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# Neural Network Models Using Thermal Sensations and Occupants' Behavior for Predicting Thermal Comfort

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## ABSTRACT
It is important to create comfortable indoor environments for building occupants. This study developed neural network (NN) models for predicting thermal comfort in indoor environments by using thermal sensations and occupants' behavior. The models were trained by data on air temperature, relative humidity, clothing insulation, metabolic rate, thermal sensations, and occupants' behavior collected in ten offices. The models were able to predict similar acceptable air temperature ranges in offices, from 20.6°C to 25°C in winter and from 20.6°C to 25.6°C in summer. The comfort zone obtained by the NN model using thermal sensations in the ten offices was narrower than the comfort zone in ASHRAE Standard 55, but that obtained by the NN model using behaviors was wider than the ASHRAE comfort zone. This investigation demonstrates alternative approaches to the prediction of thermal comfort.

## KEYWORDS
Indoor environment, Model training, Data collection, Air temperature, Relative humidity

## INTRODUCTION
Currently, people in North America spend roughly 90% of their time indoors. Therefore, it is important to create comfortable, healthy, and productive indoor environments for the occupants. To improve an indoor environment for building occupants, one would need a good method for evaluating the environment. Current evaluation methods for thermal comfort can be divided into two categories: using questionnaires under controlled indoor environments (Fanger, 1970; Chow et al, 1994; Cheong et al, 2006) and without varying controlled parameters (De Dear, 1998; Mishra et al, 2013). However, the two types of thermal comfort model do not consider the influence of occupants' behavior on thermal comfort. Therefore, the two categories of evaluation methods may not be ideal for evaluating the thermal comfort in actual environments.

Evaluation of thermal comfort should be based on thermal sensations in actual environments rather than in controlled environments. In an actual environment such as an office, occupants go about their daily activities in surroundings with which they are familiar. However, numerous studies (Langevin et al, 2015; Luo et al, 2014) have found that occupants' behavior changes their thermal sensations, because the behavior impacts their expectations of thermal comfort. Therefore, it is necessary to develop an evaluation method for indoor thermal comfort that considers occupants' thermal sensations and behavior in actual environments. The purpose of this study is to develop methods for evaluating thermal comfort in actual environments by using thermal sensations and occupants' behavior.

## METHODS

### Data collection

This investigation collected data on air temperatures, relative humidity, clothing levels, thermal sensations, thermostat set points, and room occupancy in ten offices in the Ray W. Herrick Laboratories at Purdue University, Indiana, USA. Among the ten offices, half of them were multi-occupant student offices, and the rest were single-occupant faculty offices. Five faculty members and more than fifteen students participated in the data collection. This study collected thermostat set point data from the building automation system (BAS) every five minutes. Each office had a thermostat that enabled the BAS to control the air temperature set point within the range of 18.3°C to 26.7°C. We used data loggers (Sper Scientific 800049) in each office to collect air temperature and relative humidity every five minutes. We used a questionnaire to collect the thermal sensation (-3 for cold, -2 for cool, -1 for slightly cool, 0 for neutral, +1 for slightly warm, +2 for warm, and +3 for hot) and clothing level from the occupants when they were inside the offices as well as their behaviors in adjusting the thermostat set point or their clothing level, arriving at the office, and leaving the office. This study assumed that occupants actively adjusted the thermostat set point for their comfort, because the cost of maintaining a comfortable environment is typically not on their minds. Note that all data collection in this study was approved by Purdue University Institutional Review Board Protocol # 1704019079.

### Neural network models

With the collected data, this study used neural network models to correlate the indoor environmental data with occupants' thermal sensation and behavior. As this investigation sought to correlate occupants' thermal sensation and behavior with indoor environmental parameters, it was necessary to identify two separate NN models. As shown in Figure 1, an NN model has a layered structure usually comprised of three layers: an input layer, a hidden layer and an output layer.

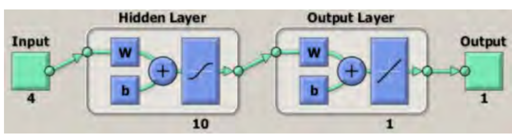


Figure 1. Structure of the NN models, with four input parameters in the input layer, ten neurons in the hidden layer, and one output parameter in the output layer. The "w" and "b" in the hidden layer and output layer represent weight matrix and bias, respectively. The transfer function in the hidden layer was a logistic function

This investigation used an NN model to predict thermal comfort. According to the PMV thermal comfort model (Fanger, 1970), six parameters have an impact on thermal comfort: air temperature, relative humidity, clothing insulation, air velocity, metabolic rate, and mean radiant temperature. Our study assumed that the mean radiant temperature was the same as the room air temperature. Our measurements showed that the air velocity in the offices was less than 0.2 m/s, and thus the impact of air velocity on thermal comfort can be neglected. To predict thermal comfort, the NN model requires only four input parameters. According to the ASHRAE Handbook – Fundamentals (ASHRAE, 2017), the occupants could sit or walk inside their offices, and the corresponding metabolic rates were 60 W/m$^2$ and 115 W/m$^2$, respectively. The insulation values for different clothing ensembles worn by participants in this study was also based on ASHRAE Handbook - Fundamentals.

This investigation used another NN model to predict occupants' behavior. We assumed that the input parameters of this NN model were again air temperature, relative humidity, metabolic rate, and clothing insulation. The output of the behavioral NN model is the occupants' behavior.

We used "-1" for raising the thermostat set point or adding clothes when occupants feel cool, "0" for no behavior when the occupants feel that the environment is acceptable, and "1" for lowering the thermostat set point or reducing the clothing level when they feel warm.

This study used Matlab Neural Network Toolbox to build and train the two NN models. The training process entailed finding the weight matrix and bias in the NN models that would minimize the error between the model outputs and targets. The targets were the actual thermal sensation and behavior occurrences that had been collected. We used the Levenberg-Marquardt algorithm to train the two NN models.

## RESULTS

### Data collection

Data were collected in all four seasons of 2017. In each season, we collected the data for more than one month in every office. Table 1 shows the percentage of occupants' behavior occurrences at different thermal sensations in the offices. When the occupants felt hot (+3) or cold (-3), they always adjusted the thermostat set point or their clothing level. However, if the occupants felt warm (+2) or cool (-2), the percentages of behavior occurrences were only 72.2% and 53.3%, respectively. When they felt slightly warm (+1) or slightly cool (-1), the percentages of behavior occurrences dropped further to 17.6% and 26.4%, respectively. According to the collected data, there were several cases in which occupants felt uncomfortable, but no behavior occurred. For example, when feeling uncomfortable immediately after entering the office, some occupants preferred to adjust the thermostat set point after some time had passed. In other cases, the HVAC system may not have responded quickly to the latest adjustment, yet the occupant waited for a while even though he/she may have felt uncomfortable. There are several possible reasons. First, sometimes the control of the HVAC system had some time delay. Second, if the occupant raised or lowered the set point a lot, it would take more time to respond. Third, the room air temperature was hard to respond the low set point if the office was occupied with many occupants and their computers were on, or because of the sunlight in exterior zone. In these cases, the occupants' behavior did not reflect their true desires in regard to controlling the indoor environment. For multi-occupant offices, meanwhile, an acceptable indoor environment may have been a compromise among several occupants. Some occupants may have felt uncomfortable, but they did not adjust the thermostat set point because the other occupants were not complaining about the comfort level, or they were unsure whether others would feel the same way. Table 1 correlates occupants' behavior occurrences with their thermal sensations.

Table 1. Percentages of behavior occurrences under different thermal sensations in the offices

| *Thermal sensation* | *Behavior occurrences* | | |
|---|---|---|---|
| | -1 | 0 | 1 |
| -3 | 0% | 0% | 100% |
| -2 | 0% | 46.7% | 53.3% |
| -1 | 0% | 73.6% | 26.4% |
| 0 | 0% | 100% | 0% |
| 1 | 17.6% | 82.4% | 0% |
| 2 | 72.2% | 27.8% | 0% |
| 3 | 100% | 0% | 0% |

### Comfort zones predicted by the two NN models

Figure 2 illustrates the comfort zones for the office environment in winter and summer obtained by the NN model using thermal sensations. The default clothing level was 1.0 Clo and 0.5 Clo in winter and summer in ASHRAE Standard 55 (ASHRAE, 2013), respectively. We assumed that the office occupants were sitting, and thus their metabolic rate was 1.0 MET. For the comfort zone outlined in green in the figure from slightly cool to slightly warm, the air temperature ranged from about 20.6°C to 25°C in winter and from about 20.6°C to 25.6°C in summer. The lower and upper bounds of the absolute humidity in the comfort zones were the minimum and maximum of the absolute humidity found in the data, which may not be equivalent to the comfort boundaries. Within the range of the data, humidity does not seem to have been a key thermal comfort parameter in the offices.

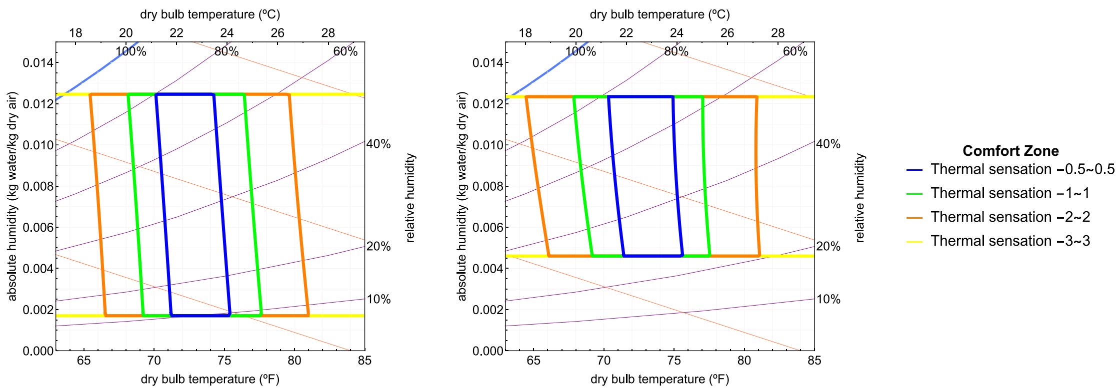


Figure 2. Comfort zones for office environments in winter (left) and summer (right) obtained by the NN model with the use of thermal sensations.

Figure 3 illustrates the acceptable zones for an office environment in the winter and summer seasons obtained by the NN model using behavior. An acceptable environment is one in which occupants can work without adjusting their behavior, although they may feel slightly uncomfortable. An unacceptable environment is one in which occupants have to adjust the thermostat set point or their clothing level. This study used the information in Table 1 to define the acceptable zones for various percentages of the occupants. The blue, green and orange zones in Figure 3 represent the humidity and temperature ranges within which 88%, 76% and 15% of the occupants did not adjust the thermostat set point or their clothing level. Under the assumption that "no behavior" signifies an acceptable environment, the acceptable indoor air temperature for 76% of the occupants ranged from 21.1°C to 25.6°C in winter and 20.6°C to 25°C in summer. The results of the behavior NN model also indicate that the humidity had little impact on behavior in the offices in different seasons. This was because our data were collected within a narrow humidity range. Furthermore, office occupants could not signify their humidity preferences by any of the adjustment actions that were recorded.

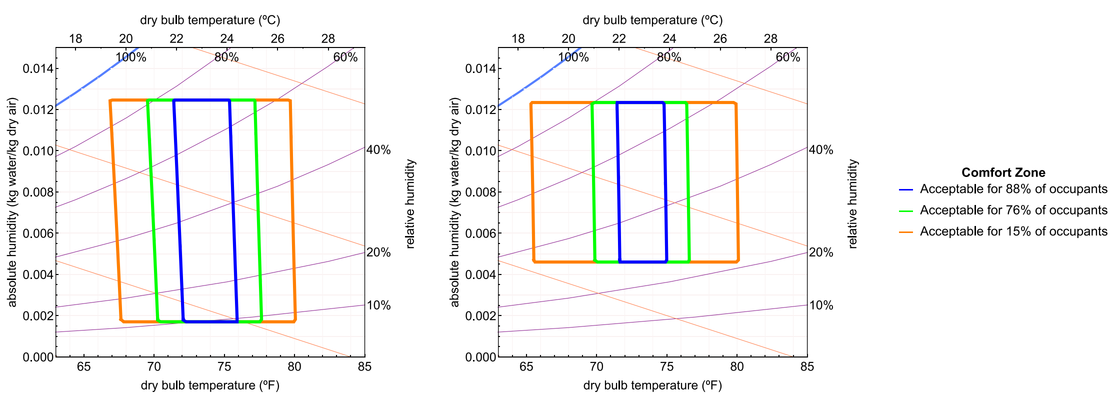


Figure 3. Acceptable zones for office environments in winter (left) and summer (right) obtained by the NN model using behavior.

The acceptable zones obtained by the NN model with the use of behavior, shown in Figure 3, are similar to the comfort zones obtained by the NN model using thermal sensations, displayed in Figure 2. The good correlation between the two sets of results implies that one may evaluate the indoor environment in offices by using either of the NN models.

**Comparison of the comfort zones with the ASHRAE comfort zones**

Figure 4 compares the comfort zones obtained by the two NN models with the ASHRAE comfort zones. The blue outlines indicate the ASHRAE zones, which uses a PMV range from -0.5 to 0.5 and an acceptability of 80% for the occupants. The comfort zones obtained by the NN model using thermal sensations are narrower than the ASHRAE comfort zone. This implies that the office occupants were pickier than the occupants participated in the study of obtaining ASHRAE comfort zone. However, the comfort zone obtained by the NN model using behaviors was wider than the ASHRAE comfort zone, especially in summer. This is because we assumed that the absence of behavior signified an acceptable environment. However, in some situations as stated before, the occupants may have felt that the environment was unacceptable, yet they exhibited no behavior. Thus, these situations led to a higher acceptability of the indoor environment in the offices.

In addition, the comfortable room air temperature predicted by the two NN models in summer was about 2.2°C lower than the temperature of the ASHRAE comfort zone. One possible reason is that the office occupants were not responsible for the electricity bill and often set the temperature lower than would be desirable in the comfort zone in order to cool the room more quickly. Actually, setting a lower temperature does not cause faster cooling but over cooling.

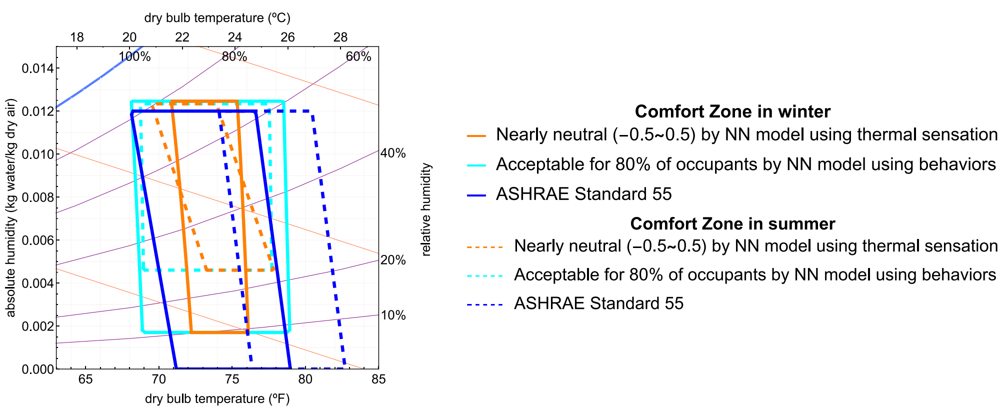


Figure 4. Comparison of the comfort zones obtained by the two NN models and the ASHRAE comfort zones in winter and summer.

**DISCUSSIONS**

The NN models have been developed to determine the relationship between the adjustment of thermostat set point and clothing level or thermal sensations, and air temperature and relative humidity. High-quality data were necessary for training the models. However, we used a questionnaire to collect clothing level data. The choices on the questionnaire were limited, but an overly long list might have confused the participants. In addition, we used metabolic rates for sitting and walking without accounting for differences in gender or age. Furthermore, the actual activities of the occupants were not limited to sitting and walking. Any discrepancies may have significantly impacted the robustness of the training process and thus the prediction accuracy of the NN models. In addition, since humidity was not controlled in the offices, the models may not be appropriate when the humidity level exceeds the range of the study.

**CONCLUSIONS**

In this study, we collected data in ten offices in Indiana, USA and built two NN models to determine the relationship between air temperature and relative humidity, and occupants' thermal sensations and behavior. This investigation led to the following conclusions:
(1) Under the assumption that a slightly cool to slightly warm environment is comfortable for occupants, the air temperature should be between 20.6℃ and 25℃ in winter and between 20.6℃ and 25.6℃ in summer. For a 76% acceptance rate, the corresponding indoor air temperature should be between 21.1℃ and 25.6℃ in winter and between 20.6℃ and 25℃ in summer. The two NN models provided similar results. Hence, we can use the behavior of occupants to evaluate the acceptability of an indoor environment in the same way that we use thermal sensations.

(2) The comfort zone obtained by the NN model using thermal sensations in the ten offices was narrower than the comfort zone in ASHRAE Standard 55, but the comfort zone obtained by the NN model using behavior was wider than the ASHRAE zone.

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