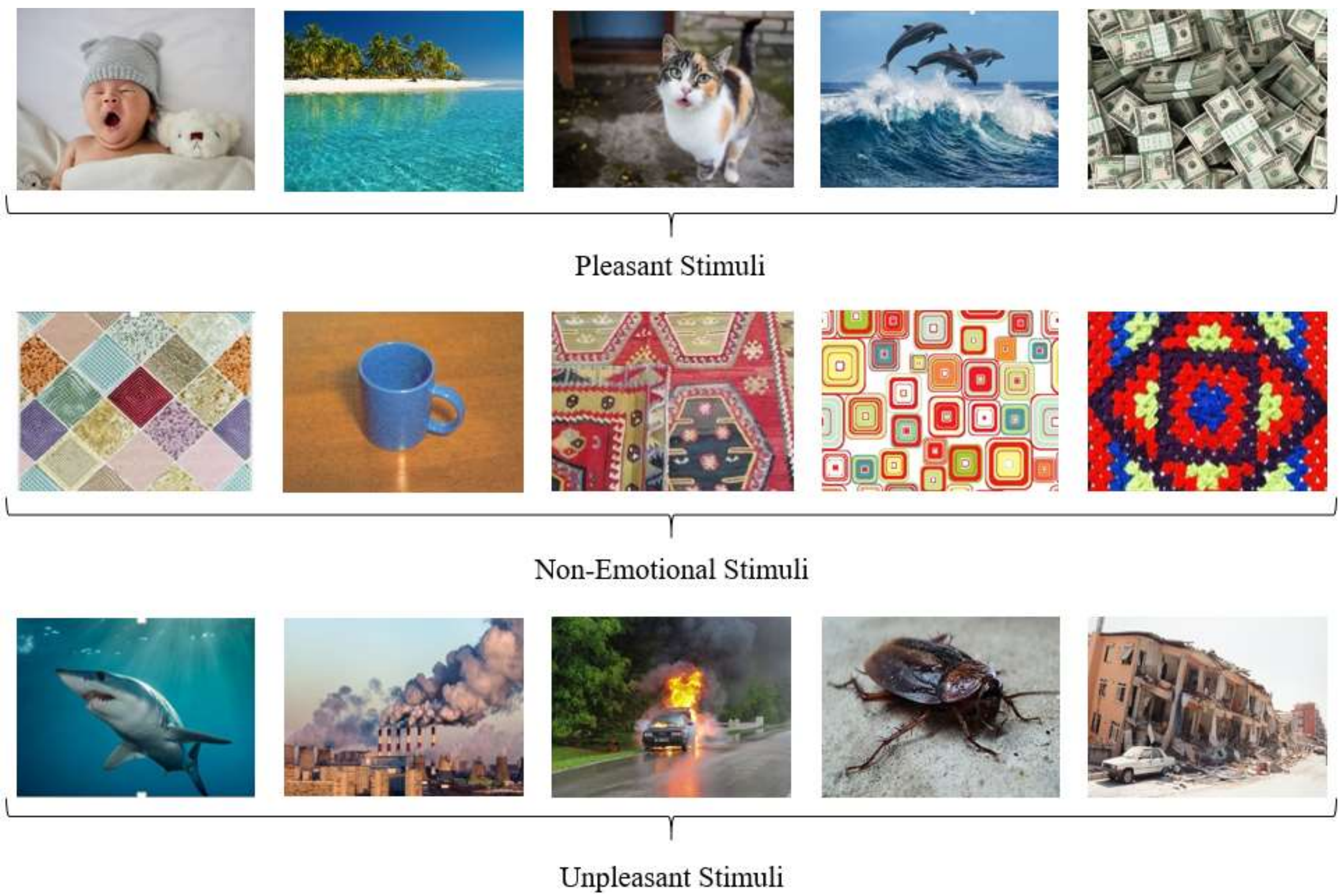


Figure 31. Pictures for different stimuli levels are only representatives of IAPS catalog [62] (detailed information were given about present studies stimuli pictures in Appendix C-1 and C-2) .

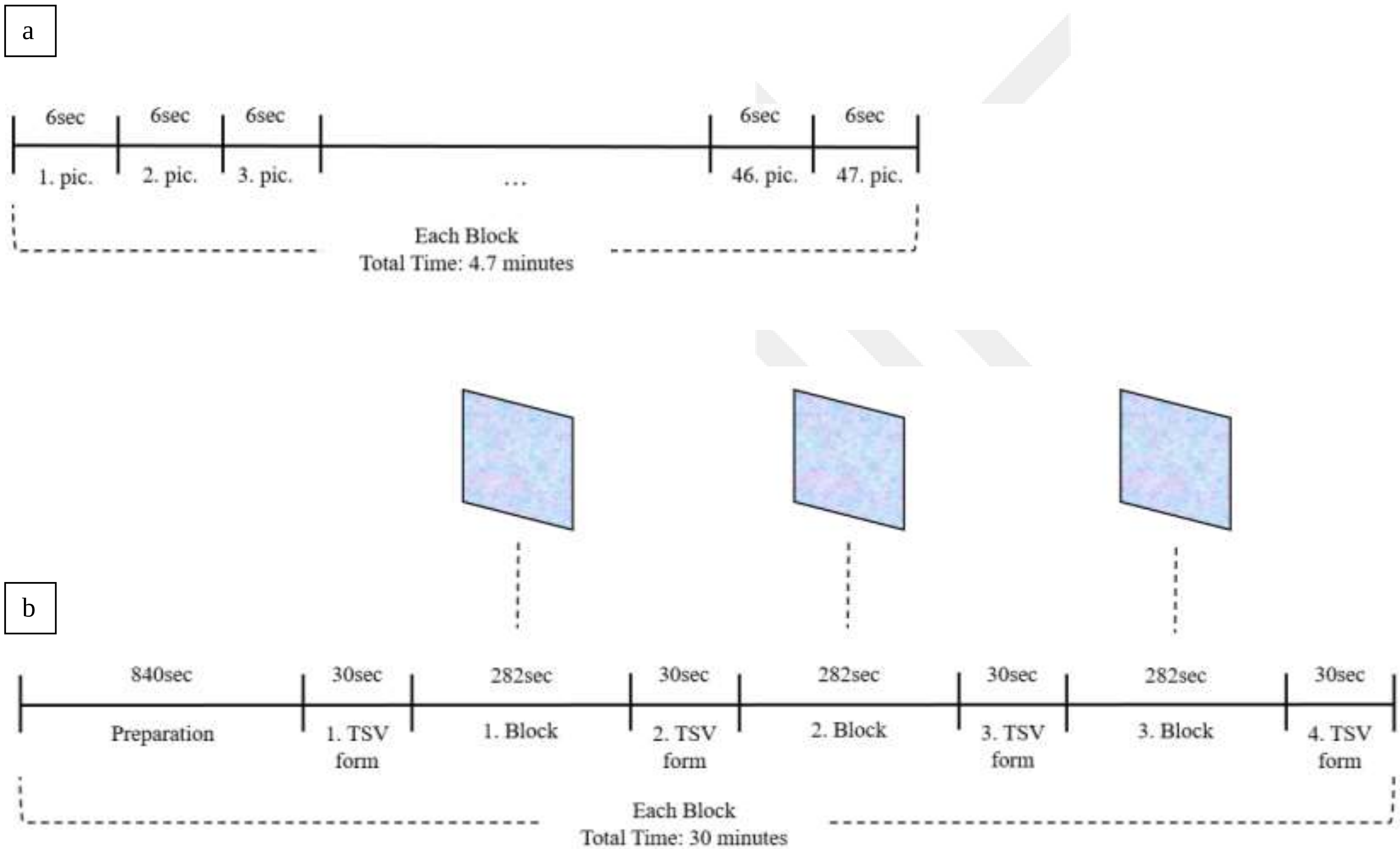


Figure 32. a. Each block (pleasant, neutral, unpleasant pictures) presentation protocol. b. Experiment stimulus protocol.

CHAPTER IV

EXPERIMENTAL RESULTS and ANALYSIS

In the first part the experiment results were assessed according to individual case conditions within specific body segments (where thermocouples are located). Regardless from the participant's personal information, their individual skin temperatures were given.

Second, for each measurement point, mean skin temperatures were compared and analyzed according to room conditions. Beside to that, during the experiment each 5 minute interval participants were fill the subjective TSV (thermal sensation vote) form and accordingly results of mean skin temperatures and TSV forms were compared and given in section 4.2.

4.1. Case Results According to Individual Body Segments

Experiments were conducted in three different thermal conditions as expressed in previous chapter. Apart from air temperature and slight differences on relative humidity for required case conditions, each tests were conducted equally. The results of each case were given in section 4.1.1 for cold room condition, 4.1.2 for hot room condition and for neutral (comfortable) room condition was given in section 4.1.3. In each experiment after participants settled thermocouples were turned on for to measure the initial skin temperatures. After that with the "ready" sign of subject, the system started to record as experiment results from thermocouples. In the graphical representation time variables were settled as; 0^{th} (starting point), 5^{th}, 10^{th} and 15^{th} minutes when TSV forms also filled in these time intervals.

Additionally, in this section the mean skin temperatures with standard deviations are represented in graphs for each case conditions.

4.1.1. Results of Uncomfortably Hot Condition (PMV +2)

During the experiment each 5 minute intervals subjects fill subjective TSV questionnaire as it was mentioned, accordingly the results of uncomfortably hot thermal room (PMV +2) were given in Figure 33, as a bar chart. It is seen from the graph that the number of people who feels "hot" slightly increases during first 10 min. but thereafter it decreases while increase in number of people who feels "slightly warm". The increase might be due to the effect of unpleasant pictures or physiological adaptation to hot environment and in parallel with the decrease in temperature after 10th min might be the reason of vasodilation signals which is activated by the thermoregulatory system.

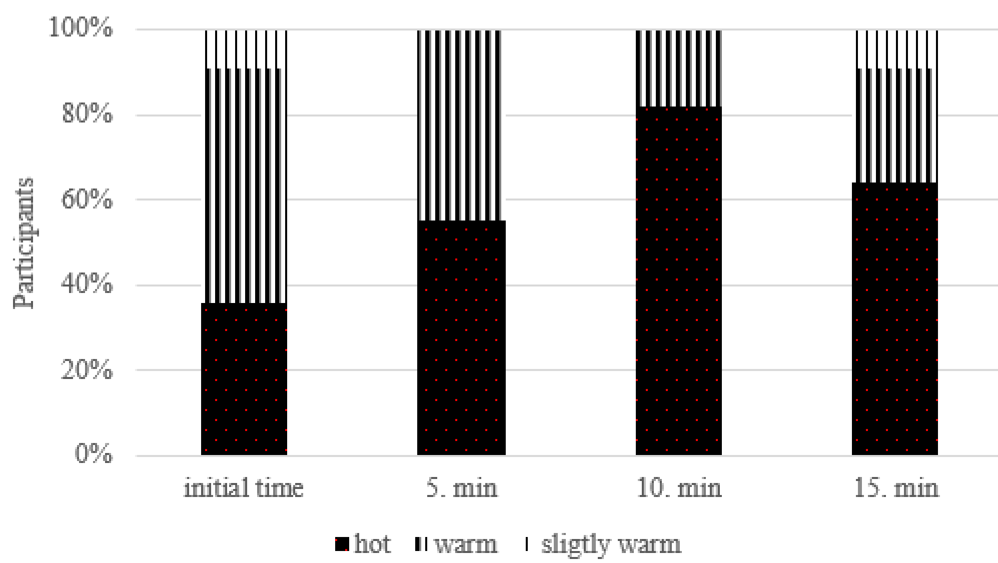


Figure 33. Thermal sensation votes of participants during the hot exposure experiment.

Results from thermocouples were represented in two different types as mean skin temperatures of all participants and individual skin temperatures for a specific body segment.

It is seen from the individual temperature result that, rate of increase in temperature is higher from starting point up to 10th minute, then it raises slowly and reaches steady state. Temperature changes in wrist and hand thermocouples were approximately 2 °C from initial point to the end of the experiment. The highest temperature changes (*ΔT*) also occurred in fingertip as 3.8 ± 0.8 °C.

It is seen from Figure 34 that hand and wrist mean skin temperature profiles goes almost parallel with each other from the initial point up to end of the experiment. Temperature profiles of hand and wrist of individual's are also acts similar with each other, accordingly change in temperature (*ΔT*) from 5th to 10th min found as 0.8 ± 0.2 °C and likewise *ΔT* of 10th to 15th min found as 0.5 ± 0.2 °C. Although the other considerable temperature change occurred on foot as 1.5 ± 0.5 °C from starting point to the end.

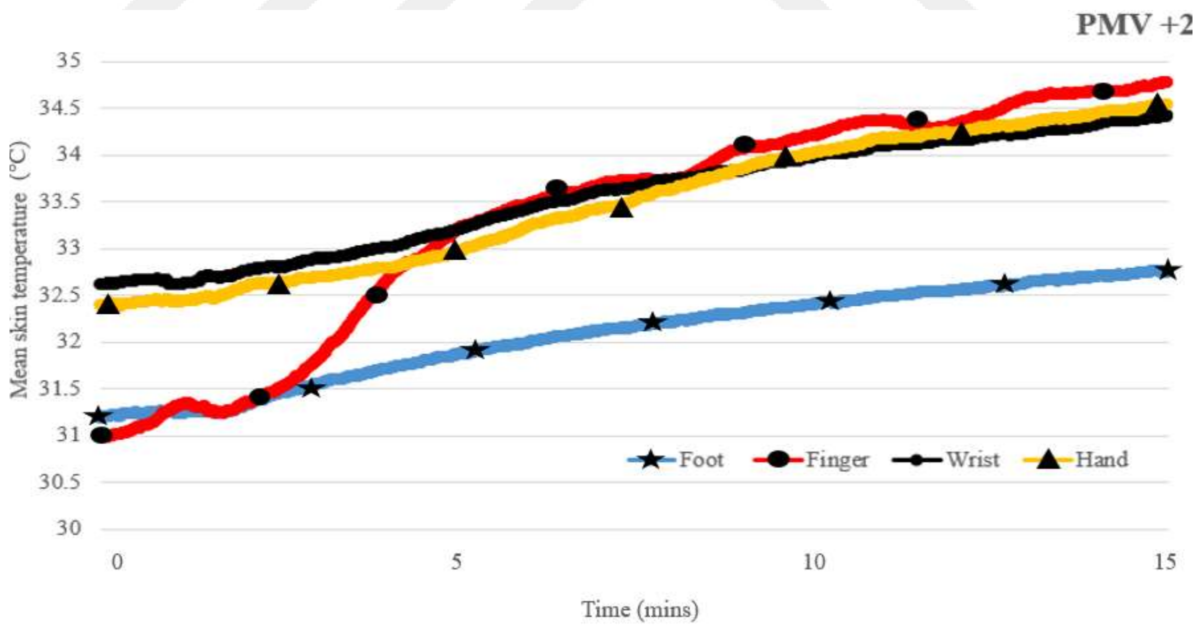


Figure 34. Mean skin temperatures of participants who attended to hot exposure experiment.

Hot exposure experiments, individual skin temperatures are presented in Appendix D (Appendix D, as Figure 32 for foot, Figure 33 for fingertip, Figure 34 for wrist and Figure 35 for hand).

4.1.2. Uncomfortably Cold Condition (PMV -2)

The results of thermal sensation votes for cold exposure experiments (PMV -2) were represented in Figure 35 as a bar chart. Likewise other experiments each TSV questionnaire filled in 5 minutes time intervals in the same manner with the change in the type of emotional stimulating pictures. It is seen from the graph that initial sensation votes were mostly selected as cold (PMV -3) and slightly cool (PMV -1). Thereafter participants watched unpleasant ESP video for 5 minutes and filled TSV questionnaire again and they were sensationally turned mostly to neutral (PMV 0), slightly warm (PMV +1) and warm (PMV +2). Between 5th and 10th minutes subjects were watching non-emotional pictures and after 5 minutes of watching neutral pictures they voted their own sensation's where it is resulted as mostly neutral with few percent of warm, slightly cool, cool and cold. In the final part subjects watched pleasant pictures. As a results of it their sensations of warm increased while decrease in the number of cold sensations.

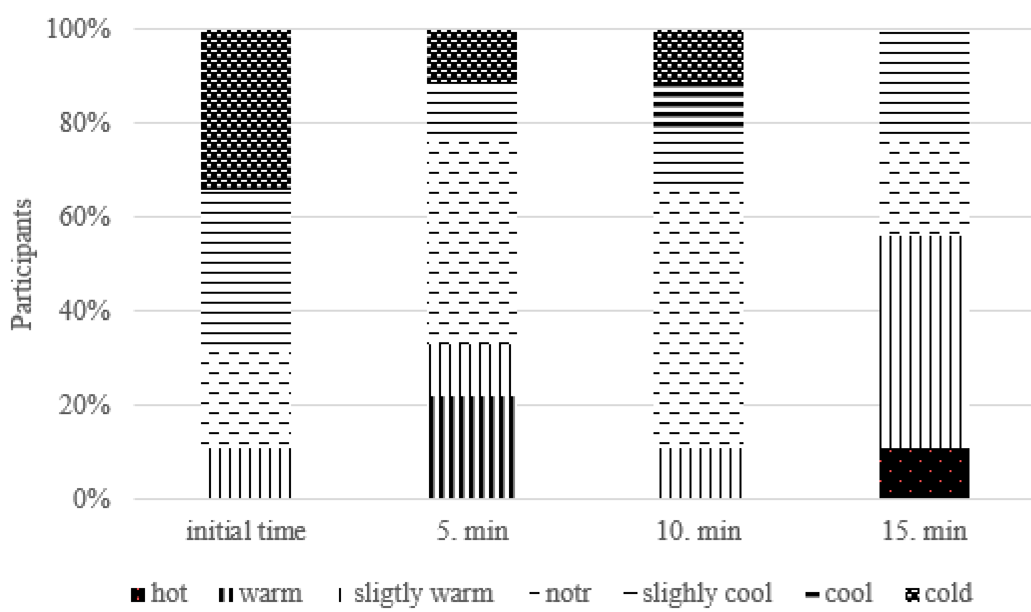


Figure 35. Thermal sensation votes of participants during the cold condition.

Beside to subjective sensation votes, results from thermocouples are given in two different ways as mean temperatures of all subjects and individual skin temperatures for specific body parts (according to measuring points).

In the graph (Figure 36) we can see that only hand temperature is increasing whereas finger and wrist temperatures are slightly decreasing beside to them foot temperature is also decreases more sharply than finger and wrist. For the first 5 minutes of the graph (Figure 36) it can be said that unpleasant pictures both helped to increase in skin temperatures on the surface of the hand in parallel with sensation votes (Figure 36) and prevent sharp decreases in skin temperatures on other measuring points.

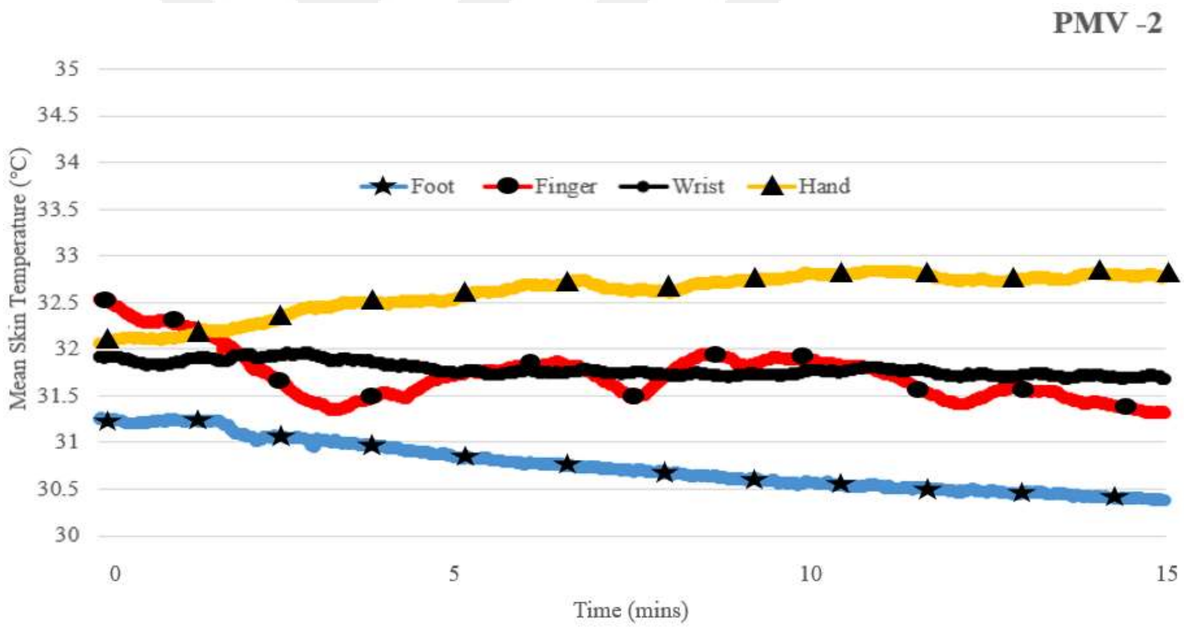


Figure 36. Change in mean skin temperatures of participants who attended cold exposure experiment.

Individual skin temperatures of cold exposure experiment are given in Appendix (Appendix D as Figure 38 for foot, Figure 39 for fingertip, Figure 40 for wrist and Figure 41 for hand).

4.1.3. Thermally Comfortable Condition (PMV 0)

The outputs of TSV questionnaires in thermally neutral condition (PMV 0) were expressed as a bar chart in Figure 37. When we analyze the results according to change in ESP type it is seen that, in the first (initial) assessment of sensations, participants vote mostly neutral, slightly cool or warm. After they watch unpleasant stimuli pictures, they remarked their sensations mostly on the warm side of the scale and few participants remained as neutral and slightly cool. Right after the second vote they watched non-emotional picture presentation and at the end of the visual stimuli it can be seen that the percent of people who feels slightly cool remained same and neutral votes increased while decrease in the percent of hot, warm, slightly warm columns. In the final step which is pleasant stimuli picture presentation, votes of participants on their thermal sensation varied between hot and cool. Percent of hot and slightly cool votes remained same whereas percent of warm and slightly cool votes increased and oppositely neutral sensations were decreased.

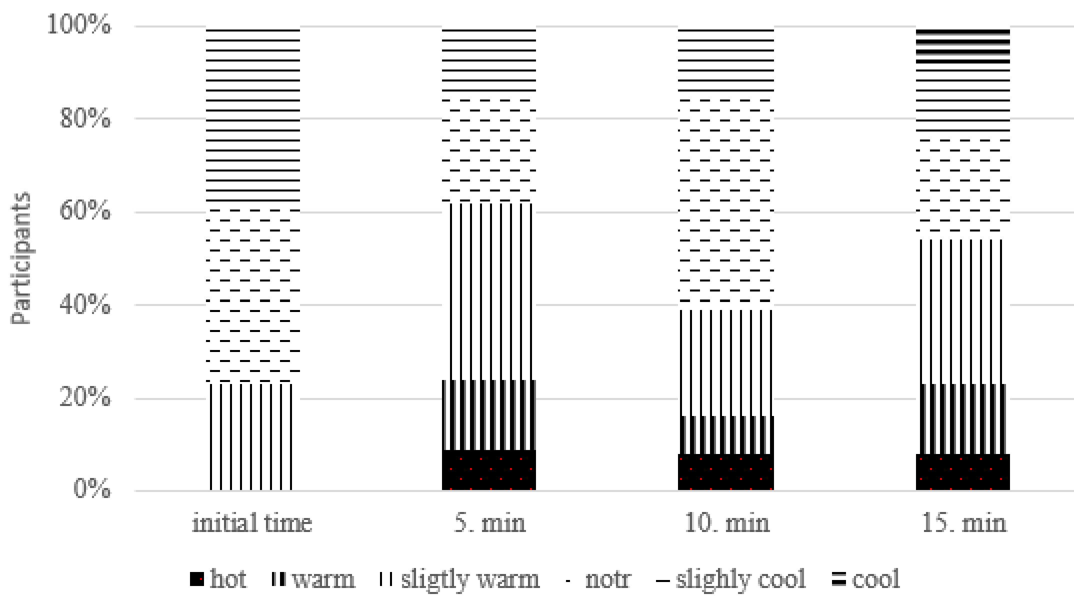


Figure 37. Thermal sensation votes of participants in thermally comfortable room condition.

In addition to thermal sensation assessments of participants, the skin temperature results were provided in Figure 43 as mean skin temperatures of all participants in comparing with different measuring parts and given in Figure 44,45,46,47 as individual results for specific body segment.

In the graphical representation (Figure 38) it is seen that except foot mean temperature, other parts of skin temperatures are increasing with different slopes from the initial point up to end of the experiment. More specifically, in the first 5 minutes, the mean temperature of fingertip have two picks as a result of sharp decrease and increase and then it continuous with small fluctuations. The wrist and hand mean skin temperature profiles goes almost with the same slope where it increases in the first five minutes, then goes slightly straight in the second five minute and finally it increases like in the first part.

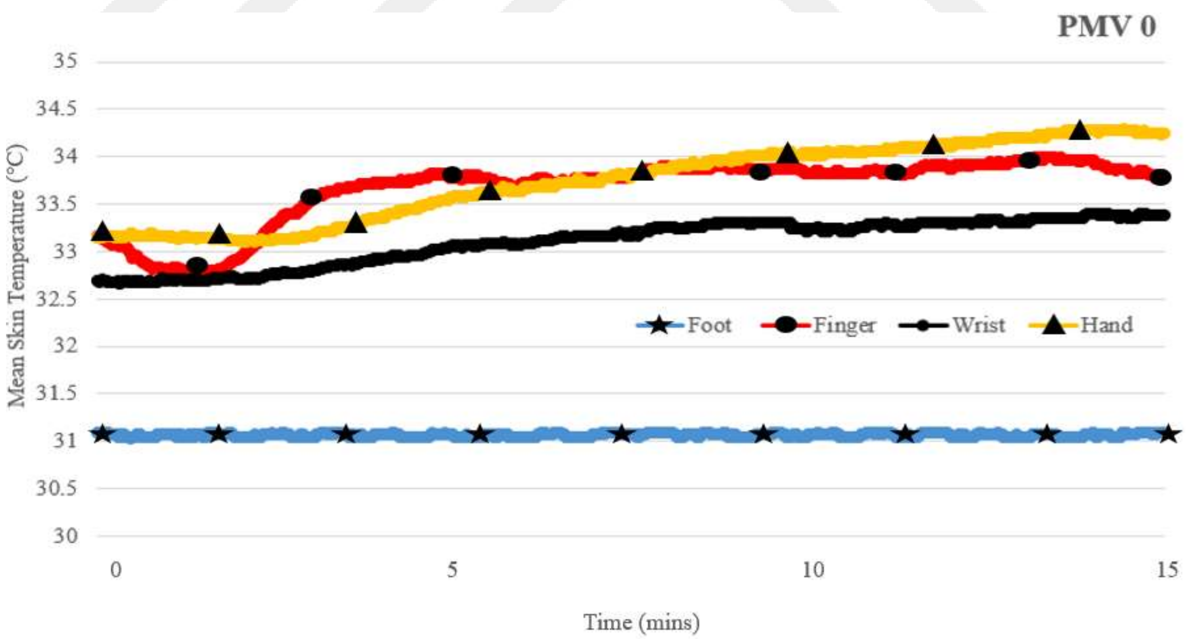


Figure 38. Change in mean skin temperatures of participants who attended thermally neutral experiment.

Individual skin temperatures of thermally neutral experiment conditions were given in Figure 44 for foot, Figure 45 for fingertip, Figure 46 for wrist and Figure 47 for hand.

Likewise previous representations the x-axis stands for time and each five minutes are given for to examine the effects of ESP type changes easily. Similarly the colorful numbers are represent a participants.

4.2. Comparison of Mean Skin Temperatures of Different Body Segments

To be able to analyze the behavioral differences between test locations non-parametric Kruskal Wallis Test was performed in SPSS program. From the results for all different test conditions and stimuli pictures, hand top, wrist and fingertip measurements pairwise comparison's significant level was less than 0.05 which shows the statistically significant correlations in between, but on the other hand pairwise comparisons of foot and other test locations significant value was greater than 0.05. Therefore, as mean skin temperatures, hand, wrist and fingertip results were assumed (details are provided in Appendix E). All test locations mean results were compared according to case conditions as given in Figure 41, 42, 43, 44.

- **Foot**

It is seen from the Figure 39 that foot skin temperature is not effecting from visual stimuli as other body parts. It is seen that for hot experiment condition (PMV +2) mean skin temperatures increases regardless from stimuli pictures likewise in the cold experiment conditions the mean skin temperature decreases. Also in the neutral room there wasn't any significant temperature change observed.

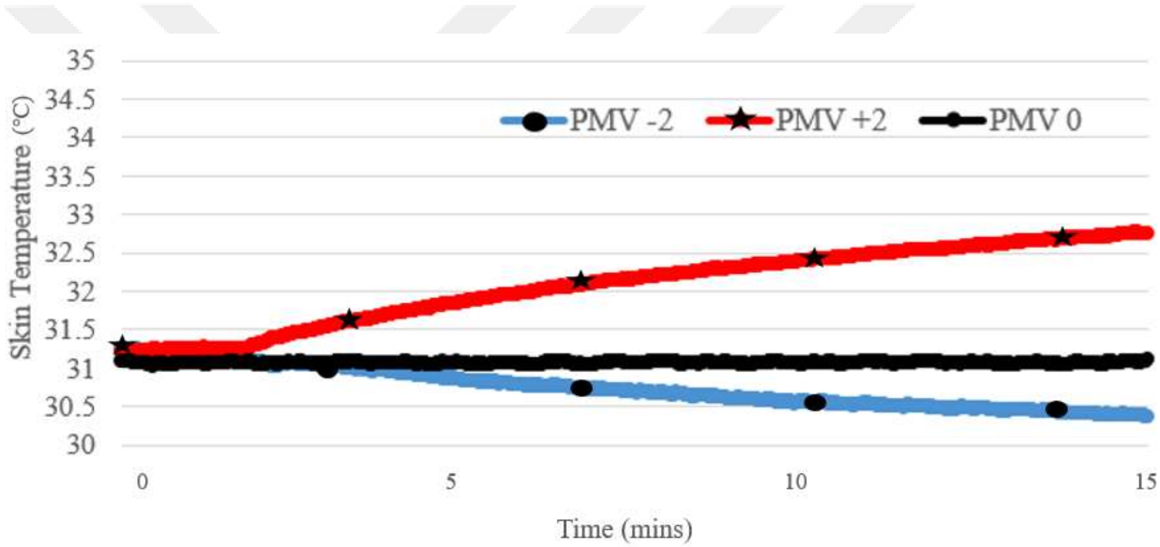


Figure 39. Mean skin temperatures in three different experiment conditions (for foot).

- **Finger**

The comparisons of fingertip results are slightly different because of the initial skin temperatures as it is varies a lot more than foot, hand top and wrist. Therefore it should be considered both in the manner of increase or decreasing curve and expected delta T. A sharp increase at the beginning of PMV +2 curve might be due to the low initial temperature moreover during the neutral picture representation (between 5min and 10min) it increases much slowly and at the last part it reaches 34.8 ℃. For cold room condition (PMV -2) after 3rd minute the graph fluctuates with in small temperature intervals and a downward peak is seen right in the middle of neutral picture presentation. For thermally comfortable room (PMV 0) apart from the little drop at the beginning of the experiment there wasn't significant temperature changed was observed.

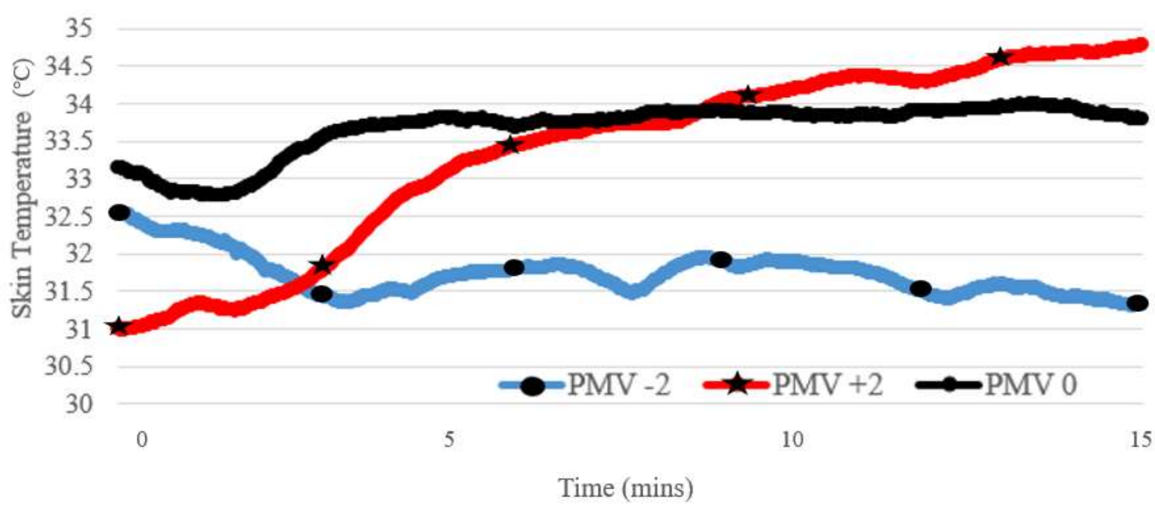


Figure 40. Mean skin temperatures in three different experiment conditions (for fingertip).

- **Wrist**

Behaviors of the wrist and hand top temperature changes are highly similar. From the wrist results, the initial temperatures where people are coming from neutral environment to test room were recorded as in between 32-32.5 ℃. It is seen from the graph (Figure 41) that for cold room conditions (PMV -2) the mean skin temperature stayed almost constant at 32 ℃. Moreover for hot (PMV +2) and neutral (PMV 0) experiments temperatures were increased due to stimuli pictures.

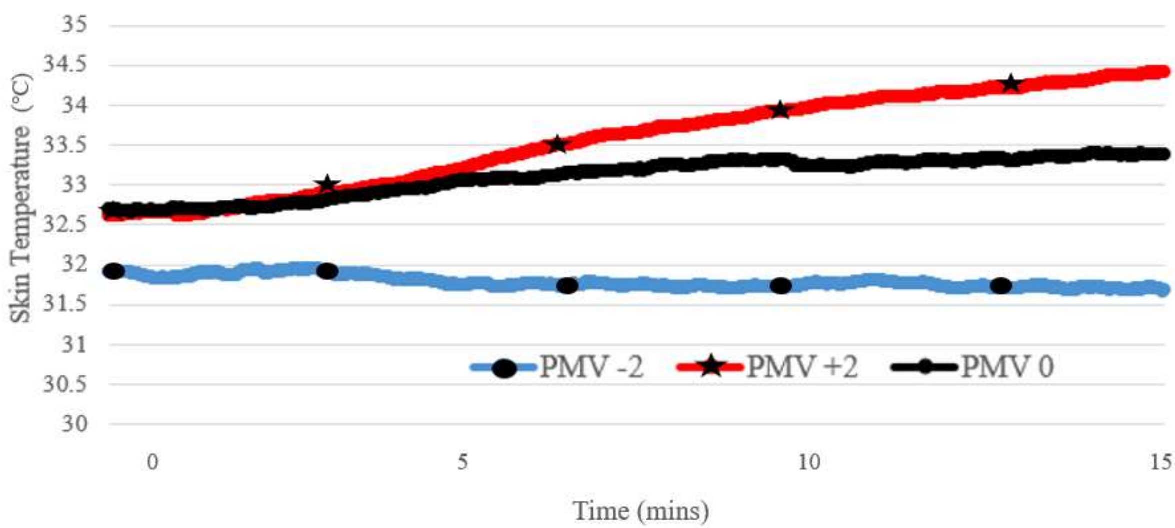


Figure 41. Mean skin temperatures in three different experiment conditions (for wrist).

- **Hand**

As it was mentioned in wrist results, the temperature changes are similer, according to PMV +2 and PMV 0 the mean skin tenperatures increases while PMV 0 temperature stays constant after a small increase at the beginning.

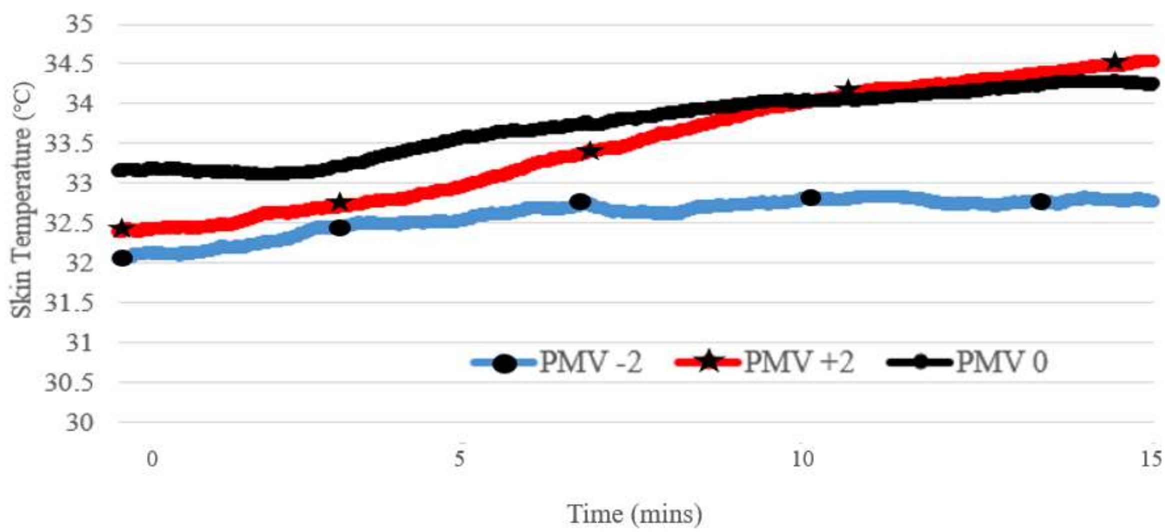


Figure 42. Mean skin temperatures in three different experiment conditions (for hand top).

The outputs of individual body part's TSV questionnaires were evaluated with overall thermal sensation votes and the results were represented in Figure 43. The first 5 minutes of these results belong to negative stimuli pictures, the second five minutes belongs to neutral pictures and the final step (from the 10^{th} min to the 15^{th} min) belongs to positive stimuli pictures. The quantity of votes were given in percent of 33 participants. As it was stated that the thermal sensation analyses conducted in two different parts as considering the total body and specific body segments. It was analyzed that while participants decide their general thermal sensations which part of their body takes significant role on this decision. It is remarked to participants that their votes should be according to their first senses.

In the first run (first 5 min), after the negative pictures were shown, 40% of people vote their arm thermal sensations exactly same with their entire body thermal sensation. Also with the same point of view head and chest results were 35%. Secondly, after the neutral (non-emotional) picture monitoring, apparently the percent of people who voted the same with their chest and arm same with their entire body thermal sensation was approximately 60%. In the last part, i.e. after the positive stimuli picture monitoring again the thermal decision spots were figured as head, chest and arm with the minor differences mostly head were voted (57%) as same with entire body thermal sensation.

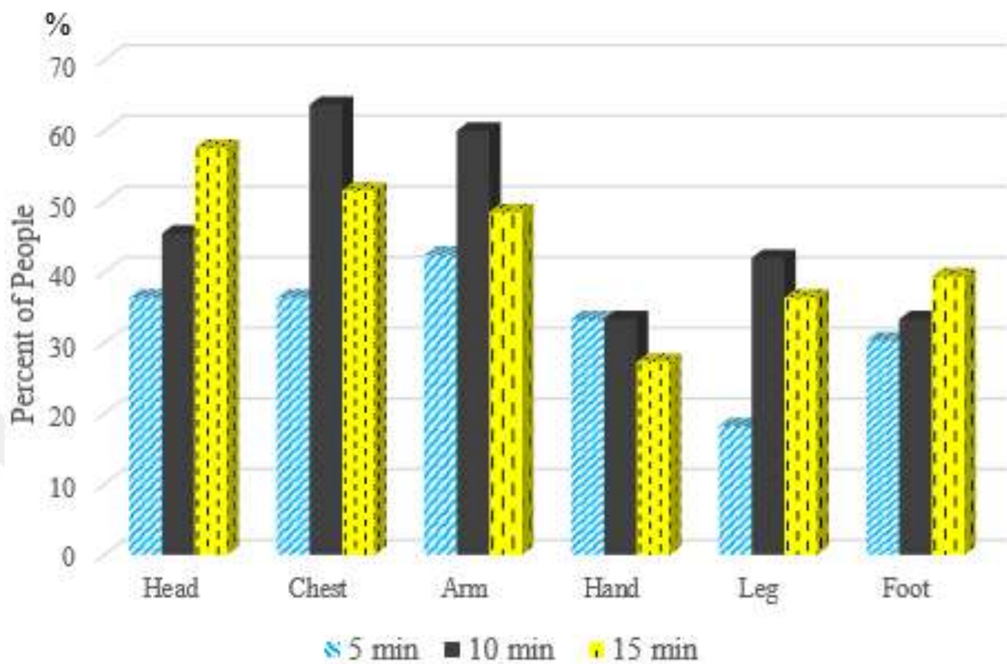


Figure 43. Individual body parts to determining overall thermal comfort (TSV).

These results show that, it is possible to generate thermal comfort by using local thermal hints. Additionally this study shows that with small environmental changes like placing art works or changing the colors of the office rooms and adjusting HVAC systems according to individual body parts could have an impact on human thermal sensation both in the manner of subjective feelings and physical results.

CHAPTER V

CONCLUDING REMARKS

5.1. Conclusion

In this thesis experimental studies were conducted with human participants to analyze the thermal comfort in a built environment. The scope of this thesis is to assess the effects of psychological stimulus on thermal comfort perceptions in different environment scenarios.

In Chapter I, general background was provided about human heat transfer mechanism, metabolism and thermal comfort parameters. Additionally the main heat exchange organ (skin) was described in detail as its structure and contributions on thermal comfort. In the literature review part the mean of thermal comfort is defined and approaches on that as rational method and adaptive method were analyzed. Also it is stated that in this study the calculations of thermal comfort based on air velocity, relative humidity, air temperature, metabolic rate, body surface area and clothing resistance.

In Chapter II, one dimensional heat transfer model of human is given. Accordingly each parameter as internal heat production, respiratory heat loss, evaporative heat loss, and also heat loss by conduction, convection, radiation were explained and formulations were provided according to Fanger method (rational method). It is stated that the model was codded in python and each thermal environment parameter was specified according to calculations. The PMV (predicted mean vote) and PPD (predicted percent dissatisfied) formulations were also given and examined in detail.

In Chapter III, experimental procedures were provided step by step. It is stated that experiments were conducted in three different environment scenarios as uncomfortably hot, uncomfortably cold and comfortable. Adjustments about the experiment were described in three particular recipe as environment's physical conditions, occupant clothing and activity level and psychological mood of the occupant. The details were given about physical conditions of the experiment room as air velocity, air temperature and relative humidity also room properties and dimensions were provided in two dimensional sketch. Measurement devices and results of thermocouples reliability tests were obtained. Occupant's clothing and activity levels were also specified and the mood of the occupant adjusted with IAPS (International Affective Picture System) data. Beside the details of the experiment room, the occupant's anthropometric characteristics were provided. The details of the emotion stimuli protocol were also indicated.

In Chapter IV, The experiment results were provided and analyzed according to individual case conditions within specific body segments (where thermocouples are located). Correspondingly regardless from the participant's personal information, their individual skin temperatures were given. And also the results were assessed according to each measurement point eventually the mean skin temperatures were compared and analyzed according to room conditions. As a consequence from the experiment and subjective sensation questionnaire results the different types of stimuli pictures has an impact on thermal comfort which means that psychological aspects effects on people's thermal sensations.

As a result of this completed study, human thermal perceptions and skin temperatures during different levels of emotion stimuli phases were assessed. Environmental parameters of thermal comfort, air temperature, relative humidity, air velocity and the participants clothing level were recorded and correlated with the Fanger's PMV indices as thermally comfortable, uncomfortably hot and uncomfortably cold. During the experiments, 33 participants were considered and the individual tests were conducted. During the tests, participants watched emotion-stimuli-pictures which were divided according to different categories as unpleasant, non-emotional and pleasant stimuli. During the tests skin temperatures were measured from the four different skin locations (hand top, fingertip, wrist and ankle) of the participants. During each test, TSV questionnaires were asked to be filled by the participants at the completion of each stimuli picture-block. Results were assessed according to the individual test points, stimulus types and room conditions.

According to the study main conclusions were given as fallow.

- Different types of stimuli pictures can influence people's thermal comfort in thermally neutral and hot room conditions which means that psychological aspects effects on people's thermal sensations.
- The most effective body parts according to TSV analyses are head, chest and arms where matches to overall thermal sensation results. This means that local heating or cooling can impact on total body thermal perceptions and the individual comfort.

5.2. Future Works

For the future developments of this study, experiments can be run with more participants and consequently data base can be formed as the relation between the emotion stimuli pictures and current skin temperatures. These pictures can also be used in office spaces or class-room buildings to make participants feel better and more comfortable at times when HVAC system use needs to be reduced. The effect of such changes on PMV value is about 0.5 – 1 unit and this can be correlated with energy use in typical office environment. The relationship between energy consumption and PMV value was explored by Dhaka et al [14], who stated that roughly energy savings can be as high as 10% for every half value change of PMV. The use of the methodology discussed here can be most effective at transitional weather times (such as late spring or early fall days) when use of a centralized HVAC system at full force may not be justified. In addition, this concept can be used at the extreme weather conditions when the heavy operation of HVAC systems is desired to be controlled.

APPENDIX A-1

Experimental Protocol and Design

Experiment Name:	Thermal Comfort
Proposed start - end date:	28.05.2019 - 30.07.2019
Experiment place:	Room #113 (living lab)
Planned frequency:	Monday, Tuesday, Wednesday, Friday in each week
Duration of the experiment:	15 min. preparation and 15min experiment for each subject. Total 30min.
Participants:	physically and mentally healthy (female/male) adults

Objectives of the experiment:

Thermal comfort is a human factor, and it is relative to the environmental fluctuations and psychological moods of people. It also depends on the temperature, relative humidity, and air motion. Since the human body changes its thermal appearance frequently, depending upon on metabolic rate, it is essential to consider the heat transfer at the skin by accounting for radiation, convection, conduction heat transfer. Furthermore, forming a thermally comfortable environment also depends on human feelings. The fluctuations on emotions happen according to the blood flow rate changes which transports heat to the skin. Accordingly, this experiment aims to identify the direct effects of human emotions on thermal comfort

1. To observe changes about human thermal comfort in different mood scales
2. To generate data base about relationship of emotions & thermal comfort

3. At which comfort scale (-2, 0, +2) emotions place significant role on human thermal comfort & thermal sensation.

Description of the experiment:

It is known that comfort is directly related to psychological moods of human therefore, it is significant to identify the instantaneous psychological state of human. By measuring body temperature, the mood of the occupant can be correlated. This way, it can be differentiated whether the increase in body temperature is due to current environment conditions or the psychological moods.

Experimental setup:

Day before the experiment subjects should be notice that, it is essential to sleep well and no drinking alcohol.

Each subject stays only in one environmental conditions and it takes 30min. During the experiment 3 types of pictures pleasant, neutral and unpleasant appears on the screen. Pictures comes with an order as 5min for unpleasant, 5min for neutral, 5min for pleasant.

At the beginning of the experiment and after each 5min subjects fills the PMV questionnaire. Additionally after each 10min subject fills PMV questionnaire for different body segments.

During the experiment temperature measurements from the environment will be measured from 3 different heights near by the subject.

Data from the sensors will be collected from the subject as, skin temperature

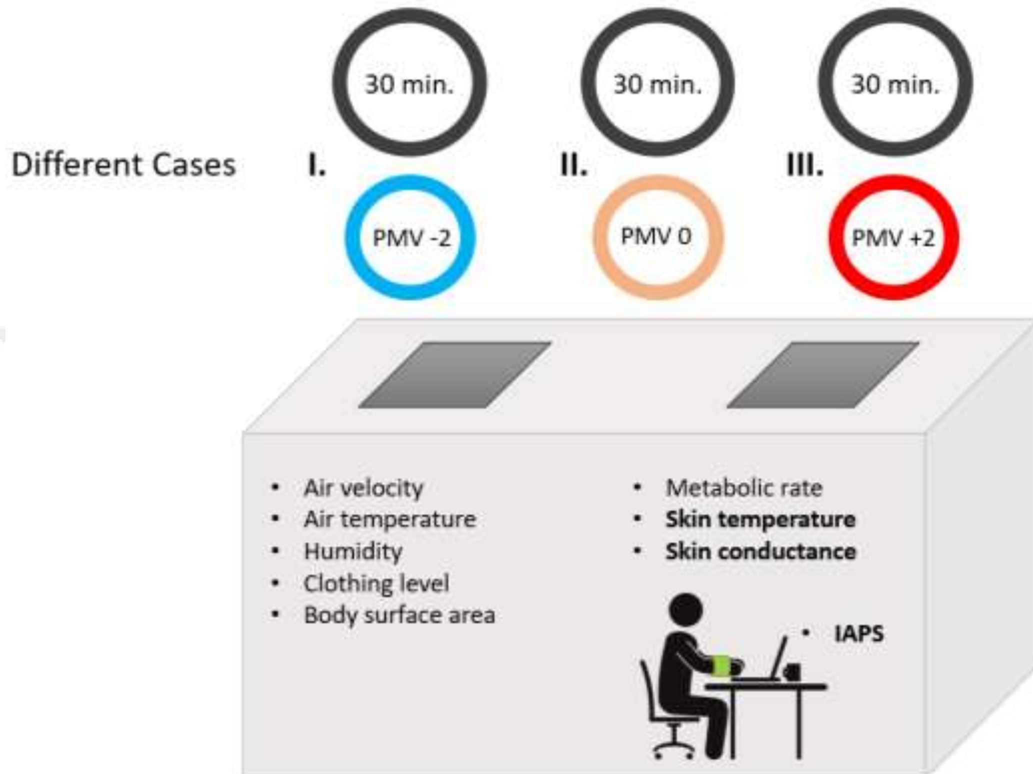


Figure 44. Representation of the experiment room and conditions.

Experimental Procedure:

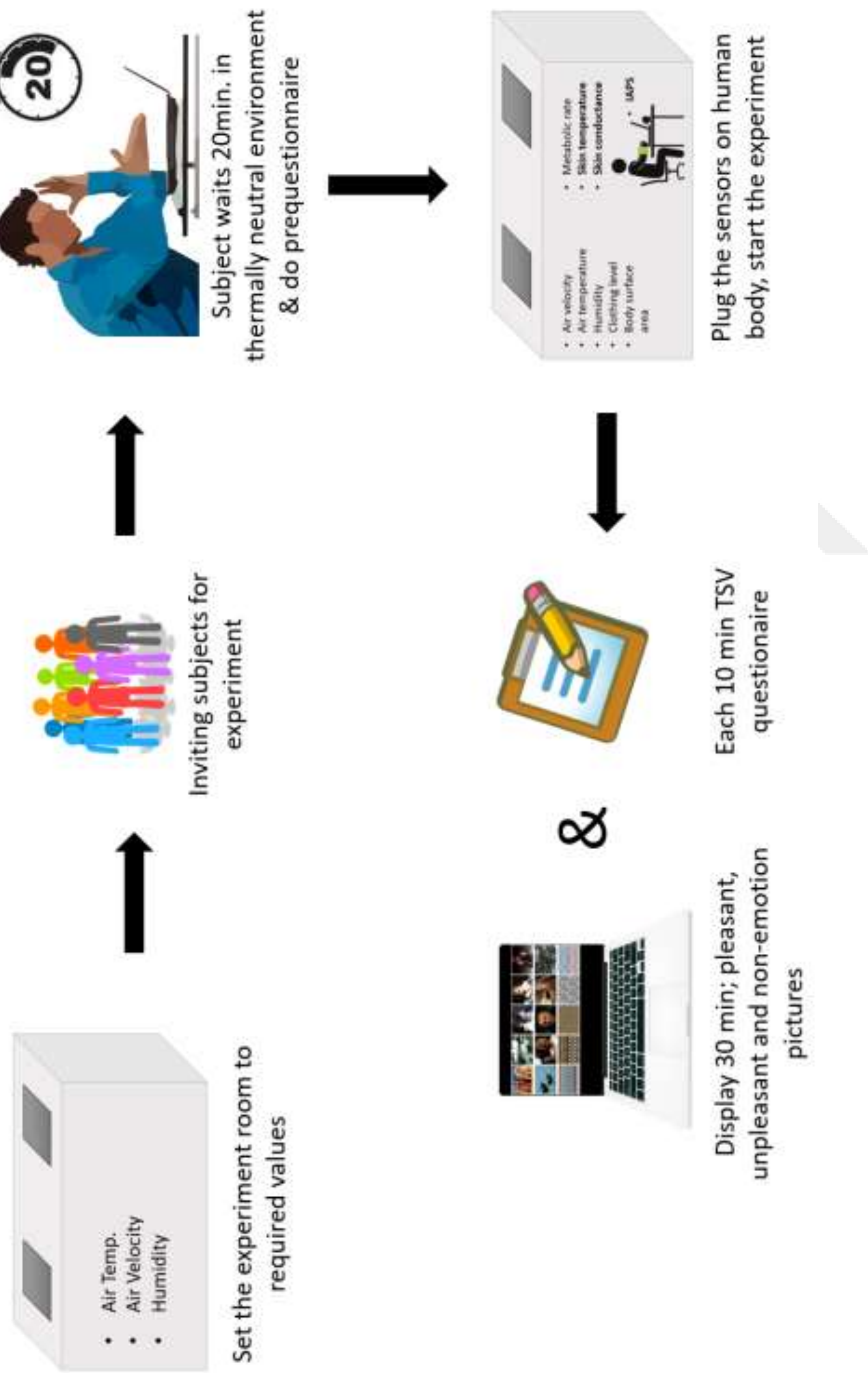


Figure 45. Schematic representation for experiment procedure.

APPENDIX A-2

Experiment Case Conditions in Detail

Pre-conditioned Room

Conditions of thermally neutral environment

- Air temperature 26℃
- Air speed $\leq 0.1 m/s$
- Relative humidity 50%
- Metabolism 1.0met (seated quiet)
- Clothing level 0.5clo (typical summer indoor clothing)

Subjects waits about 15min in thermally neutral environment (pre-experiment room) and let her/him calm down, so we expected to see decrease in heart rate and metabolic rate.

While relaxing subjects do the first questionnaire, thus those data are significant for calculating BMR and body surface area during the experiment.

It is also vital to group people according to their basal metabolic rates.

Case I

In this case room conditions adjusts as uncomfortably cold. The PMV value for the experiment room is became -2.

Experiment Room Conditions for PMV -2

- Air temperature 20.5℃
- Air speed ≤0.1m/s
- Relative humidity 65%
- Metabolism 1.0met (seated quiet)
- Clothing level 0.55clo (typical summer indoor clothing)

Case II

In this case room conditions adjusts as comfortable. The PMV value for the experiment room is became 0.

Experiment Room Conditions for PMV 0

- Air temperature 25.5℃
- Air speed ≤0.1m/s
- Relative humidity 65%
- Metabolism 1.0met (seated quiet)
- Clothing level 0.55clo (typical summer indoor clothing)

Case III

In this case room conditions adjusts as uncomfortably hot. The PMV value for the experiment room is became +2.

Experiment Room Conditions for PMV +2

- Air temperature 31℃
- Air speed ≤0.1m/s
- Relative humidity 75%
- Metabolism 1.0met (seated quiet)
- Clothing level 0.55clo (typical summer indoor clothing)

APPENDIX A-3

Pre-experiment Questionnaire

Name : Date :

Surname :

Gender :

Age :

Height :

Weight :

Please indicate how you generally feel at work / university

Warm ☐ Neutral ☐ Cool ☐

Are you generally satisfied with you thermal environment at work / university?

Yes ☐ No ☐

Please give additional information or comments which you think are relevant to the assessment of your thermal environment at work (open-office, clothing, sun light/radiation, dryness etc.)

APPENDIX A-4

TSV Questionnaire

Please answer the following questions concerned with YOUR THERMAL COMFORT.

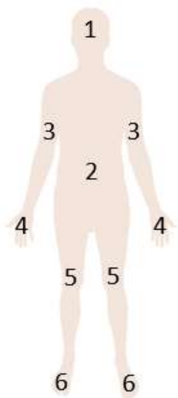
1. Indicate, each 5min, on the below scale how you feel now.

	0min	5min	10min	15min
Hot	☐	☐	☐	☐
Warm	☐	☐	☐	☐
Slightly Warm	☐	☐	☐	☐
Neutral	☐	☐	☐	☐
Slightly Cool	☐	☐	☐	☐
Cool	☐	☐	☐	☐
Cold	☐	☐	☐	☐

2. Indicate, each 5min, how you would like to be now.

	0min	5min	10min	15min
Warmer	☐	☐	☐	☐
No Change	☐	☐	☐	☐
Cooler	☐	☐	☐	☐

3. Indicate, each 5min, that how you feel specifically now.



5, 10, 15 min ...

	head (1)	trunk (2)	arms (3)	hands (4)	legs (5)	feet (6)
Hot						
Warm						
Slightly Warm						
Neutral						
Slightly Cool						
Cool						
Cold						

Thank you.

APPENDIX B-1

Details of Female Participants IAPS Pictures

Pictures are selected according to their valance numbers, higher number of valence refers to positive emotions likewise low valance numbers are considering as negative emotion stimulating pictures.

Slide No	Valence Mean (SD)	Description
2053	2.17(1.90)	Unpleasant Picture
2141	2.27(1.76)	Unpleasant Picture
2276	2.32(1.65)	Unpleasant Picture
2345.1	2.08(1.55)	Unpleasant Picture
2688	2.36(2.06)	Unpleasant Picture
2691	2.30(1.27)	Unpleasant Picture
2710	2.16(1.49)	Unpleasant Picture
2717	2.35(1.22)	Unpleasant Picture
2799	2.21(1.33)	Unpleasant Picture
2900	2.16(1.52)	Unpleasant Picture
3181	2.01(1.29)	Unpleasant Picture
3215	2.22(1.21)	Unpleasant Picture
3300	2.35(1.30)	Unpleasant Picture
6200	2.71(1.43)	Unpleasant Picture
6210	2.15(1.42)	Unpleasant Picture
6220	2.30(1.38)	Unpleasant Picture
6230	2.06(1.59)	Unpleasant Picture
6231	2.15(1.46)	Unpleasant Picture
6250.1	2.12(1.36)	Unpleasant Picture

Slide No	Valence Mean (SD)	Description
6260	2.35(1.45)	Unpleasant Picture
6263	2.06(1.29)	Unpleasant Picture
6311	2.36(1.72)	Unpleasant Picture
6370	2.20(1.31)	Unpleasant Picture
6510	2.06(1.28)	Unpleasant Picture
6550	2.08(1.90)	Unpleasant Picture
6571	2.15(1.65)	Unpleasant Picture
6830	2.31(1.70)	Unpleasant Picture
6831	2.21(1.52)	Unpleasant Picture
6838	2.20(1.34)	Unpleasant Picture
7380	2.31(1.26)	Unpleasant Picture
8230	2.11(1.23)	Unpleasant Picture
8485	2.31(1.42)	Unpleasant Picture
9000	2.33(1.45)	Unpleasant Picture
9006	2.08(1.52)	Unpleasant Picture
9007	2.30(1.51)	Unpleasant Picture
9043	2.10(1.29)	Unpleasant Picture
9184	2.17(1.32)	Unpleasant Picture
9250	2.34(1.28)	Unpleasant Picture
9295	2.31(1.41)	Unpleasant Picture
9320	2.26(1.82)	Unpleasant Picture
9321	2.01(1.32)	Unpleasant Picture
9322	2.02(1.13)	Unpleasant Picture
9419	2.32(1.32)	Unpleasant Picture
9423	2.25(1.34)	Unpleasant Picture
1616	5.21(1.12)	Non-Emotional

Slide No	Valence Mean (SD)	Description
1675	5.24(1.48)	Non-Emotional
2002	4.95(1.36)	Non-Emotional
2018	5.56(1.49)	Non-Emotional
2034	5.90(1.63)	Non-Emotional
2102	5.16(0.96)	Non-Emotional
2122	5.15(1.82)	Non-Emotional
2214	5.01(1.12)	Non-Emotional
2305	5.14(0.86)	Non-Emotional
2308	5.26(1.82)	Non-Emotional
2385	5.15(1.24)	Non-Emotional
2411	5.06(0.89)	Non-Emotional
2484	5.07(1.46)	Non-Emotional
2487	5.28(2.03)	Non-Emotional
2493	5.10(1.37)	Non-Emotional
2495	5.14(1.22)	Non-Emotional
2499	5.35(1.73)	Non-Emotional
2514	5.21(1.22)	Non-Emotional
2635	5.19(1.68)	Non-Emotional
2880	5.22(1.79)	Non-Emotional
2890	5.02(1.10)	Non-Emotional
4006	5.22(1.39)	Non-Emotional
5510	5.10(1.35)	Non-Emotional
5531	5.07(1.38)	Non-Emotional
6311	2.36(1.72)	Non-Emotional
6314	4.25(1.61)	Non-Emotional
7000	5.06(1.10)	Non-Emotional

Slide No	Valence Mean (SD)	Description
7002	5.03(0.98)	Non-Emotional
7003	5.02(1.29)	Non-Emotional
7004	5.14(0.59)	Non-Emotional
7006	5.09(0.81)	Non-Emotional
7009	4.89(0.96)	Non-Emotional
7014	5.16(1.08)	Non-Emotional
7019	5.13(1.24)	Non-Emotional
7033	5.23(1.72)	Non-Emotional
7035	5.15(0.84)	Non-Emotional
7050	5.04(0.87)	Non-Emotional
7053	5.15(0.84)	Non-Emotional
7058	5.00(1.32)	Non-Emotional
7080	5.10(0.88)	Non-Emotional
7100	5.20(1.39)	Non-Emotional
7179	5.01(1.13)	Non-Emotional
7182	5.03(1.38)	Non-Emotional
7255	5.13(1.24)	Non-Emotional
7590	5.18(1.53)	Non-Emotional
1440	8.43(1.44)	Pleasant
1441	8.14(1.33)	Pleasant
1460	8.58(0.76)	Pleasant
1463	7.81(1.96)	Pleasant
1600	7.80(1.44)	Pleasant
1610	8.39(0.91	Pleasant
1620	7.95(1.19)	Pleasant
1710	8.59(0.99)	Pleasant

Slide No	Valence Mean (SD)	Description
1750	8.59(0.75)	Pleasant
1811	7.95(1.51)	Pleasant
1920	7.94(1.61)	Pleasant
2040	8.74(0.64)	Pleasant
2045	8.17(1.21)	Pleasant
2057	8.39(0.94)	Pleasant
2058	8.24(1.07)	Pleasant
2070	8.50(1.28)	Pleasant
2071	8.21(1.29)	Pleasant
2075	7.85(1.57)	Pleasant
2080	8.09(1.47)	Pleasant
2091	8.26(1.17)	Pleasant
2150	8.31(1.49)	Pleasant
2151	7.88(1.11)	Pleasant
2154	8.17(1.10)	Pleasant
2160	8.16(1.28)	Pleasant
2165	8.29(1.17)	Pleasant
2274	7.96(1.15)	Pleasant
2311	7.96(1.15)	Pleasant
2314	7.96(1.17)	Pleasant
2332	7.94(1.39)	Pleasant
2340	8.34(1.10)	Pleasant
2341	7.82(1.57)	Pleasant
2347	8.35(0.98)	Pleasant
2360	8.20(1.59)	Pleasant
2388	8.10(1.15)	Pleasant

Slide No	Valence Mean (SD)	Description
2395	8.31(1.12)	Pleasant
2540	8.34(1.10)	Pleasant
2550	8.14(1.53)	Pleasant
2660	8.18(1.24)	Pleasant
4622	8.17(1.23)	Pleasant
4626	7.80(1.76)	Pleasant
5210	8.26(0.96)	Pleasant
5600	7.83(1.28)	Pleasant
5621	7.80(1.54)	Pleasant
5760	8.41(1.07)	Pleasant
5811	7.88(1.24)	Pleasant

APPENDIX B-2

Details of Male Participants IAPS Pictures

Pictures are selected according to their valance numbers, higher number of valence refers to positive emotions likewise low valance numbers are considering as negative emotion stimulating pictures.

Slide No	Valence Mean (SD)	Description
2053	2.78(1.80)	Unpleasant Picture
2095	2.16(1.31)	Unpleasant Picture
2141	2.72(1.39)	Unpleasant Picture
2205	2.24(1.93)	Unpleasant Picture
2301	2.93(1.28)	Unpleasant Picture
2345.1	2.52(1.28)	Unpleasant Picture
2703	2.33(1.53)	Unpleasant Picture
2717	2.83(1.40)	Unpleasant Picture
2800	2.31(1.36)	Unpleasant Picture
3101	2.23(1.28)	Unpleasant Picture
3103	2.70(1.40)	Unpleasant Picture
3160	2.73(1.12)	Unpleasant Picture
3180	2.27(1.33)	Unpleasant Picture
3181	2.79(1.54)	Unpleasant Picture
3191	2.39(1.37)	Unpleasant Picture
3195	2.56(1.38)	Unpleasant Picture
3215	2.85(1.38)	Unpleasant Picture
3220	2.59(1.28)	Unpleasant Picture
3301	2.33(1.69)	Unpleasant Picture

Slide No	Valence Mean (SD)	Description
3350	2.00(1.62)	Unpleasant Picture
3500	2.50(1.24)	Unpleasant Picture
3550	3.10(1.76)	Unpleasant Picture
6021	2.75(1.81)	Unpleasant Picture
6022	2.62(1.82)	Unpleasant Picture
6212	2.59(1.47)	Unpleasant Picture
6230	2.73(1.48)	Unpleasant Picture
6231	2.98(1.53)	Unpleasant Picture
6243	2.80(1.61)	Unpleasant Picture
6250	2.98(1.97)	Unpleasant Picture
6311	2.82(1.33)	Unpleasant Picture
6312	2.88(1.48)	Unpleasant Picture
6313	2.43(1.42)	Unpleasant Picture
6315	2.94(1.89)	Unpleasant Picture
6350	2.39(1.42)	Unpleasant Picture
6360	2.63(1.70)	Unpleasant Picture
6510	2.86(1.76)	Unpleasant Picture
6520	2.45(1.43)	Unpleasant Picture
6530	2.86(1.94)	Unpleasant Picture
6540	2.53(1.84)	Unpleasant Picture
6560	2.57(1.49)	Unpleasant Picture
6563	2.19(1.55)	Unpleasant Picture
6570	2.29(1.84)	Unpleasant Picture
6821	2.96(1.93)	Unpleasant Picture
6831	2.98(1.39)	Unpleasant Picture
6838	2.88(1.51)	Unpleasant Picture

Slide No	Valence Mean (SD)	Description
1101	3.52(1.85)	Non-Emotional
1310	4.05(1.49)	Non-Emotional
1726	4.34(2.13)	Non-Emotional
1935	5.17(1.32)	Non-Emotional
1945	5.21(1.53)	Non-Emotional
2032	5.14(0.85)	Non-Emotional
2038	5.08(1.19)	Non-Emotional
2220	5.21(1.34)	Non-Emotional
2273	5.16(1.36)	Non-Emotional
2308	5.17(1.33)	Non-Emotional
2309	5.12(1.60)	Non-Emotional
2394	5.36(1.29)	Non-Emotional
2411	5.10(0.80)	Non-Emotional
2487	5.09(1.41)	Non-Emotional
2495	5.35(0.86)	Non-Emotional
2499	5.33(1.01)	Non-Emotional
2514	5.15(0.85)	Non-Emotional
2518	5.38(1.57)	Non-Emotional
2745.1	5.22(0.89)	Non-Emotional
2749	5.15(1.18)	Non-Emotional
2770	5.12(1.39)	Non-Emotional
2780	4.75(1.33)	Non-Emotional
3302	5.00(2.18)	Non-Emotional
3550.2	5.28(1.19)	Non-Emotional
5390	5.13(1.56)	Non-Emotional
5395	5.34(1.24)	Non-Emotional

Slide No	Valence Mean (SD)	Description
5510	5.20(1.52)	Non-Emotional
5520	5.28(1.74)	Non-Emotional
5530	5.33(1.64)	Non-Emotional
5531	5.24(1.54)	Non-Emotional
5533	5.12(1.29)	Non-Emotional
6150	5.17(1.13)	Non-Emotional
7034	5.00(1.10)	Non-Emotional
7036	5.08(1.02)	Non-Emotional
7044	5.10(1.08)	Non-Emotional
7045	5.14(0.43)	Non-Emotional
7057	5.27(1.19)	Non-Emotional
7059	5.04(0.66)	Non-Emotional
7081	5.00(1.20)	Non-Emotional
7092	5.00(0.84)	Non-Emotional
7100	5.29(0.92)	Non-Emotional
7283	5.12(1.60)	Non-Emotional
7461	5.17(1.87)	Non-Emotional
7632	5.05(1.56)	Non-Emotional
8001	5.09(1.63)	Non-Emotional
8465	5.24(1.29)	Non-Emotional
1440	8.43(1.44)	Pleasant Picture
1441	8.14(1.33)	Pleasant Picture
1460	8.58(0.76)	Pleasant Picture
1710	8.59(0.99)	Pleasant Picture
1750	8.59(0.75)	Pleasant Picture
1920	7.94(1.61)	Pleasant Picture

Slide No	Valence Mean (SD)	Description
2030	6.02(1.48)	Pleasant Picture
2040	8.74(0.64)	Pleasant Picture
2045	8.17(1.21)	Pleasant Picture
2050	8.62(0.85)	Pleasant Picture
2070	8.50(1.28)	Pleasant Picture
2071	8.21(1.29)	Pleasant Picture
2080	8.46(1.20)	Pleasant Picture
2150	7.88(1.11)	Pleasant Picture
2154	8.17(1.10)	Pleasant Picture
2260	7.63(1.60)	Pleasant Picture
2340	7.65(1.36)	Pleasant Picture
2398	7.52(1.18)	Pleasant Picture
4002	7.69(1.48)	Pleasant Picture
4007	7.70(1.53)	Pleasant Picture
4008	7.75(1.54)	Pleasant Picture
4085	8.00(1.14)	Pleasant Picture
4090	7.64(1.26)	Pleasant Picture
4150	7.80(1.36)	Pleasant Picture
4180	8.21(1.34)	Pleasant Picture
4220	8.02(1.37)	Pleasant Picture
4232	7.88(1.10)	Pleasant Picture
4659	7.70(1.64)	Pleasant Picture
4660	7.63(1.30)	Pleasant Picture
4670	7.77(1.05)	Pleasant Picture
4680	7.73(1.61)	Pleasant Picture
5210	7.64(1.19)	Pleasant Picture

Slide No	**Valence Mean (SD)**	**Description**
5700	7.70(1.36)	Pleasant Picture
5760	7.69(1.28)	Pleasant Picture
5825	8.05(0.86)	Pleasant Picture
5833	8.15(1.19)	Pleasant Picture
7200	7.50(1.78)	Pleasant Picture
8080	7.73(1.25)	Pleasant Picture
8170	7.67(1.44)	Pleasant Picture
8180	7.50(1.74)	Pleasant Picture
8190	8.13(1.29)	Pleasant Picture
8300	7.54(1.38)	Pleasant Picture
8420	7.61(1.61)	Pleasant Picture
8499	7.51(1.47)	Pleasant Picture
8501	8.14(1.24)	Pleasant Picture
8370	7.67(1.19)	Pleasant Picture

APPENDIX C.

Codes of Thermal Comfort Equations

Codes are written in Python according to Fanger's thermal comfort equations. Each heat loss parameter was specified individually and overall thermal comfort and PMV were given in the last part.

```
#Heat loss by water vapor diffusion
def diff_skin(lambdaa,Pa,A_du,Ts):
        m = 6.1*(10**(-4)) # skin permeance (kg/h m^2 mmHg)
        Ps = 1.92*Ts-25.3
        Ed = lambdaa*m*A_du*(Ps-Pa)
        return Ed

#Sweat rate
def sweat_rate(H,A_du):
        Esw = 0.42*A_du*(H-50)
        return Esw

#Heat loss by latent respiration
def latent_res(Wex,Wa,lambdaa):
        V = 0.0060*M # Ventilation
        Ere = V*(Wex-Wa)*lambdaa
        return Ere

#Heat loss by dry respiration
def dry_res(Ta,Wa,M):
        Tex = 32.6 + 0.066*Ta + 32*Wa
        Ldry = 0.0014*M*(Tex-Ta)
        return Ldry

#Conduction
def conduction(A_du,Ts,Tcl,Icl):
        K = (A_du*(Ts-Tcl))/(0.18*Icl)
        return K
```

```
#Radiation
def radiation(Tcl,fcl,Tmrt):
	feff = 0.71
	Aeff = feff*fcl*A_du
	epsilon = 0.97
	ro = 4.96*10**(-8) #stefan-boltzmann constant
	R = Aeff * epsilon * ro * ( ((Tcl+273)**4)-((Tmrt+273)**4) )
	return R

#Convection
def convection(Tcl,Ta,vair,A_du,fcl):
	dummy1 = 2.05*(abs(Tcl-Ta)**(0.25))
	dummy2 = 10.4*((vair)**0.5)
	if (vair <= 0.1):
		hc = dummy1
	else:
		if (dummy1 > dummy2):
			hc = dummy1
		else:
			hc = dummy2

	C = A_du * fcl * hc * (Tcl-Ta)
	return C

#Thermal Load
def thermalload(M,A_du,Pa,Ta,fcl,Tcl,Tmrt,vair):
	dummy1 = 2.05*(abs(Tcl-Ta)**(0.25))
	dummy2 = 10.4*((vair)**0.5)
	if (vair <= 0.1):
		hc = dummy1
	else:
		if (dummy1 > dummy2):
			hc = dummy1
		else:
			hc = dummy2

	L = (M/A_du) - 0.35*(43-0.061*(M/A_du)-Pa) - 0.42*((M/A_du)-50) -
0.0023*(M/A_du)*(44-Pa) - 0.0014*(34-Ta) - (3.4*10**(-8))*fcl*( ((Tcl+273)**4) -
((Tmrt+273)**4) ) - fcl*hc*(Tcl-Ta)
	return L
```

```
#PMV
def comfortlvl(M,A_du,Pa,Ta,fcl,Tcl,Tmrt,vair):
	dummy1 = 2.05*(abs(Tcl-Ta)**(0.25))
	dummy2 = 10.4*((vair)**0.5)
	if (vair <= 0.1):
		hc = dummy1
	else:
		if (dummy1 > dummy2):
			hc = dummy1
		else:
			hc = dummy2

	PMV = ( 0.352*(2.72**(-0.042*(M/A_du))) + 0.032 ) * ( (M/A_du) - 0.35*(43-
0.061*(M/A_du)-Pa) - 0.42*((M/A_du)-50) - 0.0023*(M/A_du)*(44-Pa) - 0.0014*(34-Ta) -
(3.4*10**(-8))*fcl*( ((Tcl+273)**4) - ((Tmrt+273)**4) ) - fcl*hc*(Tcl-Ta) )
	return PMV


#PPD
def percentpd(exp,PMV):
	a = 0.03353*PMV**4
	b = 0.2179*PMV**2
	PPD = 100 - 95*exp**(-1*(a+b))
	return PPD

#User inputs
mass = 80 #float(input("Please enter your weight in kg = "))
height = 1.80 #float(input("Please enter your height in m = "))
RH = 65
#RH = float(input("Please enter Relative Humidity = "))
#In graphics RH kept 50 as constant
A_du = 0.202*(pow(mass,0.425))*(pow(height,0.725))

#Constant inputs
exp = 2.71828183
lambdaa = 575 # (kcal/kg) average calculated from table
fcl = 1 # for Nude - Short
Ta = 24 # Air temperature
Icl = 0.6 # Clothing level
Pv = 23.7735 #mmHg Taken from table according to temperature
Pa = (RH*Pv)/100
vair = 0.1
Tmrt = 26.5 # Kept constant for changing Vair and Ta values
```

```
#Inputs
H = 50*A_du # Activity [Seated = 50, Standing = 60]
M = H
Ts = 35.7-0.032*(H/A_du) # Skin temperature
Wa = 0.0083*Pa # Moisture content of breathing air
Wex = 0.029 - 0.000066*Pa + Wa # Moisture content of exhaled air
Tcl = Ts-0.18*Icl*( (M/A_du)-0.35*(43-(0.061*M/A_du)-Pa)-0.42*((M/A_du)-50)-
0.0023*(M/A_du)*(44-Pa)-0.0014*(M/A_du)*(34-Ta) )

#Display

PMV = comfortlvl(M,A_du,Pa,Ta,fcl,Tcl,Tmrt,vair)
#print('PMV = ', PMV)

PPD = percentpd(exp,PMV)
#print('PPD = ', PPD)
```

APPENDIX D.

- **Results from Ankle (foot) in hot room**

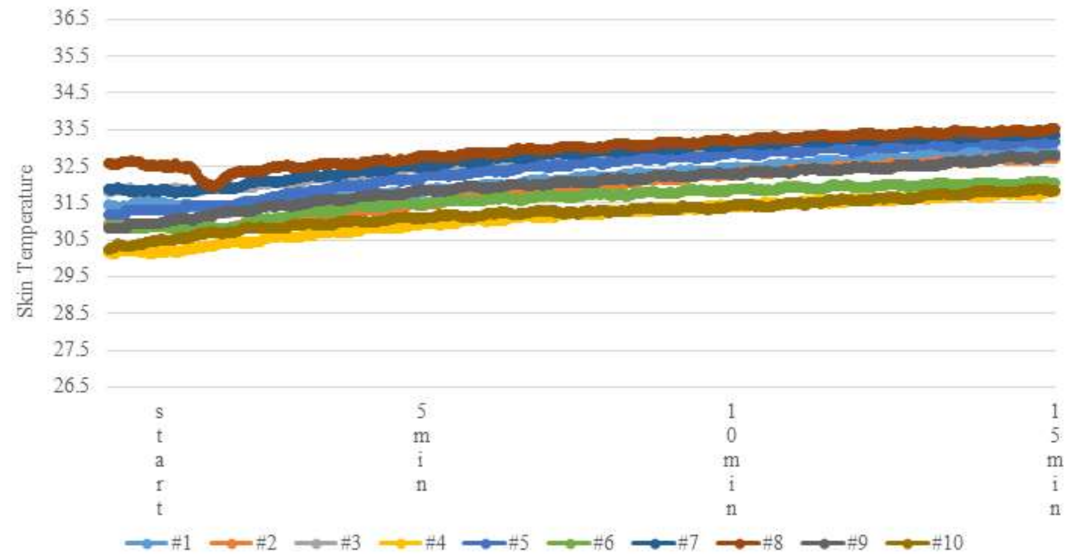


Figure 46. Time vs skin temperature changes of participants at ankle.

- **Results from Finger Tip in hot room**

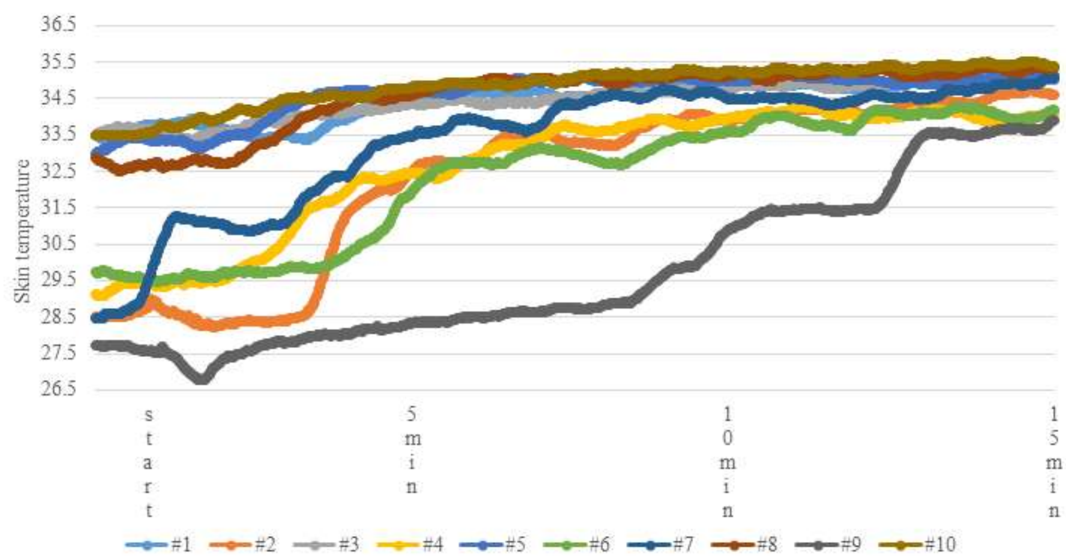


Figure 47. Time vs Skin temperature changes of participants in at finger.

- **Results from Wrist in hot room**

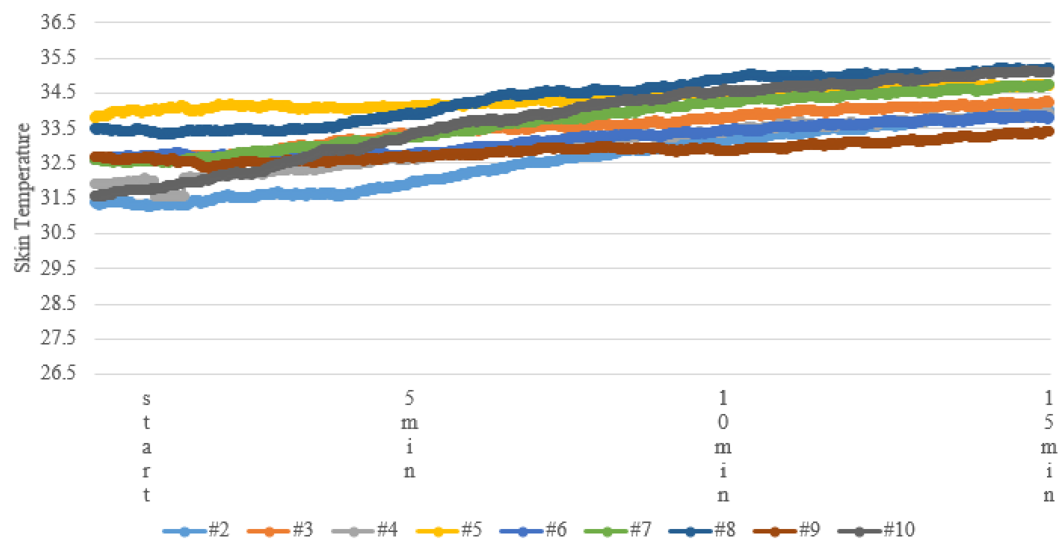


Figure 48. Time vs skin temperature changes of participants at wrist.

- **Results from Hand Top in hot room**

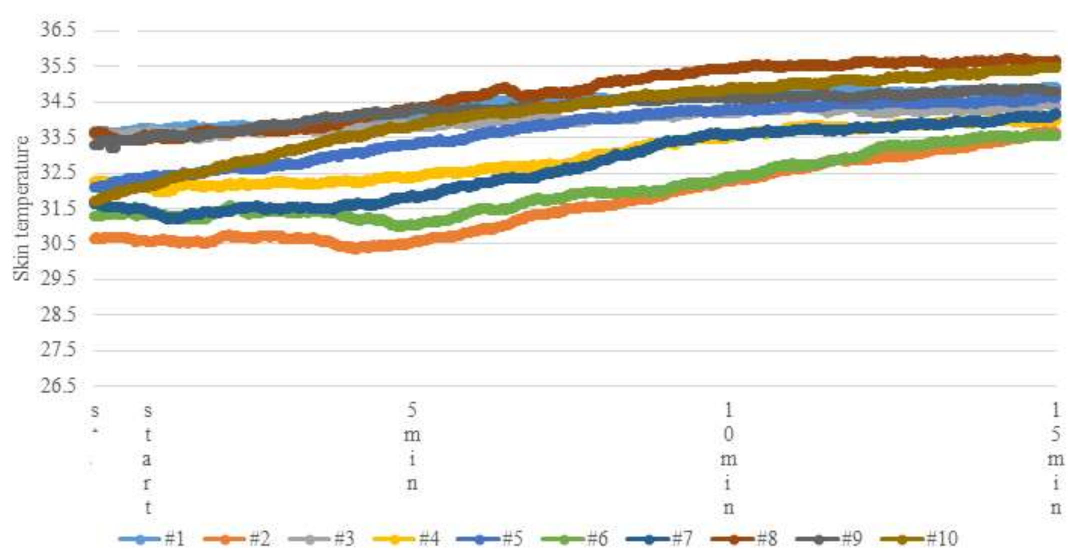


Figure 49. Time vs skin temperature changes of participants at Hand Top.

- **Results from Ankle in cold room**

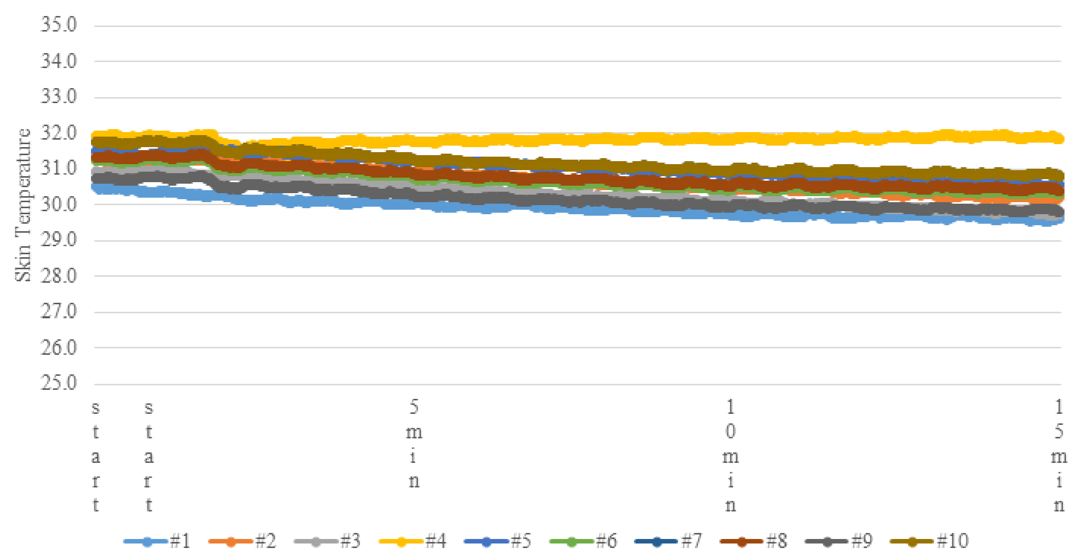


Figure 50. Time vs skin temperature changes of participants at ankle.

- **Results from Finger Tip in cold room**

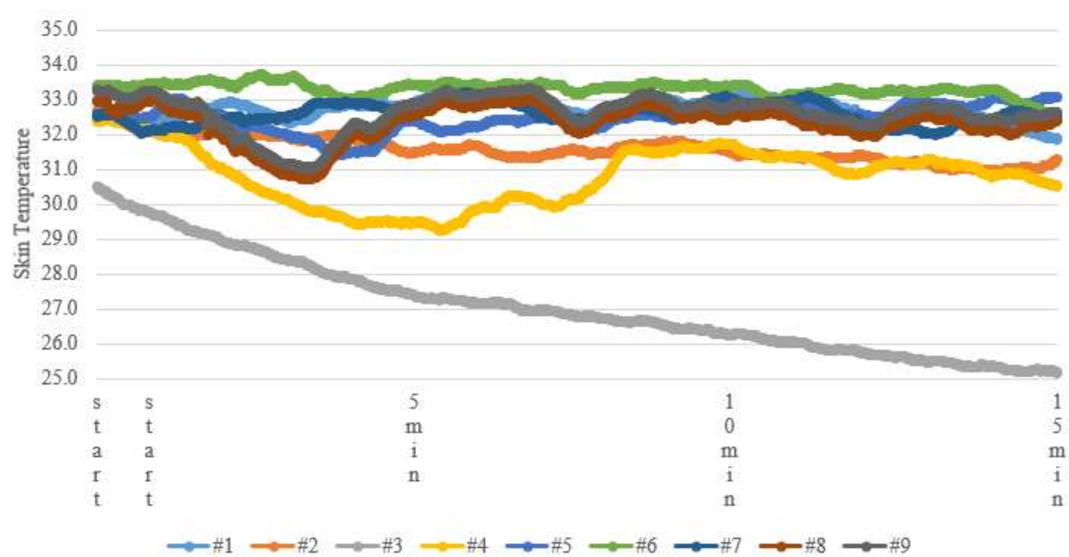


Figure 51. Time vs skin temperature changes of participants at Finger Tip.

- **Results from Wrist in cold room**

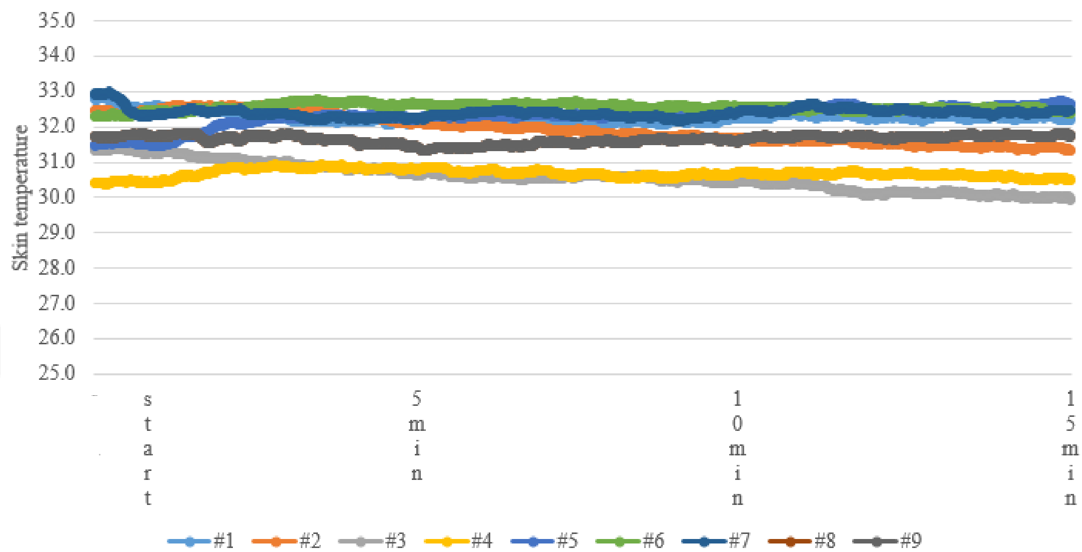


Figure 52. Time vs skin temperature changes of participants at Wrist.

- **Results from Hand in cold room**

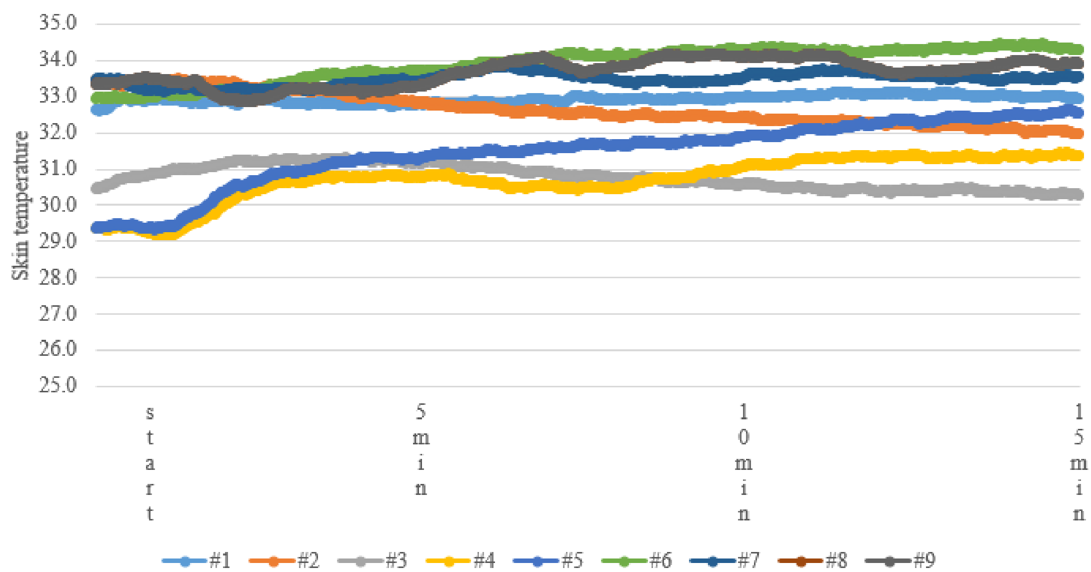


Figure 53. Time vs skin temperature changes of participants at Hand Top.

- **Results of Foot Thermocouple, at PMV 0**

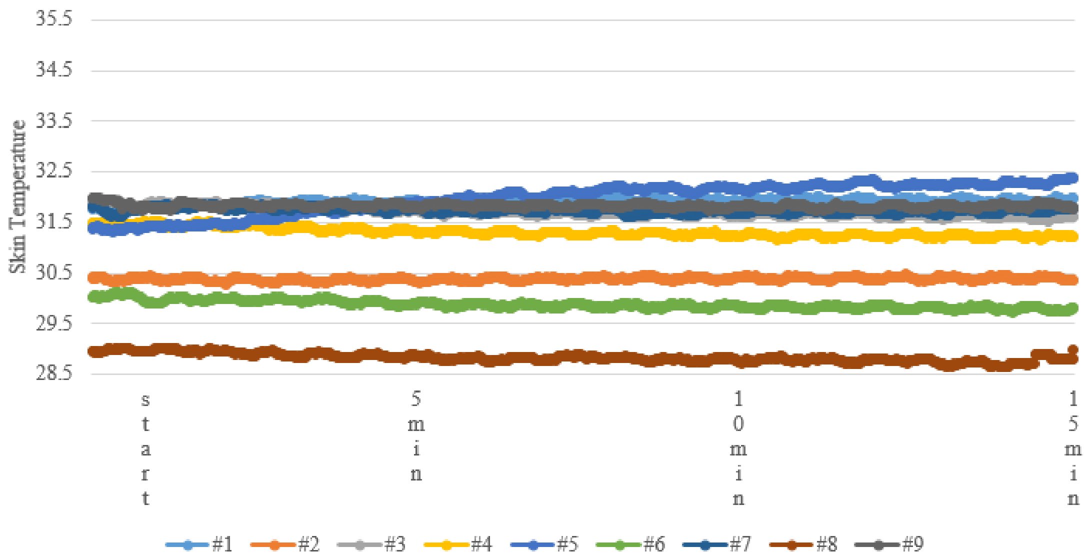


Figure 54. Time vs skin temperature changes of participants at Ankle.

- **Results of Finger Tip Thermocouple, at PMV 0**

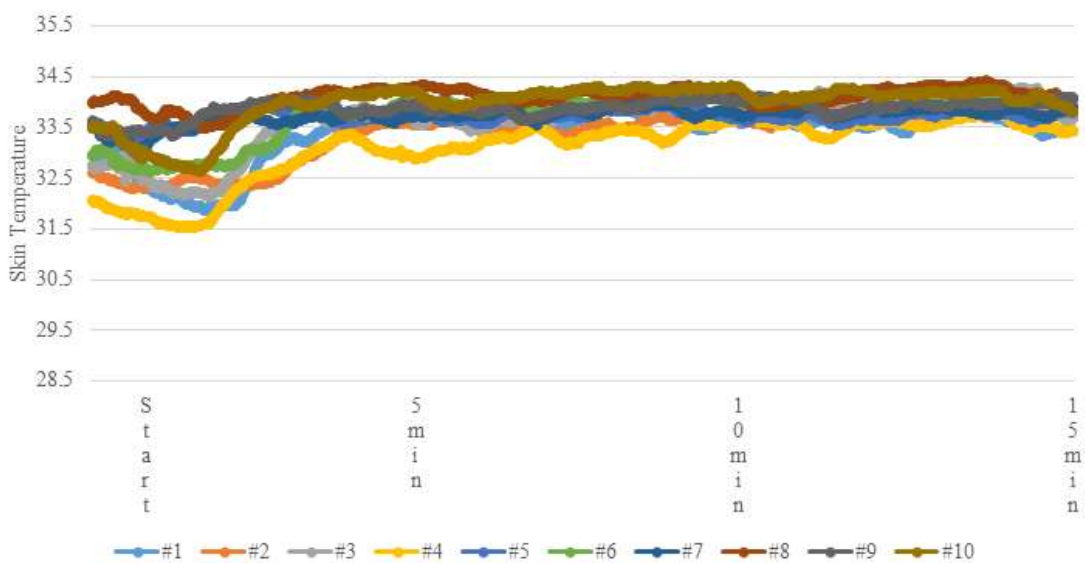


Figure 55. Time vs skin temperature changes of participants at Finger Tip.

- **Results of Wrist Thermocouple, at PMV 0**

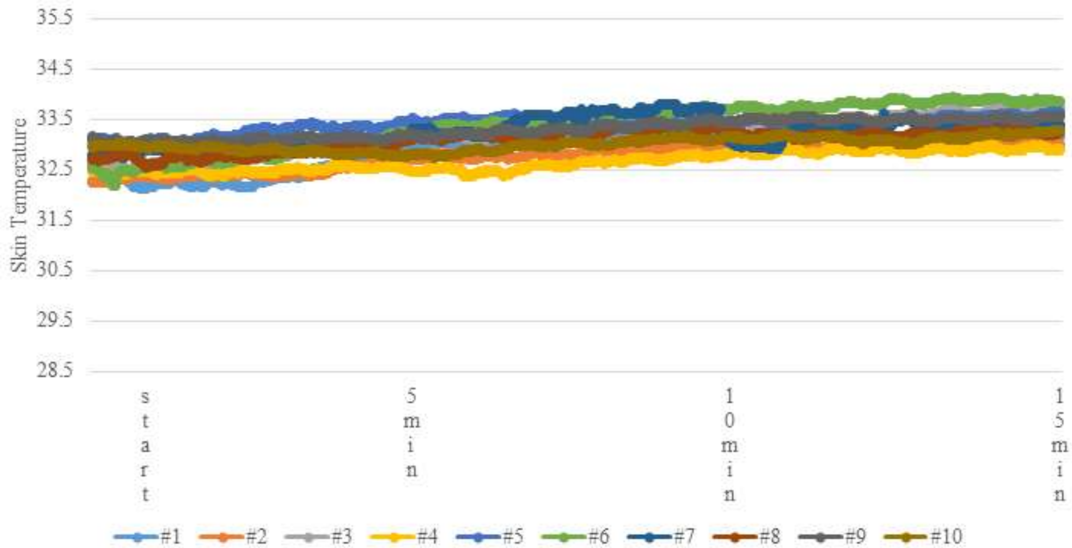


Figure 56. Time vs skin temperature changes of participants at Wrist.

- **Results of Hand Top Thermocouple, at PMV 0**

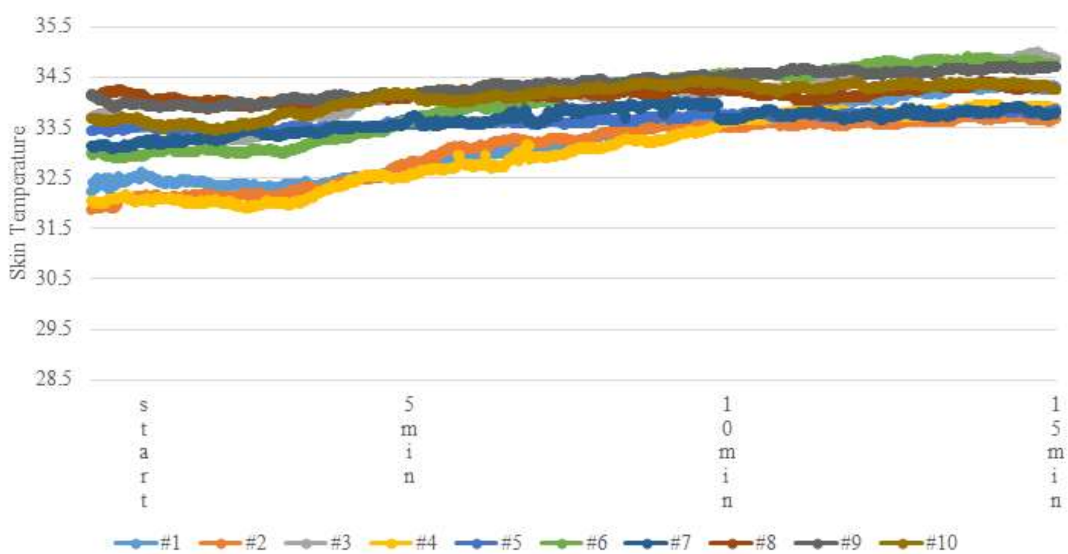


Figure 57. Time vs skin temperature changes of participants at Hand Top.

APPENDIX E.

During unpleasant, neutral and pleasant stimuli pictures location pairwise comparisons are given in Figure 59, 60, 61.

Sample1-Sample2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj.Sig.
Foot-Writs	-38,350	8,977	-4,272	,000	,000
Foot-Finger	-40,417	8,977	-4,502	,000	,000
Foot-Hand top	-46,967	8,977	-5,232	,000	,000
Writs-Finger	2,067	8,977	,230	,818	1,000
Writs-Hand top	-8,617	8,977	-,960	,337	1,000
Finger-Hand top	-6,550	8,977	-,730	,466	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is ,05.

Figure 58. Pairwise comparison of measurement places during unpleasant stimuli pictures from Chi Square analyses.

Sample1-Sample2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj.Sig.
Foot-Writs	-35,683	8,978	-3,975	,000	,000
Foot-Finger	-49,750	8,978	-5,542	,000	,000
Foot-Hand top	-50,900	8,978	-5,670	,000	,000
Writs-Finger	14,067	8,978	1,567	,117	,703
Writs-Hand top	-15,217	8,978	-1,695	,090	,541
Finger-Hand top	-1,150	8,978	-,128	,898	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is ,05.

Figure 59. Pairwise comparison of measurement places during non-emotional stimuli pictures from Chi Square analyses.

Sample1-Sample2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj.Sig.
Foot-Writs	-35,200	8,977	-3,921	,000	,001
Foot-Finger	-47,583	8,977	-5,301	,000	,000
Foot-Hand top	-54,083	8,977	-6,025	,000	,000
Writs-Finger	12,383	8,977	1,379	,168	1,000
Writs-Hand top	-18,883	8,977	-2,104	,035	,212
Finger-Hand top	-6,500	8,977	-,724	,469	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is ,05.

Figure 60. Pairwise comparison of measurement places during pleasant stimuli pictures from Chi Square analyses.

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APPENDIX F.

İNSAN ARAŞTIRMALARI ETİK KURULU
TOPLANTI TUTANAĞI

TOPLANTI SAYISI	:	**2019/8**
TOPLANTI TARİHİ	:	9.7.2019
TOPLANTI YERİ	:	Özyeğin Üniversitesi
KATILANLAR	:	Prof. Dr. G. Canan Ergin Dr. Sibel Oktar Thomas Dr. Ceren Hayran Şanlı

ARAŞTIRMA ETİK KURULU
PROJE BAŞVURU FORMU (FORM A)

Projenin Adı	Thermal Comfort
Proje Yürütücüsü	Danışman Öğretim Görevlisi: Prof. Dr. M. Pınar MENGÜÇ Elif Gizem TUNÇEL
Proje Yürütücüsünün İletişim Bilgileri	Elif Gizem TUNÇEL • +(90) 537 504 1096 • Gizem.tuncel@ozu.edu.tr
Projeye Katılan Diğer Araştırmacılar	-
Projenin Süresi (Başlangıç ve Bitiş Tarihi)	Proje başlangıç: 10.07.2019 Proje bitiş: 10.09.2019
Araştırmanın Amacı ve Özeti	Proje; insan-bina etkileşimini ısıl konfor açısından ele almaktadır. Deney ortamının fiziksel özellikleri araştırmacı tarafından önceden belirlenen bir ortamda, insanın psikolojik değişikliklerinin ısıl duyarlılığa olan etkisini gözlemlemeyi amaçlamaktadır. Yanı sıra projede, insan termal konforu, ısı transferi denklemleri aracılığıyla matematiksel olarak hesaplanabilmekte ve bununla birlikte insanın fizyolojik farklılıkları ve psikolojik durumları ile beraber de ele alınarak bir veri tabanı oluşturulması hedeflenmektedir.

Ç. CHS. SO.

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Araştırmanın Yöntemi	Ortam Koşulları: Projede ortamın sıcaklık ve bağıl nem değerleri, 3 farklı yükseklikten sensörler aracılığıyla toplanmaktadır. Isıtma ve soğutma sisteminin hava hızı en düşük seviyede çalıştırıldığından dolayı, hava hızı 0.1m/s 'den düşük kabul edilmektedir. Katılımcının deney günü tercih ettiği kıyafet, sıcaklık algısını değiştireceğinden, kıyafetler için ısı iletim bilgisi Ek.3'deki tabloya göre belirlenecektir. Deney Katılımcıları: Katılımcılar, fiziksel ve metal olarak sağlıklı kadın, erkek yetişkinlerden oluşmaktadır. Katılımcılara okulun SONA sistemi ve/veya öğrenci mailleri üzerinden ulaşmak hedeflenmekte ve gönüllülük esası ile katılımları beklenmektedir. Katılımcılar deney süresince, 26 inç bir ekranda IAPS (International Effective Picture System)'den alınan resimleri sırası ile 5dk boyunca 2.30-2.70 değerlik rahatsız edici resimler, sonraki 5dk boyunca 4.85-5.50 değerlik nötr resimler ve deneyin son 5dk'sı boyunca da 7.50-9.00 değerlik rahatlatıcı resimler olarak izleyeceklerdir. Her bir resim öncesi 2snlik uyarı ekranı ardından 6sn boyunca resim gösterilecektir. Ölçüm: katılımcıların deri sıcaklık değerlerini anlık olarak deri üzerindeki 4 farklı noktadan (el üzeri, el parmak ucu, kol üzeri, boyun) sıcaklık sensörleri aracılığı ile ölçülecektir. Bu sensörlerin bir ucu bilgisayara bir ucu katılımcıya bağlı olacak şekilde deney boyunca üzerlerinde kalacaktır. Bu sensörler yalnızca sıcaklık ölçmekte ve +- 0.01°C hassaslığa sahip sensörlerdir. Ek olarak deney süresince deri sıcaklığı ile bağlantısını saptamak için bilek üzerinden anlık kalp ritmi de ölçülecektir. Deney esnasında katılımcılardan her 5dk da bir olmak üzere kişisel termal konfor analizlerini önceden hazırlanmış olan bir anket üzerine işaretleme yaparak belirtmeleri istenecektir (Ek.)
Etik ve Veri Yönetim Planı	Deney sonuçları kişilere bağlı olarak saklanmayacak ve yorumlanmayacaktır. Her bir kontrol grubundan çıkan veriler bir havuzda toplanarak istatistiksel olarak yorumlanacaktır.
Katılımcı Özellikleri	Katılımcılar, fiziksel ve mental olarak sağlıklı yetişkin kadın ve erkeklerden oluşacaktır. Katılımcıların, deneyden bir gün önce fazla kafein ve alkol tüketmesi ve deney günü uykusuz olması deney sonuçlarını etkileyeceğinden deneye çağırı metninde bu konu hakkında

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	bilgilendirilecek ve deneye katılacak kişilere deneyden bir gün önce hatırlatma yapılacaktır. Planlanan katılımcı sayısı her bir kontrol grubu için 30 kişi olmak üzere toplam 90 kişi olarak hesaplanmıştır.
Araştırma Bütçesi ve Kaynakları	Araştırma projesi mevcut laboratuvar ekipmanları ile yapılacağından, ek bir bütçeye ihtiyaç duyulmamıştır.

Özyeğin Üniversitesi Makine Mühendisliği Bölümü öğretim üyesi Prof. Dr. M. Pınar Mengüç'ün yürütücülüğünü üstleneceği "Thermal Comfort" başlıklı proje değerlendirilmiştir.

Proje etik açısından uygun bulunmuştur. ☒
Projenin etik açısından geliştirilmesi gerekmektedir. ☐
Proje etik açısından uygun bulunmamıştır. ☐

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