Thermal preferences and cognitive performance estimation via user's physiological responses

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ABSTRACT: This study investigated the relationship between occupants' thermal sensation, physiological responses, and cognitive performance to quantify the priorities of the selected physiological responses for optimal productivity. In order to quantify variables for optimal productivity estimation, this study considered the following factors: 1. Local body skin temperature as an occupant's physiological responses; 2. Participants' individual factors such as gender; 3. Cognitive performance in operation span task; 4. Environmental data such as indoor temperature, wind velocity, CO_2 level and indoor humidity; 5. Individual ratings of subjective thermal sensation. A series of human experiments were conducted to collect physiological responses and cognitive performance in a different room temperature conditions. The skin temperatures and environmental data were recorded in every minutes, and thermal sensation was surveyed by the Likert 7 point scale questionnaires. The operation span (OSPAN) task was used to measure working memory as a cognitive performance for occupant's productivity. Total 39 participants' data was collected for comparative analysis. The results revealed significant correlations between overall thermal sensation and local body skin temperatures. Also, the OSPAN score showed that it has a significant correlation with indoor temperature, thermal sensation as well as physiological responses. The OSPAN results were higher when indoor temperature was relatively low or when participant's thermal perception was either slightly cool or cool. Most local body skin temperatures were negatively correlated with the cognitive test scores, therefore it was concluded that a little low temperature has a significant impact to promote occupant's productivity. This study also determined the priority of local skin temperatures and gender by their impact to estimate the occupant's cognitive performance.

KEYWORDS: Thermal sensation, Physiological response, Skin temperature, Cognitive performance, Operation span

INTRODUCTION

In modern daily life, people spend 87% of their time indoors (Klepeis et al. 2001), thus the environmental quality have become an important aspect for occupant's well-being and productivity. Most modern buildings depend on mechanical systems to provide comfortable thermal environment, based on the existing thermal comfort model, such as predictive mean vote (PMV) (ASHRAE 2013). However, these models rarely consider individual physical and psychological differences, such as gender, age, or personal preferences, which were studied and verified as significant factors for thermal comfort (J.-H. Choi and Loftness 2012). This caused various issues for the occupants in the built environment, such as occupant's thermal dissatisfaction and low productivity.

Various engineers and scientists have tried to solve this issue from different perspectives. Some studies suggested micro-scale or personalized systems for thermal environment, focusing on individual control system (Goyal, Ingley, and Barooah 2013; Purdon et al. 2013), which showed higher occupant's satisfaction as well as less energy consumption (Murakami et al. 2007; Veselý and Zeiler 2014). Some researchers have investigated the occupant's physiological responses as a control factor and its relationship with indoor thermal environment (Ghahramani et al. 2016; Zhang et al. 2010b, 2010a), and the occupant's thermal sensation prediction model was developed as a function of human physiological responses (J.-H. Choi and Yeom 2017a). Also, a heating or cooling control model was investigated based on the selected physiological signals (J.-H. Choi and Yeom 2017a, 2019).

Regarding occupant's productivity, many researchers have proved that indoor thermal condition has a significant impact on the occupant's productivity, varies by temperature (Lan, Lian, and Pan 2010; Lan, Wargocki, and Lian 2014), and others also showed the influence of indoor temperature on the occupant's thermal sensation and productivity, such as motivation and work performance (Lan, Wargocki, and Lian 2011; Cui et al. 2013). However, these studies rarely investigated physiological responses, which has a great potential as a significant factor to predict optimum thermal sensation for the occupant's productivity.

Therefore, the purpose of this study is to investigate the relationship between occupants' thermal sensation, physiological responses, and cognitive performance, and to quantify the priorities of the selected physiological responses for optimal productivity in the office environment. This study, in order to quantify the physiological responses for optimal productivity estimation, considered the following factors: 1. Local body skin temperature as an occupant's physiological responses; 2. Participants' individual factors such as gender; 3. Cognitive performance in operation span task; 4. Environmental data such as indoor temperature, wind velocity, CO_2 level and indoor humidity; 5. Individual ratings of subjective thermal sensation.

1.0 METHODOLOGY

1.1 Experiment procedure

A series of human experiments were conducted to collect physiological responses and cognitive performance in a various room temperature conditions. The experiment was approved by the IRB (Institutional Review Board: Approval #01418) of the Lawrence Technological University (LTU), and the consent form was signed by each participant before the experiment.

The participants were mostly volunteered students and staffs at LTU, and the total number was 39 (Table 1). 80% of the participants were in their 20s (Avg.: 25.6; Min.: 15; Max.: 39; SD: 5.25), and the average BMI (Body Mass Index) was 25.29, which indicates that most participants are either slightly overweight or healthy condition. Each participant's physical condition was initially checked by the survey, and no one reported any specific health conditions or sickness which could affect the experiment results. Each participant was requested to wear basic clothes which was Clo level 0.55 or 0.59 (long sleeve T-shirt or shirts: 0.25, long pants: 0.25, socks: 0.02, panties: 0.03, bra: 0.04). The participant's basic information was also surveyed, such as age, height, and weight.

Table 1: Demographic information (Number of participant)

Gender	Temperature distribution by group (°C)						Total
	18	20	22	24	26	28	
Male	3	3	3	4	3	3	19
Female	3	3	4	4	3	3	20
Total	6	6	7	8	6	6	39

Upon arrival, the participant stayed in the waiting area for 20 minutes to stabilize their physiological conditions, where indoor temperature was controlled and maintained by central HVAC system at 22°C. The participant was asked to take the initial demographic survey and sign the consent form. The participant was randomly assigned to one of 6 experiment groups, which was 18°C, 20°C, 22°C, 24°C, 26°C, and 28°C, and independent heating and cooling system in the experiment room controlled the temperature during the experiment. Once the participant moved into the experiment room, the skin temperature sensors were attached to the participant. Total 7 local body areas were chosen from the 16 thermoregulation models which were chosen frequently (J.-H. Choi and Yeom 2017a; J. Choi et al. 1997; Yeom, Choi, and Zhu 2017). The local body areas used were forehead, neck, chest, arm, inner wrist, back wrist, and lower back. The Likert 7-point scale was used for thermal sensation survey (Table 2), which was based on ASHRAE PMV (ASHRAE 2013).

Table 2: Thermal sensation questionnaire using the Likert 7-Point Scale

-3	-2	-1	0	1	2	3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

Once the experiment started, the participant remained seated on general office chair by the desk, where the laptop is located. The whole procedure took about 45 minutes, and the location and posture of the participant was maintained same. After initial thermal sensation survey, the participant took the operation span task (OSPAN) to measure the working memory. In this task, the participant need to read and verify the simple math problem (Yes or No) and read a word on the screen after the operation. After a random series of problems and words (maximum 6), the participant need to recall and choose the words in correct order. Once the participant finished the OSPAN, thermal sensation survey was conducted again.

All indoor environment data and human physical data were recorded in every minute, and recorded data was analysed by various statistical methods, such as two-sample T-test, ANOVA, correlation analysis, stepwise regression, etc. Microsoft excel, Minitab, and data-mining software (WEKA) was mainly used as an analysis tool, and every analysis were conducted at 95% significance.

2.0 EXPERIMENT ROOM AND EQUIPMENT

The experiment was conducted in the experiment room at LTU, and the size of the room is 3m (W) x 5m (D) x 3m (H) (Fig. 1). An independent heating and cooling system with two separate nozzles was installed to control indoor temperature, and the air velocity in the room was maintained under 0.2 m/s, considering ASHRAE recommendation (ASHRAE 2013). Regular office desk and chair were located in the center of the room, and building's central HVAC system was disconnected for the experiment. The indoor temperature of the room was monitored at four different locations for monitoring stable thermal condition, and the one on the desk was used for the analysis. During the experiments, the relative humidity was recorded around 30% and the air velocity was 0.1 ± 0.05 m/s at the level of the participant's chest, which is appropriate, based on ASHRAE 55 standard (ASHRAE 2013).

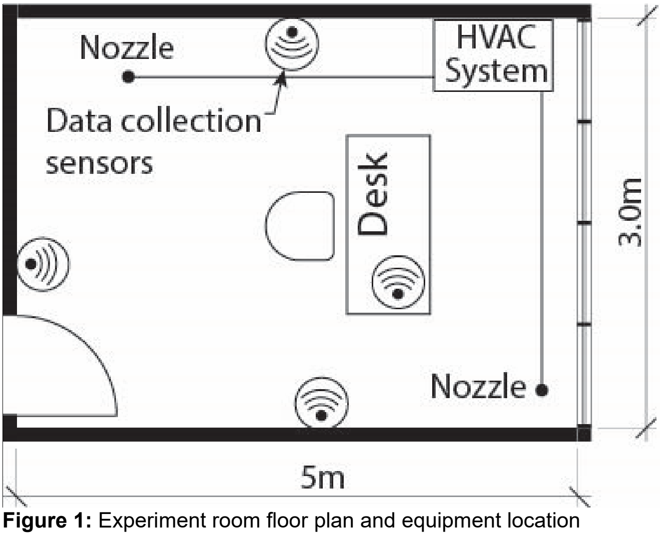

Figure 1: Experiment room floor plan and equipment location

Lab quest Mini of Vernier Software & Technology was used as a data acquisition (DAQ) system to collect participant's skin temperature as well as air velocity, which was installed in the laptop. HOBO sensors were also placed at the multiple spots of the room to record temperature and relative humidity (RH). Specifications of sensors and systems are shown in Table 3.

Table 3: Specification of the equipment

Sensor	Model	Specification
Air temperature	U12-012	Accuracy: ±0.35°C (from 0°C to 50°C), Resolution: 0.03°C,
Air velocity	Testo 405-V2	Accuracy: ±0.1m/s + 5%, Resolution: 0.01 m/s
Relative humidity	U12-012	Accuracy: ±2.5% from 10% to 90%, Resolution: 0.05%
Skin temperature	SBS-BTA	Accuracy: ±0.5°C, Resolution: 0.03°C
Data acquisition system	Lab quest mini	Resolution: 13 bit, Sampling rate: 10kS/s

3.0 RESULTS

3.1 Comparison of thermal environment and physiologial responses

This study chose 7 local body skin temperatures as an occupant's physiological responses. Every local body skin temperature showed significantly different results between each experiment group (Table 4). It is very clear that local body skin temperatures increased as indoor temperature increased, and the analysis of variance (ANOVA) proved that it is significantly different ($p<0.001$). Some local body spots, which is close to the core body (Chest, Back, Neck, Forehead), showed relatively higher average skin temperatures, and the arm and both wrist (Back and In) appeared lower. Among 7 local body spots, the forehead was the most stable skin temperature, and the wrist (Back) showed the largest temperature fluctuation. Table 5 shows that every local skin temperatures were positively correlated to the indoor temperature, and every results were statistically significant. The wrist (back) skin temperature had relatively stronger correlation than the others, and the back skin temperature showed the weakest correlation.

Table 4: Analysis of local body skin temperatures at each experiment group

Group	Forehead		Arm		Wrist (Back)		Wrist (In)		Chest		Back		Neck	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
18	33.0	1.40	30.9	4.57	28.5	2.62	31.9	2.40	32.5	2.21	34.4	2.66	32.1	2.48
20	32.7	1.70	31.6	2.28	30.3	2.17	31.4	1.49	33.3	2.13	33.1	1.88	32.9	1.65
22	34.1	0.80	32.1	0.99	30.1	2.25	32.2	1.99	34.1	1.33	33.1	1.48	34.2	1.83
24	34.4	1.28	33.0	1.29	31.7	1.89	32.8	1.07	34.4	1.00	34.4	1.50	34.1	1.58
26	34.3	1.17	34.3	1.24	33.1	1.51	33.9	1.37	35.0	1.14	34.0	1.97	34.4	1.22
28	35.2	1.27	34.3	1.00	31.7	1.76	33.6	1.37	35.0	1.66	34.6	1.32	34.5	1.62
ANOVA	P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*	

Table 5: Correlation analysis between indoor temperature and local skin temperatures

	Forehead	Arm	Wrist (Back)	Wrist (In)	Chest	Back	Neck
Spearman R	0.496	0.457	0.529	0.459	0.461	0.138	0.381
P-value	P<0.001*	P<0.001*	P<0.001*	P<0.001*	P<0.001*	P<0.001*	0.001*

To analyze the relationship between occupant's subjective and physiological responses, the average local body skin temperatures were analyzed at each OTS level (Table 6). No participants marked at OTS level -3 (Cold) or 3 (Hot). It is clear that local body skin temperatures increases generally when OTS increases, and every local skin temperatures were correlated significantly with OTS (p<0.001). The average local skin temperatures were ranged from 28.9°C to 35.2°C. The back skin temperature showed the smallest temperature variation, while the wrist (back) had the largest fluctuation. Also, the forehead, both wrist (Back & In), and the chest showed relatively constant temperature increase between each OTS level. Thus, it is safe to say that the wrist (back) has a potential as a significant factor to estimate the occupant's optimal OTS.

Table 6: Analysis of local body skin temperature at OTS level

OTS	Forehead		Arm		Wrist (Back)		Wrist (In)		Chest		Back		Neck	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
-2	33.1	1.21	33.0	0.77	28.9	0.83	31.8	0.73	33.7	1.77	34.1	0.70	34.7	0.77
-1	33.1	1.84	31.4	3.53	29.4	2.57	31.7	1.66	33.2	2.07	33.7	1.82	32.6	2.19
0	34.0	1.36	32.7	1.93	31.1	2.45	32.3	2.15	34.2	1.69	33.6	2.31	33.7	1.89
1	34.7	1.07	33.8	1.35	32.3	1.68	33.7	1.26	34.6	1.48	34.4	1.63	34.5	1.38
2	34.9	0.74	33.7	0.77	32	0.98	33.1	0.74	35.2	0.61	33.9	1.39	33.4	1.15
ANOVA	P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*	

4.0 COMPARISON OF COGNITIVE PERFORMANCE AND PHYSIOLOGIAL RESPONSES

To measure the occupant's productivity, this study adapted the operation span (OSPAN) tasks. It is generally used to predict cognitive performance, and have been known for its reliability and validity (Unsworth, Heitz, and Engle 2005). The OSPAN score is the sum of the sequence lengths that the participant recalled correctly, thus the higher number means the participant recalled it more in correct order. Total 18 operations were conducted in this study, and the average OSPAN score was 41.76 out of 60 (SD: 9.95).

Fig. 2 illustrates the interval plot of OSPAN score at each experiment group. It is clear that low temperature groups (18, 20, 22) shows higher score than high temperature groups (24, 26, 28). Experiment group 18 showed the highest score, and group 24 appeared as the lowest. The OSPAN score and experiment group was negatively correlated with a significant p-value (Person R: -0.171, p<0.001), and the analysis of variance (ANOVA) also verified its statistical significance between each group (p<0.001).

To analyze the relationship between OSPAN score and local skin temperature, the OSPAN score was split into two category, high and low functional group, based on the mean OSPAN score (41.76), which was used frequently (Zakrzewska and Brzezicka 2014; Delaney and Sahakyan 2007). High and low functional group showed significant difference of the average skin temperature at every spot (Table 7). The skin temperature of the arm, back, and both wrist (Back & In) were lower in high functional group than the one in low functional group, while the forehead, chest and neck showed the opposite results. The chest skin temperature showed the largest gap between high and low functional group, and the wrist (In) skin temperature revealed the least difference.

The result of the correlation analysis between OSPAN score of each functional group and local skin temperatures are shown in Table 8. The forehead was the only local skin temperature which showed negative correlation in both high and low functional group with a significant p-value, and the arm and neck skin temperature appeared positive in high functional group and negative in low functional group with significant p-value. The others appeared differently by functional group.

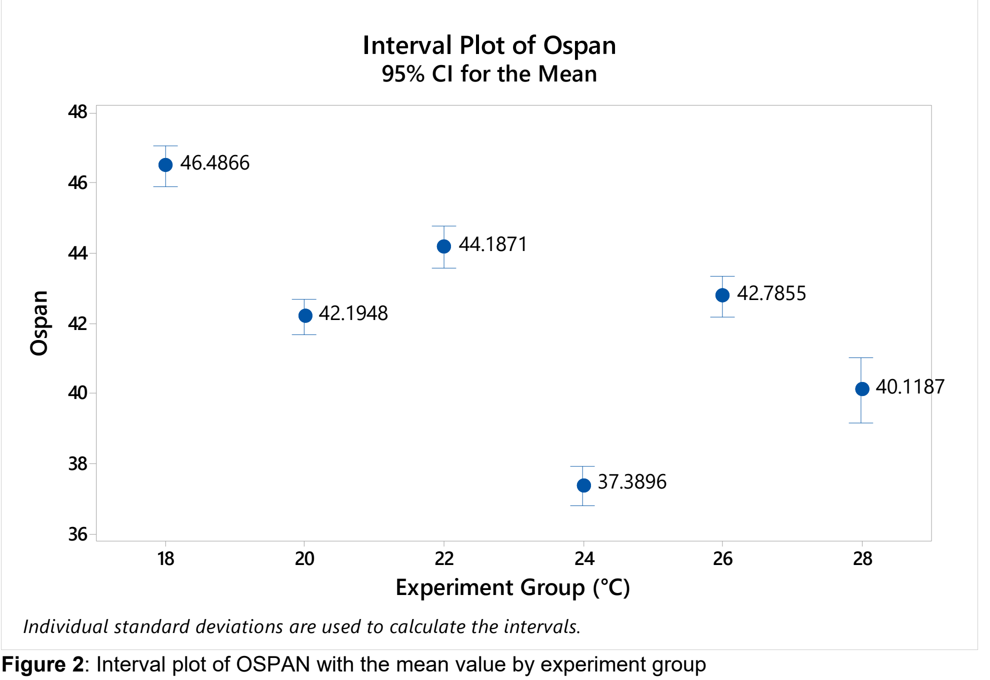

Figure 2: Interval plot of OSPAN with the mean value by experiment group

Table 7: Two sample T-test of local body skin temperature by high/low functional group

Group	Forehead		Arm		Wrist (Back)		Wrist (In)		Chest		Back		Neck	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
High	34.2	32.5	32.5	2.77	30.4	2.96	32.5	2.20	34.8	1.53	33.8	2.51	33.8	1.91
Low	33.7	33.1	33.1	1.05	31.1	1.73	32.7	1.12	33.3	1.46	34.2	1.23	33.5	2.52
T-test	P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*	

Table 8: Correlation analysis between high/low functional group and local skin temperatures

Group		Forehead	Arm	Wrist (Back)	Wrist (In)	Chest	Back	Neck
High Functional	Spearman R	-0.048	0.321	0.029	-0.005	-0.281	-0.251	0.051
	P-value	0.009*	P<0.001*	0.127	0.781	P<0.001*	P<0.001*	0.005*
Low Functional	Spearman R	-0.456	-0.219	0.127	-0.305	-0.016	0.015	-0.422
	P-value	P<0.001*	P<0.001*	P<0.001*	P<0.001*	P: 0.503	P: 0.521	P<0.001*

4.0 DISCUSSION

5.1 Comparative analysis by gender

Various studies have revealed a significant impact of gender difference on thermal perception. This study also verified that there are clear difference in thermal perception and local skin temperature variations between male and female, which also resulted in different productivity.

In Table 9, the arm and both wrist showed higher skin temperature in male group, while female group showed higher local body skin temperature at the chest, back and neck. A similar study also showed same results in the female group, but there was a difference in the male group, where the arm didn’t show any significant difference by gender group (J.-H. Choi and Yeom 2017b). The reason could be the different experiment setting or sample size of the participants, which requires further investigation for both studies.

It is also interesting to see that the forehead, arm, and both wrist in male group showed higher skin temperature than female group for both high and low functional group with a significant p-value, and the skin temperature of female group was higher at the chest, back and neck significantly, except the back in low functional group (Table 10). Thus, it is clear that gender has a significant influence on thermal perception and physiological responses, which is also correlated with the occupant's productivity.

Table 9: Two sample T-test of local body skin temperature by gender group

Gender	Forehead		Arm		Wrist (Back)		Wrist (In)		Chest		Back		Neck	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Male	34.0	1.63	33.5	1.60	31.8	1.91	33.2	1.20	33.8	1.71	33.7	1.77	33.3	2.49
Female	34.0	1.54	31.9	2.62	29.5	2.59	31.8	2.17	34.7	1.45	34.2	2.44	34.2	1.62
T-test	0.234		P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*	

Table 10: Two sample T-test of local skin temperatures in high/low functional group by gender

Group	Gender	Forehead		Arm		Wrist (Back)		Wrist (In)		Chest		Back		Neck	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
High Func.	Male	34.3	1.36	33.7	2.13	32.2	1.94	33.5	1.22	34.1	1.87	33.2	2.02	33.4	2.16
	Female	34.1	1.53	31.5	2.83	29.2	2.93	31.7	2.45	35.3	0.95	34.2	2.77	34.2	1.63
T-test		P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*		P<0.001*	
Low Func.	Male	33.7	1.80	33.2	0.71	32.9	1.12	31.5	1.84	33.5	1.48	34.2	1.30	33.1	2.77
	Female	33.9	1.57	33.0	1.54	32.2	0.98	30.2	0.92	32.7	1.24	34.3	1.08	34.3	1.59
T-test		0.010*		P<0.005*		P<0.001*		P<0.001*		P<0.001*		P: 0.188		P<0.001*	

5.2 Estimation of the occupant's optimal productivity

This study verified some relationship between occupant's thermal perception, physiological responses, and productivity. In this chapter, human physiological responses and gender were analysed and prioritized to estimate the occupant's productivity.

Table 11 shows the summarized results of the stepwise regression analysis of the participants and gender group on the functional group estimation. In general, the chest and back showed relatively higher impact than the others on the functional group estimation, and the combination of all valid variables reached 30.11% of accuracy. It is also interesting that there is clear difference in accuracy and most significant variables between male and female group. Female group showed significantly higher accountability than that of the male group, with a single variable or the combination of all variables. Therefore, gender should be included in the predictive model, and the chest, wrist (Back), back and arm showed relatively high influence on functional group estimation.

In the stepwise analysis, overall accuracy was 30 ~ 65%, which is relatively low. The functional group data is discrete number, while the skin temperatures are continuous, and this can be the reason of low accountability which was also mentioned in the similar study (J.-H. Choi and Yeom 2019). To address this issue, this study used J48 algorithm to develop a classification model which treats functional group as a nominal data. The accuracy was calculated by 10-fold cross validation, and Table 12 shows the results.

The arm, wrist (Back) and chest showed valid accuracy higher than 80%, and gender appeared significantly lower than local body skin temperatures. The combination of all variables can achieve 99% accuracy, however this study suggested the combination of gender and the skin temperature of the arm and wrist (back), which achieved 98.80 % of accuracy, considering practical application. It is also interesting to compare that the priority of the attributes are different from the similar study (J.-H. Choi and Yeom 2017b), where they developed the estimation model for the overall thermal sensation. This reveals the possibility that different sets of physiological attributes are required to estimate occupant's thermal sensation and productivity, which need to be investigated further.

Table 11: Stepwise analysis results (Cumulative R-sq) for high and low functional group estimation (%)

Step	All participants		Male		Female	
1	Chest	19.03	Back	9.79	Chest	49.71
2	Back	26.35	Forehead	27.61	Wrist (Back)	58.79
3	Wrist (Back)	29.35	Arm	33.22	Arm	64.12
4	Arm	29.86	Neck	34.53	Wrist (In)	65.02
5	Forehead	30.02	Wrist (Back)	37.84		
6	Neck	30.11	Wrist (In)	38.77		
7			Chest	39.83		

Table 12: 10-cross validation results of high and low functional group estimation

#	Attribute	Accuracy (%)
1	Arm	87.03
2	Wrist (Back)	83.38
3	Chest	83.34
4	Forehead	79.38
5	Neck	76.21
6	Back	73.74
7	Wrist (Front)	70.88
8	Gender	60.84
8+1	Gender + Arm	91.84
8+1+2	**Gender + Arm + Wrist (Back)**	**98.80**
1-8	Gender + 7 local body skin temperatures	99.76

CONCLUSION

This study investigated the relationship between occupants' thermal sensation, physiological responses, and cognitive performance to quantify the priorities of the selected physiological responses for the occupant's optimal productivity, through the series of human experiments including 39 participants.

In this study, it was revealed that there is a significant correlation between overall thermal sensation, local body skin temperatures, and cognitive test scores. The cognitive test results (OSPAN) was higher when indoor temperature was relatively low or when participant's thermal perception was either slightly cool or cool. Most local body skin temperatures were negatively correlated with the cognitive test scores, therefore it is safe to conclude that a little low temperature has a significant impact to promote occupant's productivity. Additionally, this study also determined the priority and optimum combination of local skin temperatures and gender for cognitive performance estimation. Considering practical application, gender, arm, and wrist (Back) were determined as an optimal combination for cognitive performance estimation, with 98.80% accuracy.

The result of this study can be applied to the HVAC system as a control algorithm. The results can contribute to develop personalized control system, with the help of related technologies, such as smart watch, thermographic camera, and smart fiber. However, even though the results showed significance statistically, this study was based on the participants' data who are mostly in their 20s (Avg. 25.6), which means in their prime physical condition. Thus, larger number of participants are still required to investigate other variables, such as age, BMI, ethnicity, etc. Broader temperature range should be considered in the future study as well as subjective factors, such as thermal preference. Lastly, various types of cognitive performance test should be included to increase the validity and accuracy of the analysis results.

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