INVESTIGATION OF THE RELATIONSHIP OF THE THERMAL COMFORT PERCEPTION BETWEEN THE LOCAL AND WHOLE BODY SEGMENTS IN A WORKPLACE ENVIRONMENT

Qi Wang[1], Joon-Ho Choi[1], Marc Schiler[1], Douglas Noble[1]
[1]University of Southern California, Los Angeles, California

ABSTRACT: Traditional air-conditioning methods maintain temperatures in a whole room at a constant level, and much work has been done to assess and improve the thermal comfort and sensations of people in a workplace environment. This study endeavors to identify the relationship of the thermal comfort perception between the local and whole body segments in a workplace environment. A total of 20 human subjects were tested in the University of Southern California's climate chamber to determine their physiological parameters and subjective perceptions of environment. Ambient temperature was documented during the tests, while the human subjects were exposed to a warm, cool, or neutral environment. Based on these tests, correlation and stepwise analysis are applied to identify the relative thermally sensitive skin areas, their contribution rate to the overall thermal sensation, and potential skin area combinations that have high correlation with overall thermal sensation. Results show that local thermal sensations are high correlated with the overall thermal sensation, the thermal sensation of arm is particularly strongly correlated with the overall thermal sensation with the reference to the Pearson R value of 0.918. Besides, with different genders and BMIs, there exists a sensation difference even in the same environment temperature. The study also identifies the different impacts of local thermal sensation while predicting the overall thermal sensation by applying data driven model.

KEYWORDS: Thermal sensation, Thermal comfort, Thermal environment

1.0 INTRODUCTION

People spend most of their time indoor, it has been proven that Indoor Environment Quality (IEQ) can significantly influence human mood and working productivity (Fisk 2000). IEQ can be determined by many factors, including indoor environment conditions such as temperature, lighting, humidity, glare, and air quality(ASHRAE 2016). Thermal comfort is one of the significant factors that highly correlate with the satisfaction of IEQ. But research from Huizenga shows that in only 11% of the 215 surveyed buildings in different countries, 80% or more of the occupants are satisfied with their thermal comfort in building (C.Huizenga 2006). Considering people's extreme dissatisfaction with the environmental quality in the interiors, a method that uses local body areas to predict the overall thermal sensation may give the designer practical and accurate way to evaluate the thermal environment of the building.

The traditional thermal sensation model is based on the thermal equilibrium of heat input and output. Researchers tried to combine four environmental factors (temperature, humidity, air speed, and mean radiant temperature) with thermal sensation. In 1970, P. O. Fanger proposed the equilibrium of heat input and output of the human body (P. O. Fanger 1970). In 1989, the researcher Wyon proposed the concept of "Equivalent Homogeneous Temperature" (EHT) to evaluate the non-uniform environment in a car based on the combination of thermal manikin and five years of vehicle environment research. (Wyon 1989).

Some researchers studied the local thermal sensation in different environment conditions. Edward Arens and others in the Center for the Built Environment (CBE) studied the thermal sensation and comfort in different uniform environments including slightly warm, warm, cool, and cold environments. The result from their study showed that the thermal sensation of the breathing zone tended to be warmer than the sensations of other body parts like head, neck, and face in cool and cold environments. (Edward Arens, Partial- and whole-body thermal sensation and comfort 2006). Some researchers studied the correlation between local thermal sensations and the overall thermal sensation. Humphreys measured temperatures of 2000 fingertip and collected the overall thermal sensation data in different thermal conditions. He proposed that a combination of hand temperature and environment temperature can predict the overall thermal sensation well (M.A. Humphreys 1999). Researcher Danni Wang studied finger temperature and the combination of air and finger temperatures to predict the overall thermal sensation. He found that the skin temperature range of fingers was narrow when compared to that of other local skin temperatures in cool conditions. This indicated that the skin temperature of the finger is a significant sensitive indicator of the body's thermal sensation and comfort in cool conditions (Danni Wang 2007).

Gender is one of the significant factors that can influence thermal sensation in similar thermal environments (JoonHo

Choi 2010). In recent years, researchers also investigated the gender differences in thermal comfort (W. Pasut 2015). The researcher Karjalainen (Karjalainen 2012) found that females are more sensitive than males when the environment condition is cool. Other researchers also investigated sensation of male and female in different environment conditions. It has been proved that there is only small overall thermal sensation difference between the genders in neutral or slightly warm environment conditions, but females tend to feel cooler when the environmental temperature is relative cool (KC 2002).

Researchers also use machine learning approaches to predict thermal demands based on skin temperatures. Researcher Changzhi found that by using the support vector machine (SVM) model, thermal demands can be well predicted based on the local skin temperatures (Changzhi Dai 2017). Although the thermal demands can be well predicted in this model, other machine learning methods such as decision tree or Artificial Neuro Network are not used to predict the thermal demand or sensation.

2.0 OBJECTIVE

The purpose of the study is to understand the correlation between overall thermal sensation and local thermal sensations. At the same time, accuracy estimation to predict the overall thermal sensation is also evaluated. The potential use of some local skin spot to predict the overall thermal sensation can be achieved based on the method of correlation analysis, step-wise analysis, and the application of data-driven algorithm.

3.0 METHOD

A method to investigate how local skin temperature and local thermal sensation correlates to human thermal response is proposed. The workflow of the proposed method can be divided into three steps: chamber arrangement, data acquisition, and data analysis (Figure 1).

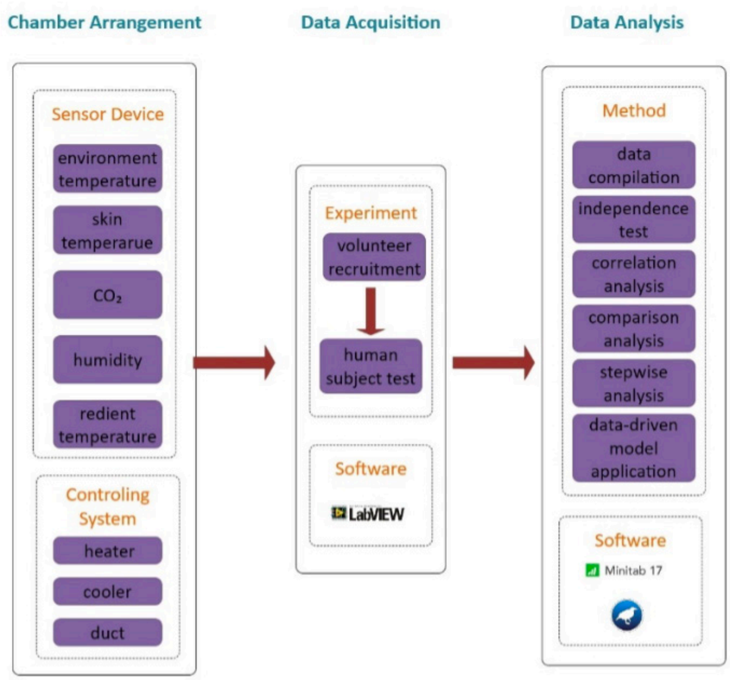

Figure 1: Overall workflow of proposed method

The human subject tests were conducted in the University of Southern California's (USC) experiment chamber. The experiment chamber is in basement of Watt Hall. As shown in Figure 2, the chamber is 4.0 meters long, 2.8 meters wide and 2.4 meters high. The temperature of the environmental chamber was regulated by two air conditioners and four portable heaters. Four diffusers were distributed uniformly beside the desk. One of the challenge for the project was to identify a program that could efficiently collect environmental data in the chamber. The Laboratory Virtual Instrument Engineering Workbench (LabVIEW) software was used in this project to achieve the purpose.

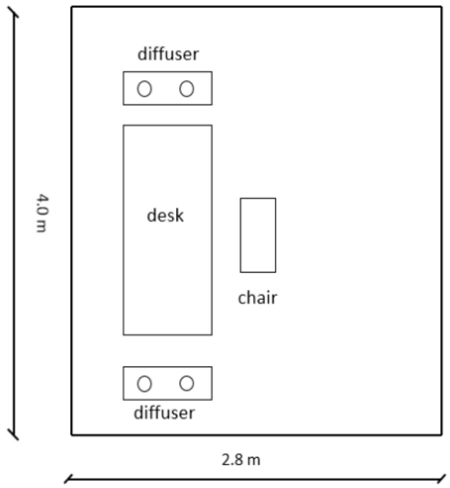

Figure 2: Floor plan of environmental chamber at USC (Unit: meter)

A total of 20 volunteers (10 males, and 10 females) participated the experiment, the overall demographic information is shown in Table 1; they were all college students from the University of Southern California. All subjects selected were in good health and had no background information about the thesis topic.

Table 1: *Demographic information about subjects*

Age					BMI			
Avg.	23.8				21.3			
St. Dev	2.668				1.822			
Range		20–25	26–30	Subtotal	Underweight ≤ 18.5	Normal weight ≤ 24.9	Overweight ≥ 30	Subtotal
Number	Female	8	2	10	2	8	-	-
	Male	7	3	10	-	10	-	-
	Total	15	5	20	2	18	-	-

The experiment carried on for around 80 minutes, which consists of 60 minutes in the environmental chamber and 20 minutes' rest outside the chamber, the detail of the experiment procedure is shown in Figure 3.

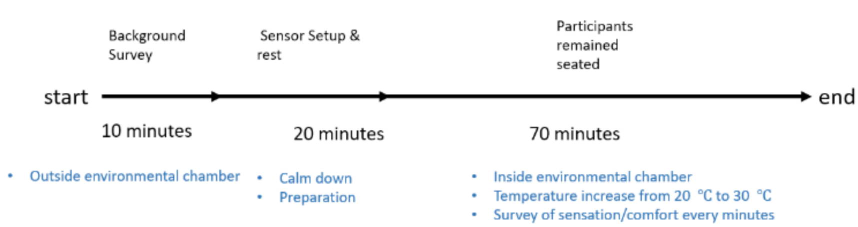

Figure 3: Experiment procedure diagram

Figure 4 is a photograph of a subject wearing sensors in a calm condition. Based on thermoregulation models of thermal sensation and physiological response (J. K. Choi 1997), the seven local spots were forehead, neck (at the back), back (upper back), chest, arm (upper arm), wrist, and belly. The subjects could engage in some simple activities such as reading a book or listening to soothing music.

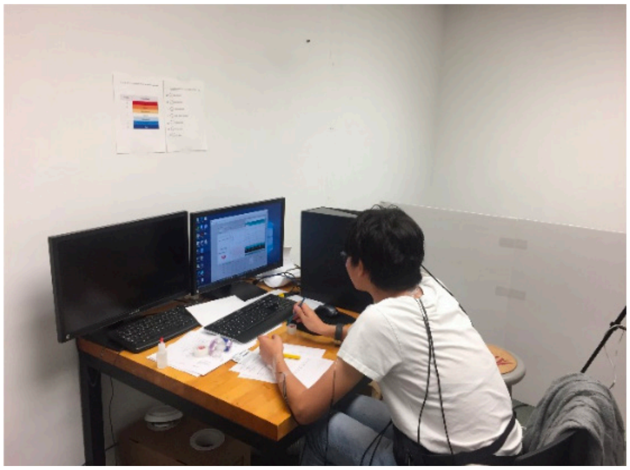

Figure 4 : Photograph of a subject wearing sensors in a calm condition

Subjects' local and whole body thermal sensations and comfort were surveyed by the questionnaire, Thermal sensation and comfort data from different parts of the subjects' body and from their whole body were documented every five minutes.

4.0 DATA ANALYSIS

4.1 Overall and local thermal sensation analysis

Figure 5 shows the interval plot of local sensation votes under neutral overall thermal sensation (0). When the overall thermal sensation is neutral, the sensation level of different body parts is around zero. The local thermal sensation of the wrist is close to neutral ($p < 0.05$). The sensations of forehead, back, chest, and belly are warmer than neutral ($p < 0.05$), while the sensation of the arm ($p < 0.05$) is cooler than other locations on the body. This phenomenon indicates that in the condition of neutral overall thermal sensation, the sensations in the breathing zone and head region are more likely warm; the sensation in the trunk is more likely cool.

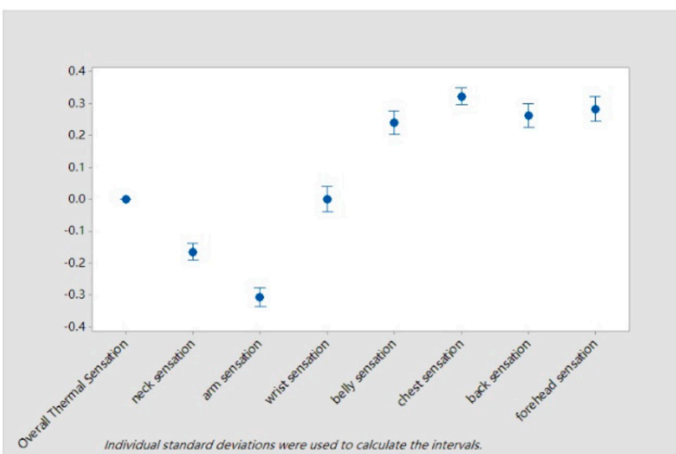

Figure 5 : Interval plot of local thermal sensation votes under neutral condition (Sample size: 20)

Table 2 shows the Pearson correlation between the overall thermal sensation and local thermal sensation. Each local thermal sensation had a very strong correlation (Pearson $R > 0.8$) with the overall thermal sensation ($p < 0.05$). The thermal sensation of the arm was particularly strongly correlated with the overall thermal sensation with the reference to the Pearson R value of 0.918; the forehead sensation also had a strong correlation with the Pearson R value of 0.871. The thermal sensation of the belly showed a relatively low correlation with the overall thermal sensation (Pearson $R = 0.82$, $p < 0.05$).

Table 2: Pearson correlation between the overall thermal sensation and local thermal sensation

	Forehead	Neck	Back	Chest	Belly	Wrist	Arm
Pearson R	0.871	0.869	0.842	0.865	0.820	0.85	0.918
p-value	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*

Table 3 shows the stepwise analysis of the local thermal sensation and overall thermal sensation. As shown in Table 5.2, thermal sensation of the forehead had a strong correlation with overall thermal sensation. The first step of the stepwise analysis focused on the arm with an R-sq value of 84.3%. Forehead sensation combined with that of the arm had the R-sq value of 86.8%; the Δ R-sq value was 2.5% in total. With the combination of the thermal sensation of seven local bodies, the R-sq value could up to 88.1%. By combining the arm and the forehead, the R-sq value could be 84.3%, which is close to 88.1%.

Table 3: Stepwise analysis of the local thermal sensation and the overall thermal sensation

	Step 1		Step 2		Step 3		Step 4	
	Coef.	P	Coef.	P	Coef.	P	Coef.	P
Arm	.968	.000	.684	.000	.599	.000	.528	.000
Forehead			.417	.000	.309	.000	.3061	.000
Chest					.217	.000	.1697	.000
Wrist							.1271	.000
R-sq	84.3%		86.8%		87.4%		87.7%	
Δ R-sq	-		2.5%		0.6%		0.3%	

	Step 5		Step 6	
	Coef.	P	Coef.	P
Arm	.455	.000	.445	.000
Forehead	.235	.000	.216	.000
Chest	.104	.000	.059	.000
Wrist	.159	.000	.150	.000
Neck	.183	.000	.179	.000
Back			.093	.000
R-sq	88.0%		88.1%	
Δ R-sq	0.3%		0.1%	

4.2 Demographic factor analysis

In total, 20 subjects were divided into two groups: six subjects were in the low BMI group (< 20 kg/m2) and 14 subjects were in the high BMI group (≥ 20 kg/m2).

As shown in Figure 6, The indoor temperatures of both high and low BMI groups increased consistently when the overall thermal sensations change from −3 (cold) to 3 (hot). In the sensation level of −1 (slightly cool) and +1 (slightly warm), the environment's temperature experienced by the high BMI and low BMI groups were similar. The biggest temperature difference occurred when the overall thermal sensation level was neutral (0).

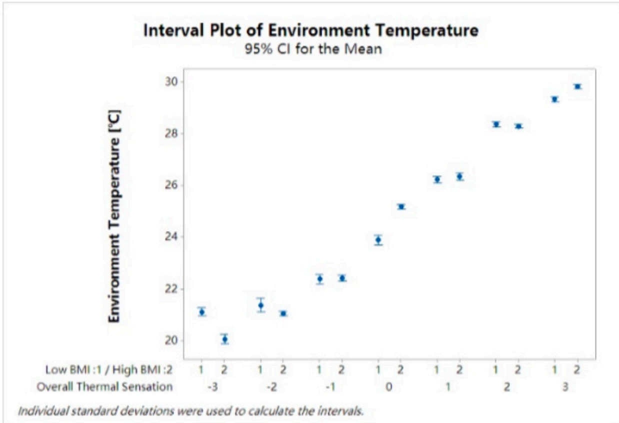

Figure 6: Interval plot of the indoor temperature by the overall thermal sensation and BMI (Sample size: 20)

As shown in Table 4, all body locations in the low BMI and high BMI group showed a very strong correlation with the overall thermal sensation. The low BMI group showed a higher correlation than the high BMI group with the reference to most body locations (forehead, chest, belly, wrist, arm). The Pearson R difference was not significant while considering the local thermal sensation of the neck, back, and chest. It is worth noting that there existed a relatively high correlation difference of the forehead between the low BMI (Pearson R = 0.906) and the high BMI (Pearson R=0.853) group.

Table 4: Correlation analysis of the overall thermal sensation and local thermal sensation by BMI

		Forehead	Neck	Back	Chest	Belly	Wrist	Arm
Low BMI	Pearson R	0.906	0.863	0.832	0.869	0.854	0.892	0.937
	p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
High BMI	Pearson R	0.853	0.874	0.848	0.866	0.816	0.832	0.909
	p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000

In total, 20 human subjects (10 male and 10 female subjects) were tested in the experimental chamber. As shown in Figure 7, the thermal sensation level of both male and female subjects increased continuously. The thermal sensation of male subjects increased from −2 (cool) to +3 (hot), while that of female subjects increased from −3 (very cool) to +3 (hot). There was no male subject who felt cold during the test; this indicated that in very cool conditions, the male feels warmer than female. When male and female subjects had the same thermal sensation level (except +3), the mean environment temperature for male subjects was lower than that of female subjects. When the overall thermal sensation was hot (+3), the environment's temperature for male subjects were higher than that of female subjects. This indicted that in very warm conditions, male tends to feel warmer than female.

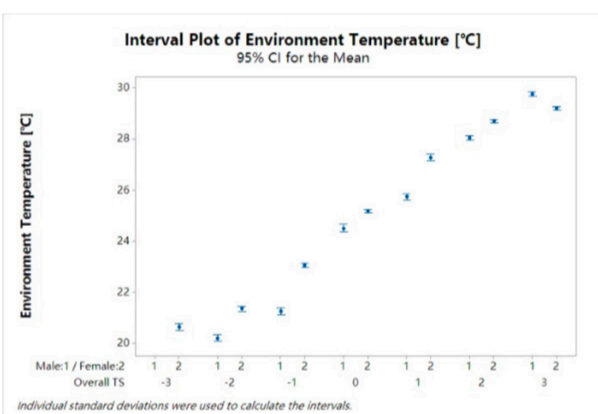

Figure 7: Interval plot of the indoor temperature by the overall thermal sensation and gender (Sample size: 20)

As shown in Table 5, female subjects showed a higher correlation than male subjects with the reference to these body locations: forehead, back, and arm. The local body thermal sensation of the belly in the female group showed a relatively low Pearson R value, which means that the sensation of the belly was not highly correlated with the overall thermal sensation. Although the Pearson R value was different in the male and female group, the difference in the value was not significant.

Table 5: Correlation analysis of the overall thermal sensation and local thermal sensation by gender

		Forehead	Neck	Back	Chest	Belly	Wrist	Arm
Male	Pearson R	0.834	0.879	0.806	0.857	0.817	0.846	0.902
	p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Female	Pearson R	0.871	0.838	0.840	0.842	0.781	0.822	0.914
	p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000

4.3 Estimation of the overall thermal sensation by the local thermal sensation

To estimate the overall thermal sensation, this paper takes the subject's physiological status (gender and BMI) and environment temperature as the baseline attributes and combines the local thermal sensation in different spots as the changeable attributes. The data-driven algorithm decision tree (J48) is used to estimate the accuracy (Correctly Classified Instances) of the prediction result and uses the ten-fold cross validation method for the test option. As shown in Table 6, The accuracy is at a relatively low level while not considering the environment temperature in the baseline attributes. The arm had maximum accuracy (75.77%), and the neck had minimum accuracy (68.71%). Although the forehead had the highest accuracy when the environment's temperature, the BMI and gender in baseline attributes were considered, the accuracy was not the highest without considering the environment's temperature.

Table 6: Accuracy of using baseline attributes (BMI, gender, environment temperature) and single local thermal sensation factor to estimate the overall thermal sensation

	Forehead	Neck	Back	Chest	Belly	Wrist	Arm
Accuracy (gender, BMI environment temperature)	98.58%	98.02%	98.44%	97.19%	98.05%	97.73%	98.05%
Accuracy (gender, BMI)	72.93%	68.71%	73.65%	71.46%	69.28%	74.13%	75.77%

5.0 RESULT AND DISCUSSION

The study aimed to enhance the researcher's understanding about the relationship of the thermal comfort perception between the local and whole body segments in a workplace environment, the relationship between the local thermal sensation and the overall thermal sensation was statistically analyzed with consideration for an individual's physiological factors (e.g., gender, BMI). The results from the correlation analysis of the local thermal sensation and overall thermal sensation showed that all the local thermal sensations have a strong correlation level with the overall thermal sensation. The stepwise analysis showed the exact combination order of local thermal sensations (arm, forehead, and chest), which were most correlated with the overall thermal sensation. Based on the correlation analysis, local thermal sensations are highly correlated with the overall thermal sensation (Pearson R > 0.8). By conducting stepwise regression analysis, the first step (arm) can have a high R-sq value of 84.3%. When the baseline attributes are gender, BMI, and the environment's temperature, the local thermal sensation in one spot that has the highest accuracy (Correctly Classified Instances) comes from the consideration of baseline attributes and forehead (98.58%). When the baseline attributes are gender and BMI, the sensation of arm has the maximum accuracy (75.77%).

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