

# ASSOCIATIONS BETWEEN THERMAL PERCEPTION AND PHYSIOLOGICAL INDICATORS UNDER MODERATE THERMAL STRESS

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## ABSTRACT

This study reports the findings from subjective responses of tropically-acclimatized people and their relationships with cutaneous indicators at three air temperatures, i.e. 20.0, 23.0, and 26.0°C. A blind intervention study was conducted in a simulated office environment. Ninety-six subjects were recruited and divided into 6 groups of 16 subjects. Each group was asked to perform simulated office tasks in the room for a continuous four-hour session. The subjects also completed surveys on general thermal comfort and sensations at various body locations. Measurement of skin temperature was carried out at five locations of the body, i.e. forehead, upper arm, hand, back, and foot, while sweat rate was measured at the upper arm. Correlation analysis was performed on both the subjective and physiological data. Subjects were unable to maintain thermal neutrality during the four-hour exposure at 20.0 and 23.0°C ( $P < 0.0001$ ). They felt most comfortable at 23.0°C ( $P < 0.0001$ ) despite reporting a slightly cool thermal sensation. Reduction of skin temperature was more profound at the extremities of the body, i.e. the hand and foot, under exposure of 20.0°C. Mean skin temperature appeared to be a strong predictor of the body thermal sensation.

## KEYWORDS

Thermal sensation, Skin temperature, Sweat rate, Blind intervention, Tropics

## INTRODUCTION

Thermal equilibrium for comfort is generally achieved when a person is able to maintain body thermal neutrality through thermoregulatory controls (Fanger 1970). Under moderate thermal stress, the body core temperature changes are unlikely to be large enough to evoke thermal discomfort (Hardy 1970), thus, thermal sensation is better associated with the skin responses which depend on bio-feedbacks from very sensitive nerve endings or skin receptors (Gagge et al. 1937). Upon entering an environment, skin receptors would sense the temperature difference between the body and the environment and signal the brain to initiate either vasodilation or vasoconstriction, which determines the blood flow rate. Cold receptors would reduce the flow to the skin and cause transient reduction of skin temperature during exposure to the cold air, while the warm receptors would initiate higher blood flow to the skin and the sweating mechanism during exposure to the warm air.

To better understand the physiological mechanisms leading to thermal perceptions of the tropically acclimatized people, a study was conducted to investigate thermal comfort and thermal sensation responses and their associations with skin temperature and sweat rate of young adults exposed to moderate thermal stress in an office setting.

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## METHOD OF EXPERIMENT

### Experimental conditions and design

Experiment was conducted between July-August 2004. Counter-balanced experimental design with repeated-measures was adopted to balance three experimental conditions and minimize learning effect. The experimental conditions were within the acceptable range of room air temperature, not uncommon to the actual office environment. These conditions and the experimental design are given in Table 1. During interventions to room air temperature, the level of relative humidity was kept at 60%Rh and outdoor air supply rate at 9.0L/s/p. All other indoor environmental parameters were also kept constant.

Table 1 Experimental conditions and design

Subjects group	1 <sup>st</sup> exposure	2 <sup>nd</sup> exposure	3 <sup>rd</sup> exposure
1	20.0°C	23.0°C	26.0°C
2	26.0°C	23.0°C	20.0°C
3	26.0°C	20.0°C	23.0°C
4	23.0°C	20.0°C	26.0°C
5	23.0°C	26.0°C	20.0°C
6	20.0°C	26.0°C	23.0°C

### Subjects characteristics

Ninety-six young adults were recruited through online advertisement. The subjects screening criteria are as follows: health backgrounds (no chronic illnesses and allergic reactions), smoking habits (non smoker/ never smoker), initial performance test results obtained from the training session (computer literate and understanding of task instructions), and personal interviews (self-motivation). A summary of subjects' characteristics is provided in Table 2. The subjects were divided equally into six groups of 16 people with each group having an equivalent number of male and female participants. To satisfy the research ethics, the subjects also signed the subjects consent form for their participations. The subjects wore typical clothing attires for office workers in the tropics. Throughout the experiments, subjects were encouraged to adjust their clothing attires as and when necessary for achieving and maintaining thermal neutrality. In the moderate warm conditions, several subjects were observed removing their shirt and continued working with only light t-shirt. Under the moderate cold stress, the subjects were seen putting on additional clothing such as light sweater, jacket, or an extra shirt.

Table 2 Subjects' characteristics

Parameters	Gender	
	Male	Female
Number of subjects	48	48
Age (years)	22±1	21±1
Weight (kg)	68±5	55±3
Height (cm)	170±4	163±4

### Research facility (Field Environmental Chamber)

For the purpose of the study, a field environmental chamber (FEC) was developed into a simulated office environment, complete with two printing machines, sixteen personal computers and four clusters of workstations for the subjects. The dimension of the field environmental chamber is approximately 11.20m X 7.50m X 2.70m (length X width X height). The air distribution system of the FEC, which was capable of switching between mixing, displacement, and under-floor ventilation system, adopted a closed air distribution system. For the study, only mixing ventilation system (ceiling supply) was used while other modes were turned off throughout the experiment. Conditioned air was supplied to and

exhausted from the FEC through the fully ducted system. In order to maintain total air flow rate to the chamber, the supply air fan was locked at constant frequency of 45Hz. It is worth noting that the indoor air quality in the room was designed to achieve Class 1 indoor air quality stipulated by ASHRAE (2004), i.e. with low contaminant concentration, low sensory-irritation intensity and inoffensive odor.

### **Occupants' response measurements**

Throughout each experimental session, subjects were asked to complete questionnaire regarding their perceptual responses on 1) thermal environment, namely thermal comfort, perceived body and inhaled air thermal sensations, 2) local thermal sensations at forehead, front and back sides of the neck, chest, back, upper arms, lower arms, hands, thighs, calves, and feet, 3) perceived indoor environmental parameters that included air humidness, stuffiness, and stillness, and 4) thermal-related symptoms, such as cold hand and cold feet. In order to record the changes to subjects' clothing attires throughout the experiment, subjects were also required to provide information about their clothing on a clothing checklist.

Skin temperatures were measured by calibrated ET-series thermistors with accuracy level at  $\pm 0.05^{\circ}\text{C}$ . The type thermistor is also commonly used as sensor in digital thermometer and other medical appliances. Thermistors were affixed on the skin surface at five locations using thin dermiform tape: 1) forehead (at the center of forehead), 2) upper arm (c.a. 5cm below the armpit), 3) back (c.a. 15cm below shoulder), 4) hand (upper side of the hand, next to middle finger), and 5) foot (c.a. upper side of the foot, near ankle). Resistance data from the sensors was recorded by a data acquisition module and subsequently converted into temperature units in degree Centigrade. A simple Trans Epidermal Water Loss (TEWL) device was used to measure the moisture emitted from the skin surface. In principle, the system used room air that was drawn across a desiccant pack, which removed any moisture present in the room air. The dried air subsequently transport any moisture found in the sweat emitted from the skin through a skin capsule to measuring sensors. There, an accurate measure of the amount of moisture found within the air sample was made. The unit was capable of measuring sweat rate within the range of 0-1000 nl/min at the accuracy level of  $\pm 5\%$ . The skin capsule, which covered an area of  $5.06\text{ cm}^2$ , was fixed onto the skin of the subjects at the inner section of the upper arm with special cloth strap.

## **RESULTS ANALYSIS**

### **Thermal perceptions**

Figure 1 shows the thermal comfort ratings as the function of time of exposure. As subjects entered the office, there was clear a delineation that  $26.0^{\circ}\text{C}$  was the least preferred condition, however as the exposure progressed, they felt gradually more comfortable and after approximately 2 hours, the thermal comfort level was almost equivalent to that of exposure to  $23.0^{\circ}\text{C}$ , although towards the end of exposure (after 4 hours), there seemed to be a slight reduction of thermal comfort ( $X^2=38.42$ ,  $P<0.0001$ ). This slight difference of thermal comfort at the end of exposure between  $23.0^{\circ}\text{C}$  and  $26.0^{\circ}\text{C}$ , however, was not statistically significant. On the other hand, a significant reduction of comfort levels after approximately 60-minute was observed in the exposure to  $20.0^{\circ}\text{C}$  ( $P<0.0001$ ). This decreasing trend continued as the exposure progressed ( $X^2=56.38$ ,  $P<0.0001$ ). At  $23.0^{\circ}\text{C}$ , subjects were able to maintain their thermal comfort level within the range of 0.3-0.4 or slightly above "just comfortable". Despite this, the gradual changes over time were observed ( $X^2=10.37$ ,  $P<0.035$ ). In the first two-hour exposure, reduction of thermal comfort level was observed, while in the second half of the session, the comfort state was more consistent.

A consistent trend of decreasing thermal sensations across the three air temperatures is depicted in Figure 2 ( $P<0.0001$ ). Most notable reduction in body thermal sensation occurred during the first hour of exposure and most profoundly observed at  $20.0^{\circ}\text{C}$ , which was associated with reduced thermal comfort.

This effect was a result of the subjects' inability to maintain their body thermal balance as evident in later section on the skin temperature measurements. While the body thermal sensations were maintained just above thermal neutrality on the warmer side at 26.0°C, the small but gradual change of body thermal sensation in the cooling direction correspondingly improved thermal comfort. Moreover, the reversion of thermal sensation, i.e. subjects felt warmer, during the last hour of exposure to 26.0°C could be responsible for the slight decrease of thermal comfort. At 23.0°C, reductions of body thermal sensation were maintained within "neutral" to "slightly cool" region. The result could indicate that this region of thermal sensation response was generally preferred for comfort by the tropically acclimatized subjects.

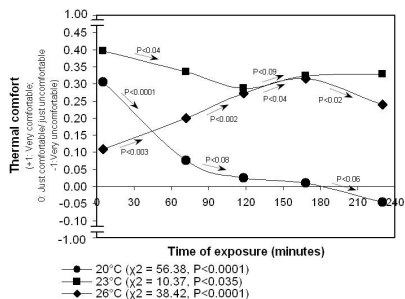


Figure 1 Thermal comfort

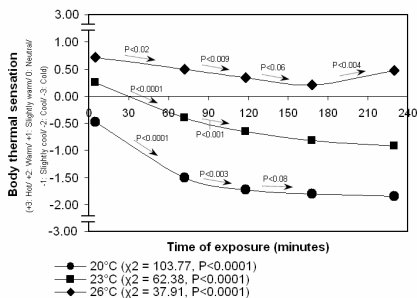


Figure 2 Body thermal sensation

Figure 3 demonstrates that mean skin temperature decreased with time under all three conditions with the least magnitude of change observed at 26.0°C. At the start of exposure, mean skin temperature at 20.0°C was approximately 0.95 times of the mean skin temperature at 26.0°C. By the end of exposure, skin temperature at 20.0°C became approximately 0.90 times of the mean skin temperature at 26.0°C. Here, the non-weighted mean skin temperature was used to show the relative effects of air temperature on skin temperature. Analysis of variance based on the repeated measurements data suggested that lower air temperature significantly reduced the skin temperature ( $P < 0.0001$ ). Furthermore, the magnitude of effects of air temperature were dependent on locations of measurement on the body as expected ( $P < 0.0001$ ). The same analysis also revealed that effects of air temperature were not influenced by gender differences ( $P < 0.10$ ), although between-subjects analysis indicated that the skin temperature of male subjects (mean (CI): 33.4 (33.2-33.5)) were slightly lower than that of the female (mean (CI): 33.8 (33.6-33.9)).

Sweat rate of subjects' performing sedentary office works were expectedly low (Figure 4). The recorded values were generally below 100 nano liter per minute (nl/min) with the steady-state level reaching 20 nl/min. Similar to measured skin temperature profiles, there was the effects of time of exposure on the sweat rate ( $P < 0.0001$ ). At air temperatures 20.0 and 23.0°C, the first-hour of exposure caused the highest decline of sweat rate, while at 26.0°C there was a gradual decrease over time. Despite the low values, the effects of air temperature on sweat rate was significant ( $P < 0.0001$ ). The differences across air temperature were, however, dependent on time of exposure. In other words, the magnitude of impacts of air temperature on sweat rate became smaller as time progressed. The equilibrium sweat rates under sedentary activities were achieved after approximate exposure duration of 4 hours at 26.0°C, 3 hours at 23.0°C, and one hour at 20.0°C. Based on average sweating over 4 hours, the total sweat volume generated at 26.0 and 23.0°C was c.a. 1.60 and 1.25 times higher than that generated at 20.0°C, respectively.

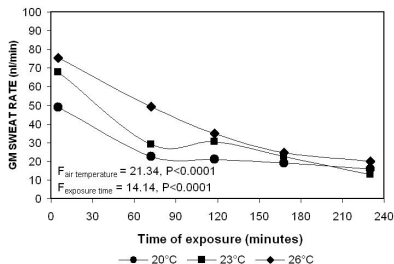
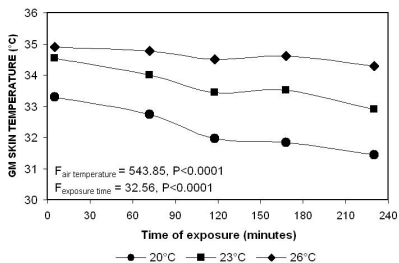


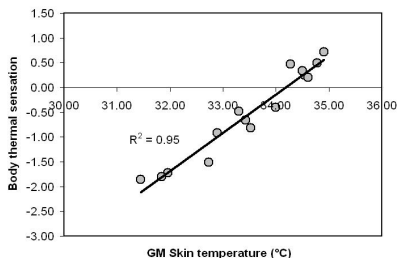
Figure 3 Geometric means of skin temperature

Figure 4 Geometric means of sweat rate

## DISCUSSIONS

Subjects felt most comfortable throughout the 4-hour occupation at 23.0°C although thermal sensation slowly decreased over time and reached the steady state level after 3 hours. The relationship derived from the subjective votes on thermal comfort and thermal sensation indicated that subjects felt most comfortable when thermal sensation was around the mid-point between “neutral” and “slightly cool” (thermal sensation = -0.40). In air-conditioned environment, subjects in temperate climate may prefer “neutral” sensation for comfort (Fanger and Toftum 2002), while in the tropics subjects show preference for thermal sensation “between neutral and slightly cool”.

Within the range of moderate air temperatures, mean skin temperature appeared to be a strong predictor of body thermal sensation following a linear correlation ( $R^2=0.95$ ) (Figure 5). A mean skin temperature above 34.0°C was rated slightly above neutral on the AHSRAE thermal sensation scale, while skin temperatures below 34.0°C were perceived below neutral or on the colder side of the scale. The skin temperature below 32.0°C corresponded to perceived “cool” thermal sensation. Further look at the impacts of the skin temperatures at various locations on local thermal sensations shows that skin temperatures within 33.0-36.0°C (from measurements at the forehead and back) were perceived about neutral. As the skin temperature continued to decrease from 33.0°C to 27.0°C (from measurements at the upper arm, hand, and feet), subjects reported profound increase of cooling sensation. Evaporative heat loss through the skin by means of sweating during sedentary activities did not strongly affect thermal sensation. This is contrary to the case of skin temperature, which receptors provide strong feedbacks to body thermoregulatory system for conserving or releasing the body heat.



The strong correlations between skin temperatures and thermal sensations at the respective locations of the body has been reported by Tamura and An (1993), while the association between sweating rate and local thermal sensation is perhaps best shown at high ambient water vapor pressure (Berglund and Gonzalez 1977) but less profound during moderate thermal stress at a constant relative humidity. The

selected air temperatures in the present study was kept reasonably in the neutral zone of human body thermoregulation, within which, according to Huizenga et al. (2004), a reduction in skin temperature related to local cooling effects is correlated with higher body core temperature as the result of skin blood flow control.

## **CONCLUSIONS**

Tropically acclimatized people prefer a slightly cool thermal environment for their comfort. Within the range of moderate air temperatures, the skin temperature appears to be a good predictor of body and local thermal sensations. Mean skin temperature within 33.0-34.0°C, which is attributable to room air temperature at 23.0°C, leading to a thermal sensation slightly below "neutral" is considered most comfortable.

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