Measuring Human Comfort for Smart Building Application: Experimental Set-Up using WSN

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ABSTRACT
Realizing the importance of the effect of thermal comfort on the health and productivity of people, many researches have been done in this area at the beginning of last century. These works are carried out in climatic chambers or in situ, or models or with human beings. They aim to identify the conditions of comfort and acceptability of the thermal environment without trying to understand the mechanisms involved. Following this work, several indices of thermal comfort have been developed based on models of thermal comfort. The developed models are different; there are the physical models are often measuring instruments whose physical responses to the thermal environment are similar to those of the human body. Besides, one of the key objectives in studying the behavior of people in certain environmental and personal conditions is to predict the degree of satisfaction/dissatisfaction with the thermal environment. The objective is to propose a predictive model of the thermal sensation of the users of indoor environments using subjective variables.

CCS Concepts
• **Information systems applications → Human factors**
• **Hardware → Sensor applications and deployments.**

Keywords
Human Thermal Comfort; Productivity; Thermal Sensation; HVAC; Indoor Environment; Predictive Model; Subjective Variables.

1. INTRODUCTION
The relationship between people, environment, and buildings is complex and interdependent and has a great impact on human comfort and energy efficiency. Temperature setting of the heating, ventilation, and air conditioning (HVAC) systems provides users the ability to control their comfort in the built environments and the same time the ability to save energy. In cooling the building, the lower the temperature setting, the higher the energy consumed by the HVAC system, which constitute around 50% of the total energy needed by buildings. Many authors have conducted, for decades, investigations related to thermal comfort and indoor environment, which includes developing models and indices, conducting experiments in climatic chambers, field surveys and establishing standards of comfort and evaluation methods [12]. However, these models are relatively static and don't include parameters that are personalized to the occupants. This paper develops an experimental set up to measure human comfort using wireless sensor network and explores the impact of biometric parameters, namely height and girth, on occupant comfort. These parameters can be dynamically captured current sensing system such as smart door system we developed [24] and can be utilized to dynamically adapt the comfort of the environment.

Comfort as defined by ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineer) is "the state of mind that expresses satisfaction with the thermal environment" [2]. As being a complex and subjective concept, thermal comfort depends on each individual and it is a way to measure occupant satisfaction, which impacts productivity and quality of life [3]. Comfort is related to the heat balance of the body as a whole with which depends on air temperature, humidity, radiation (radiant temperature) and air velocity. However, comfort setting in commercial building is static and is governed by regulatory standards (e.g., ISO 7730:2005 [21] and ASHRAE 55:2013[2]) that establish optimal levels of environmental parameters, which are also references in verifying proper operation of the HVAC systems.

In recent years, several scientific studies have analyzed aspects related to thermal comfort and/or indoor air quality in educational institutions [8, 11, 14, 25, 27, 34, 35]. Others have observed the behavior of users and their thermal, physiological and psychological responses to the built environment in order to develop mathematical models that can predict these responses to guarantee thermal comfort [4]. With the advent of the Internet of Things (IoT) it is possible to monitor the temperature in different rooms [4] through embedded wireless sensor systems using XBee modules. These modules use the IEEE 802.15.4/ZigBee protocol to implement ad-hoc networks, presenting low power consumption, auto-configuration, and self-healing. The theoretical approach made in [31] shows that WSN networks make it possible to reduce energy consumption in zone-based HVAC systems. The use of con-

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-cepts related to IoT applications and WSN networks provides a cost-effective technological alternative to improve efficiency of HVAC systems. For these IoT based solution to be efficient while satisfying the comfort of occupants, they need to dynamically capture the user comfort and adjust the system accordingly. The research question that this paper is addressing is, is it possible to dynamically infer user actual preference using height, weight, and girth of occupants?

In this paper, we implemented a WSN-based system that monitors indoor air quality using CO2, temperature and relative humidity and controls the temperature while interacting with occupants to evaluate their comfort. We recruited 10 occupants and measured their perceived comfort as a function of temperature and humidity. We also collected demographic data and biometric information such as weight, height, and girth. The contribution of the paper is as follow:

- Designed, developed and implemented a WSN based environment monitoring system that takes user inputs and controls the temperature of the environment to capture user comfort perception.
- Collected data from 10 participants and derived a correlation between user comfort and height and girth.

The remain of the paper is organized as follow. Section II present the background and related work. The proposed system is described in section III. Section IV presents the methodology and data collection while section V presents conclusion and analysis.

2. BACKGROUND

Since the beginning of the twentieth century, researchers have studied the behavior of users and their thermal, physiological and psychological responses to the built environment in order to develop mathematical models that can describe thermal comfort. Houghton [17] develop the concept of effective temperature (ET) and is considered one of the greatest contributions in research related to thermal comfort. Gagge [15] demonstrated the application of the first law of thermodynamics for the human body, describing the energy exchange between the body and the environment.

A great number of indices have been established for analysis of internal climates for the purpose of HVAC control systems [13, 29, 30, 32]. Chu [7] studied the Least Enthalpy Estimator (LEE) index to calculate the difference between the climatic conditions of the environment and the optimum comfort condition. The LEE combines the concept of thermal comfort, through the ET index and the enthalpy theory to generate this thermal comfort index. In particular Fanger [13] proposed the Predicted Mean Vote (PMV) index based on a set of variables that include temperature, relative humidity, mean radiant temperature, air velocity and personal factors such as metabolic rate and clothing thermal rate. PMV is currently the most recognized index and is adopted by ISO 7730:2005 and ASHRAE standards. PMV is modeled by the following formulate:

$$PMV = \left[0.303 \cdot e^{(-0{,}036.M)} + 0.028\right] .$$
$$(M - W) - 3.05 \cdot\ 10^{-3}. [5733 - 6.99 \cdot (M - W) - p_a] - 0.42 \cdot [(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) - 3.96 \cdot 10^{-8} \cdot\ f_{cl} \cdot [(t_{cl} + 273)^4 - (\overline{t_r} + 273)^4] - f_{cl} \cdot h_{cl} \cdot (t_{cl} - t_a) \quad (1)$$

Where, M denotes the metabolic rate of a person, W effective mechanical power, $\overline{t_r}$ mean radiant temperature, p_a relative humidity, t_{cl} the clothing surface temperature, t_a indoor (ambient) temperature, f_{cl} is the clothing surface area factor, h_c is the convective heat transfer coefficient.

The PMV index can be determined in two different ways:

- Direct use of the equation (1);
- Consulting tables containing PMV values for various combinations of activity level, ambient temperature and air velocity.

The ISO 7730-2005 standard considers that space has thermal comfort conditions when no more than 10% of occupants feel uncomfortable. ISO 10551:1995 [20] recommends to have PMV measured subjectively by probing the individuals present in the thermal environment. These individuals can vote using a seventh thermal scale (Table 1) that indicates the individual thermal preference. This scale is also used by ISO 7730-2005 and ASHRAE 55-2010.

Table 1. 7-point ASHRAE scale in PMV model

Vote	Comfort level
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

In order to decrease the number of people who are dissatisfied with the environment, Fanger [7] developed also the Predicted Percentage of Dissatisfied (PPD) index for given environment. The PPD establishes a quantitative estimate of the percentage of people who are thermally uncomfortable due to the cold or heat (votes -3, -2 for cold and +2 and + 3 for heat) [23].

$$PPD = 100 - 95 \times e^{-0{,}03353 \times PMV^4 - 0{,}2179 \times PMV^2} \quad (2)$$

The relationship between PMV and PPD is shown in Figure 1 where it is perceived that even with $PMV = 0$, which indicates that the individual would be in thermal comfort, the PPD=5%. This means that even maintaining optimal climatic conditions of temperature, humidity, and so forth, there would still be 5% of people dissatisfied with the thermal environment.

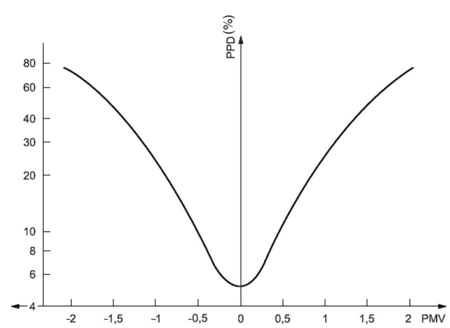

Figure 1. Relationship between PMV and PPD [21].

From Fanger's research, new studies developed adaptive indices for the thermal comfort. Humphreys [18] proposed an adaptive model that makes the internal temperature of building be also function of the external temperature. This study is based on the concepts of acclimatization, and the factors considered may include inherent characteristics of demographics such as gender, age, and social class. The adaptive comfort has a clear potential for energy savings, with an estimate that can reach up to 10% savings in final energy consumption for each degree of comfort zone [9]. Indeed, the ASHRAE 55 standard is used to evaluate thermal comfort by the adaptive model by presenting a graphical model of thermal comfort (Figure 2) which relates the comfort temperature T_{comf}, with the monthly mean external temperature T_m. Brager [5] proposed equation (3) that support this model.

$$T_{comf} = 0.31 \cdot T_m + 17.8 \tag{3}$$

- T_{comf} is the comfort temperature;
- T_m is the monthly mean external temperature.

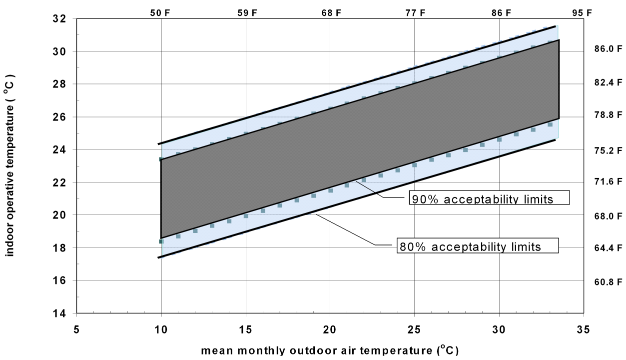

Figure 2. Adaptive thermal comfort model [1].

Another adaptive model that can be used to evaluate thermal comfort conditions is presented in EN 15251 [6]. This model defines the operative comfort temperature, T_{oc}, as a function of the exponentially-weighted running means external temperature, T_{rm}, through equation (4).

$$T_{oc} = 0.33 \cdot T_{rm} + 18.8 \tag{4}$$

T_{rm} is the running mean external temperature for the last 7 days.

$$T_{rm} = (T_{ed-1} + 0.8\,T_{ed-2} + 0.6\,T_{ed-3} + 0.5\,T_{ed-4} + 0.4\,T_{ed-5} + 0.3\,T_{ed-6} + 0.2\,T_{ed-7})/3.8 \tag{5}$$

T_{ed-i} is the daily mean external temperature for the previous day (i).

These comfort indices are used as input to a control system that set the temperature reference to adjust the comfort level of the building. Currently, research works have been directed towards more advanced control structures, based on artificial intelligence (AI) taking in consideration user preference over time [26]. These AI based systems need to capture user preferences as suggested by the PMV method [13]. In commercial applications user preference is either ignored (following a standard setting of the temperature and adjusting if in case there a complaint). In other new emerging systems, user preference is also captured with smart phone apps. With the advent of smart sensing system, the [24] it is possible to capture occupant bio-metric information such as height, width. This paper explores the use of biometric information to predict user preference and without the need to use a smart phone app. As a first step we developed an experimental set up to measure the user comfort and determine the relationship between biometric information and comfort.

3. SYSTEM DESIGN OVERVIEW

3.1 System Architecture

To measure occupant comfort, we develop a wireless sensor network-based monitoring and a control system that can interact with the occupant and adjust the environment based on their liking. The system records both the environment parameters (*temperature, humidity, and CO2*) as well as their comfort level indication using ASHRAE thermal sensation scale. The data is then collected for further analysis to measure the comfort level indicated by the user and find any correlations. The proposed system is equipped with the following three modules:

- Arduino based sensor node for data collection and control;
- Raspberry-Pi as a hub system to manage locally the data collection and control;
- Web server for data archival and user interaction during the experiment.

Figure 3 illustrates schematically the block diagram of different components of the system. The data collected by the sensors are sent to the Raspberry-Pi that plays the role of processing and control. It evaluates the observed values of the monitored parameters and adjusts the setpoints of the environment based on the user preference indication. In addition, data collected by the system are sent in real time to a remote server, allowing the provision of a web page for easy access by the researchers.

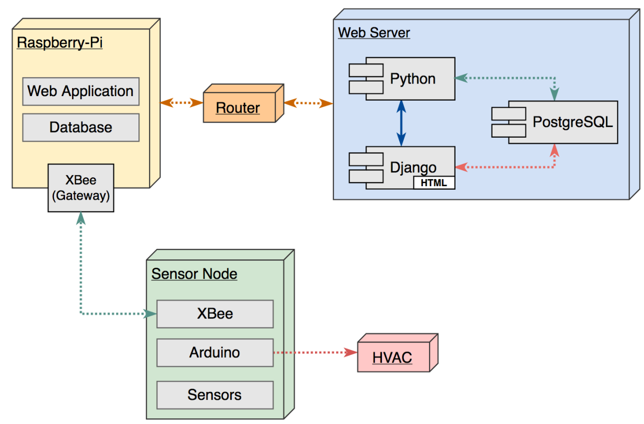

Figure 3. General architecture of the system.

In the following sections we will describe the implementation of modules that make up the system. To do so we will divide it into two parts: *hardware and software*.

3.1.1 Hardware components

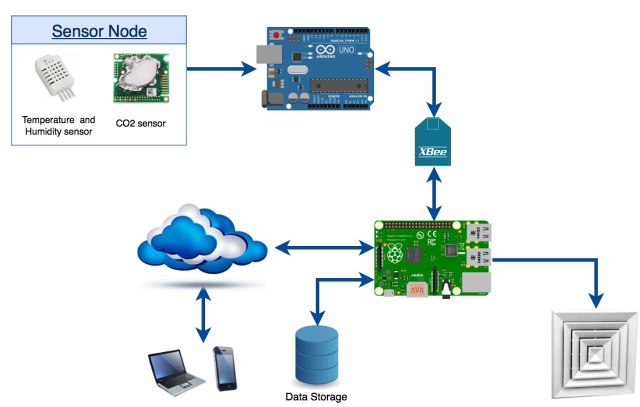

Figure 4. Figure showing the hardware components used for the development of the system.

Figures 4 and 5 show the hardware component and flow diagram of the prototype implementation. We will describe the system starting from the sensors and actuators where data is generated and acted upon to the server where data is stored.

3.1.1.1 Arduino based sensors and actuators

In this project, the Arduino was used as an embedded computer system whose function was to measure the temperature, relative humidity, and CO2 of the air through sensors and to activate HVAC control devices through the analog pressure-based actuators. Arduino is an open-source electronic prototyping platform, based on flexible, easy-to-use hardware and software. The microcontroller on the board is programmed with the Arduino programming language, based on Wiring language, and the Arduino development environment, based on Processing environment [33].

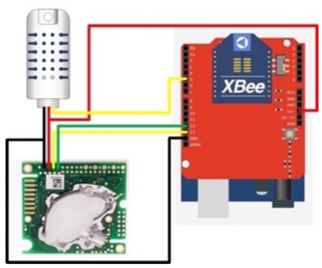

Figure 5. Sensor node schematic.

Arduino hardware has set of sockets or pins that allows them receive or transmit signals and add additional boards called Shields, thus expanding the features of this architecture, such as adding GPS receivers, LCD screens, Ethernet network connection and drive for SD memory card. In this project we used a shield to interface a Zigbee interface. The ZigBee Protocol (XBee) was used to communicate with the Raspberry PI. The implementation of the standard ZigBee communication is performed through the XBee S2 modules [36]. Arduino interfaces the following sensors and actuators.

DHT22 relative humidity and air temperature sensor which is also known as AM2302 or DHT03, is a digital temperature and relative humidity sensor, encapsulated in a white plastic structure, and has a low power consumption. The sensor is digital and communicate data via MaxDetect 1-wire bus. It is calibrated in a precision chamber and the calibration coefficient is saved in an EPROM OTP sensor memory [10].

K-30 Carbon dioxide sensor that provides the CO2 reading of the environment and incorporates an automatic calibration mechanism, called ABC (Automatic Background Calibration) [22]. It is digital sensor that communicates through serial port configured to operate at a speed of 9600 bits/s.

Pressure based transducer, which controls the air handler to open and close the airflow to the room to adjust the temperature of the room.

3.1.1.2 Raspberry-Pi

The Raspberry PI (RPI) is a very powerful low-cost ARM based processor board capable of performing functions like any computer with the advantage that it has a reduced physical structure [19]. We used RPI-Model B which is based on ARMv7 processor and runs Linux distribution operating system.

3.1.2 Software design and programming environment

Data collection at the server is implemented using the Message Queue Telemetry Transport (MQTT) protocol. MQTT is a publish/subscribe network protocol, where some devices publish their messages to the server and then the server publishes the messages to other devices that subscribe to them [23]. This protocol is lightweight, simple and open, making it ideal for M2M (Machine-to-Machine) and the Internet of Things (IoT) application [19].

RPi disposes a flexible Python library that implement clients that publishes and subscribes to the MQTT broker. In addition, the algorithm running on RPI (figure 7) was developed using Python. The algorithm communicates with a webservice that was developed using the Django framework. The web application stores data on PostgreSQL data management system and implements control and dynamic update of the sensed data.

Django [16] is open source framework based on MVC (Model-View-Controller) paradigm. It has its own embedded data based (SQLite) and implements AJAX (Asynchronous JavaScript and XML) for dynamic update of data. PostgreSQL [28] is an advanced open source relational object database management (ORDBMS) system. It uses a client/server model and uses multiprocessing instead of multithreading to ensure system stability. PostgreSQL has interoperability with another DBMS: SQL; the storage is reliable, consistent and robust with a powerful, flexible and efficient manipulation. One of the main advantages of this database engine is simplicity in both installation and administration. As it is free, it can be available for any organization that would implement information systems.

The system is implemented in room 219 in the Technology building at the University of Houston and tested using 10 participants. Figure 8 shows the temperature and humidity of the environment. As the temperature of the environment is being decreased, the relative humidity increases automatically. This is concurrent with the thermodynamics and the relationship between relative humidity and temperature of the environment.

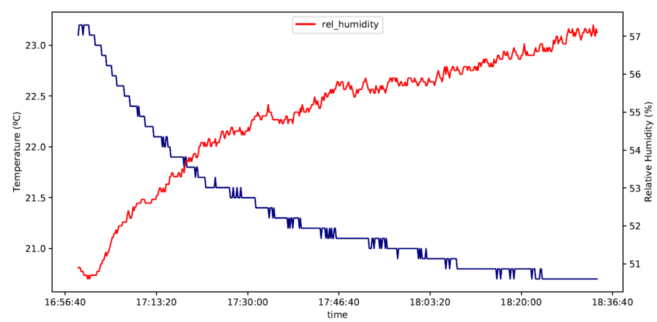

Figure 6. Temperature vs. Humidity.

4. EVALUATION

The main research question we're addressing with this work is "do temperature preference of people is the actual level where they feel comfortable?" and then is it possible to find a correlation between temperature preference and biometric indices such as height, width, and weight? To answer these questions, we designed two scenarios that we took the participants through.

4.1 Scenario Description

The study was conducted in the same room where the set up was implemented. Participants from the student population were recruited following the UH IRB procedures. They were asked about their demographics and the temperature preference that will be taken in consideration in the scenarios described below. The experiment was run during the summer session, and each

Figure 7. Data-flow diagram for entities connection.

participant was expected to wear similar clothes (given that the weather is very hot outside in the Houston area).

While going through the test, the participant had access to the designed website in which they increased or decreased the temperature according to the following two strategies (see figures 8 and 9), (we note that the user didn't see the actual temperature of the room but he could change it with a precision up to 1°F).

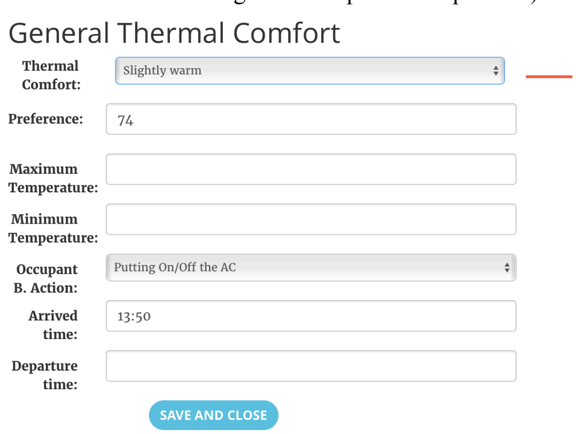

Figure 8. Figure showing the general thermal comfort information stated by the user at the beginning of the experiment.

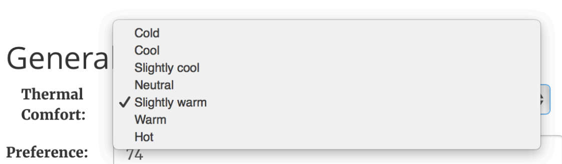

Figure 9. Figure showing that the user expressed his/her thermal sensation according to the seventh-point scale.

- Strategy 1:
  - Set up a temperature at 4 degrees lower than the preference (stated by the user in questionnaire);
  - The user will be asked to state his sensation when getting his conformable zone;
  - The system will keep increasing the temperature and ask the participant to stop it when they feel not comfortable.
- Strategy 2:
  - Set up a temperature at 4 degrees higher than the preference (stated by the user in questionnaire);
  - The user will be asked to state his sensation when getting his conformable zone;
  - The system will keep decreasing the temperature and ask the participant to stop it when they feel not comfortable.

Each test had a maximum duration of 90 minutes and at the end of the test the perception and evaluation questionnaires were applied, the activities of the lab followed normally, and the temperature was adjusted again, according to the desire of the individuals.

4.2 Data Analysis

One of the key objectives in developing this WSN-based system is to collect data to predict the degree of satisfaction/dissatisfaction with the thermal conditions using parameters such as age, height, girth as well as weight. With the development of such model, users won't need to enter their satisfaction value that could be used as part of a vote entry in the PMV model. This will represent a paradigm shift in the way systems set the temperature in commercial buildings.

The following table list the variables used in the model:

Table 2. The variables and indicators of the research model.

	Variables	Indicators
Comfort Parameters	**Personal**	Height (m) Girth (m)
	Ambiental	Air temperature (°C) Relative Humidity (%)
Subjective Parameters	**Thermal Sensation**	Seventh-point perception scale and preferences of ISO 10551:1995
	Thermal Evaluation	

We used the logistic regression model to correlate thermal comfort indexes to independent variables. The higher the correlation coefficient, the greater the degree of association between variables. The objective of these correlations is to verify the existence of an association between the dependent variable and the independent variables, and thus select those that will be used in the modeling.

4.3 Results Analysis and Discussions

4.3.1 Treated Variables

In this section we describe what variables will be treated. Since this is an exploratory study, several variables of different natures were collected. In the sample treated, 70% of the respondents were males. The mean age of participants was 25 years, with a standard deviation of 4.51 years, the weight was 68.08 kg with a standard deviation of 11.55 kg as well as the height with a mean of 1.65 m and a standard deviation of 0.086 m.

Thermal Perception Vote that contains the thermal perception of the interviewees. Each participant was asked to record his thermal perception during all sessions, using the scale shown in table 3. The arithmetic mean of the responses of each respondent was obtained, in order to get their average sensation throughout the experiment. Hence, the average perception of the participants was -0.9 (-1.0 for males and -0.67 for females), which means the sensation of the participants regarding the environment was between neutral and slightly cool.

Ambient thermal perception which is designed to express the ambient thermal perception according to the interviewees. The rating scale used for this is shown in table 3.

Table 3. Scale of thermal evaluation of the environment.

Value	Evaluation
0	Comfortable
1	Slightly comfortable
2	Uncomfortable
3	Very uncomfortable

In this work, the variable ATP has an average of +0.63, i.e., the majority of respondents considered the environment between comfortable and slightly comfortable.

Air Temperature (T_A) contains the air temperature measured in the indoor environment in which the experiment conducted. It is a continuous variable with a mean varied between the minimum of 17 °C and the maximum of 23 °C.

Relative Humidity (R_H) represents the relative humidity measured indoors. It is a continuous variable and varies between a minimum of 30% and a maximum value of 60%.

4.3.2 Questionnaire analysis

In order to collect their perceptions, the occupants completed a questionnaire based on ASHRAE 55/2010 standard. Table 4 summarizes the average and the standard deviation of the demographic and biometric data about the participants (M is for male and F is for Female).

Table 4. Describing the characteristics of the participants.

No. Subject		Age (years)	Height (m)	Width (m)	Weight (kg)
M	70%	26 ± 2.24	1.65 ± 0.05	0.74 ± 0.01	60 ± 3.00
F	30%	27.67 ± 1.53	1.75 ± 0.03	0.84 ± 0.02	74.71 ± 3.64

The statistical analysis (average and standard deviation) of the subjective thermal sensation data is presented in tables 5 and 6. Table 5 summarizes the data collected for strategies 1 and 2 as soon as the participants starts the strategies. While table 6 summarizes the data collected for strategies 1 and 2 as soon as the users reaches their preferred temperature. It is observed that 70% of the users were feeling between [slightly cool – cool] in strategy 1, while 50% of them report feeling warm in strategy 2.

Table 5. Percentages of votes for thermal perception and corresponding T_A and R_H (classified by gender).

Thermal Perception	No. Subject		T_A (°C)		R_H (%)	
	M	F	M	F	M	F
Hot	0	0	---	---	---	---
Warm	0	0	---	---	---	---
Slightly Warm	1	1	21.6	24.4	37	32.4
Neutral	1	0	20.5	---	35	---
Slightly Cool	2	1	21.39 ± 0.40	20	32.25 ± 1.77	24.8
Cool	3	1	21.00 ± 0.52	20.16	30.33 ± 5.61	34.5
Cold	0	0	---	---	---	---

(a) Strategy 1

Thermal Perception	No. Subject		T_A (°C)		R_H (%)	
	M	F	M	F	M	F
Hot	2	0	22.89 ± 1.00	---	39.10 ± 6.51	---
Warm	4	1	23.11 ± 0.38	23.3	40.58 ± 8.23	32.2
Slightly Warm	1	2	22.33	23.15 ± 1.07	36.3	35.75 ± 6.72
Neutral	0	0	---	---	---	---
Slightly Cool	0	0	---	---	---	---
Cool	0	0	---	---	---	---
Cold	0	0	---	---	---	---

(b) Strategy 2

In addition, during the experiment most of the participants (90% for both strategies) stated that they were feeling comfortable or slightly warm when getting their preferences.

However, in strategy 1, 70% of the participants were feeling neutral when the system reached their preference temperatures that they indicated when the interviews (30% of them felt comfortable when reaching 22.22°C). While for strategy 2, 75% of those who were feeling neutral when reaching 22.22°C.

Table 6. Percentages of votes for thermal evaluation for temperature and humidity (classified by gender).

Thermal Perception	No. Subject		T_A (°C)		R_H (%)	
	M	F	M	F	M	F
Hot	0	0	---	---	---	---
Warm	0	0	---	---	---	---
Slightly Warm	3	2	23.14 ± 0.32	22.77	46.97 ± 3.46	31.95 ± 1.34
Neutral	3	1	22.04 ± 0.32	22.22	38.98 ± 6.85	37.2
Slightly Cool	1	0	21.67	---	34.2	---
Cool	0	0	---	---	---	---
Cold	0	0	---	---	---	---

(a) Strategy 1

Thermal Perception	No. Subject		T_A (°C)		R_H (%)	
	M	F	M	F	M	F
Hot	0	0	---	---	---	---
Warm	1	0	22.77	---	41	---
Slightly Warm	1	1	23.33	22.77	45.9	32.2
Neutral	5	2	22.22 ± 0.68	22.5 ± 0.39	39.07 ± 10.34	34.11 ± 2.96
Slightly Cool	0	0	---	---	---	---
Cool	0	0	---	---	---	---
Cold	0	0	---	---	---	---

(b) Strategy 2

4.3.3 Modeling and results interpretations

The choice of a model involves a compromise between the complexity of the model, which in this case is observed by the number of variables involved, and by the observed error. Thus, the analysis starts with the total of the regressors and after fitting the model, the AIC (Akaike Information Criterion) index which is the information criteria is observed; lesser is the better. Next, the least significant variables according to the t-test were removed (if $P > 0.0001$).

The variable to be modeled is vote which implies the thermal sensation vote taking ordered values in the range [-3, +3]. In order to apply a logistic model, it is more suitable to reduce the number of categories (the seventh scale) into three as:

- Comfortable for $vote = 0$;
- Slightly uncomfortable for $vote = -1$ and $vote = 1$;
- Uncomfortable for $vote \leq -2$ and $vote \geq 2$.

Table 7. Results of Ordinal Logistic Regression model

	Coefficient	St. Error	t_value	p-value
Height	1007.3056	65.0984	15.4736	5.23062e-54
Width	4722.7533	11.4312	413.1453	0.0000e+00
Weight	-677.8715	151.5496	-4.47293	7.7153e-06
Intercept_1	5168.9363	21.5724	239.6085	0.0000e+00
Intercept_2	5183.9627	86.4890	59.9377	0.0000e+00
Intercept_3	5184.0575	92.7800	55.8747	0.0000e+00

After the selecting the variables, the following potential predictors were found in the model: height, girth and weight. Hence, after fitting the model to the data we got the estimate probabilities of comfortable $\hat{\pi}_1 = \mathrm{P}(vote = 0)$, slightly uncomfortable $\hat{\pi}_2 = P(vote = 1 \mid\mid vote = -1$, and uncomfortable $\hat{\pi}_3 = P(vote \leq -2 \mid\mid vote \geq 2)$.

For one unit increase in Vote, we expect about 1007.3056 increase in the extended value of Height in the Log Odds scale, given that other variable i.e., Width in the model is held constant.

The model is then:

$$\hat{\pi}_1 = \frac{e^{-(5168.9363+1007.3056\,\mathrm{Height}+4722.7533\,\mathrm{Width}-677.8715\,\mathrm{Weight})}}{1+e^{-(5168.9363+1007.3056\,\mathrm{Height}+4722.7533\,\mathrm{Width}-677.8715\,\mathrm{Weight})}} \quad (6)$$

$$\hat{\pi}_2 = \frac{e^{-(5183.9627+1007.3056\,\mathrm{Height}+4722.7533\,\mathrm{Waist}-677.8715\,\mathrm{Weight})}}{1+e^{-(5183.9627+1007.3056\,\mathrm{Height}+4722.7533\,\mathrm{Waist}-677.8715\,\mathrm{Weight})}} \quad (7)$$

$$\hat{\pi}_3 = \frac{e^{-(5184.0575+1007.3056\,\mathrm{Height}+4722.7533\,\mathrm{Waist}-677.8715\,\mathrm{Weight})}}{1+e^{-(5184.0575+1007.3056\,\mathrm{Height}+4722.7533\,\mathrm{Waist}-677.8715\,\mathrm{Weight})}} \quad (8)$$

All the coefficients are statistically significant (*p-value <0.0001*), this implies that there is a model correlating the categorized vote and the presented independent variables. However, the obtained pseudo-R^2 was 0.464 (i.e., 46.4%) shows that the regression model is still poor. The factors that contribute to this low adherence of the data model are a small sample size (only 10 data points). A more significant and better distributed sample would bring a better fitting model, as well as the inclusion of additional variables which will be part of future work. Despite all this, the proposed model provides some insight into the topic in question, showing biometric factors influencing the individual thermal preference and perception.

In the model presented, the risk factor associated with the gender variable cannot be totally reliable, since in the sample the number of female participants is much higher that the number of participants of the opposite gender.

Finally, it is concluded that the use of the multinomial model brought benefit to the data analysis, and hence a contribution to ergonomics, and its use may bring even more future benefits.

5. CONCLUSION

Smart buildings are expected to be equipped with sensors that can provide information about occupants. This paper proposed an experimental implementation of WSN-based system that can measure the thermal comfort of users and adjust the environment accordingly. The experiment was deployed at a real laboratory room at the University of Houston and data was collected about 10 participants. The data was statistically analyzed and a logistic regression model was developed to fit the data. The model shows that a logistic regression predictive model of thermal sensation could be developed using biometric information of occupants. Indeed, height and waist could be used as input to a predictive model of thermal sensation for smart buildings. Given the sample size of the population, the authors are planning to increase the sample size of the population and develop more accurate model. These results are significant, as they will pave the way to develop systems that adjust the environment automatically to users occupying it.

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