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# Personalized human comfort in indoor building environments under diverse conditioning modes

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ABSTRACT

In practice, building heating, ventilation, and air conditioning (HVAC) systems are essentially set at nominal levels according to industry guidelines. However, several studies have demonstrated that this conventional practice is unlikely to meet the thermal requirements of occupants in a single or multi-occupancy space due to occupants' diverse preferences, activities and needs. To improve occupants' thermal comfort, this study develops and tests a smartphone application framework which is capable of dynamically determining the optimum room conditioning mode (mechanical conditioning or natural ventilation) and HVAC settings (thermostat setpoint) in single and multi-occupancy spaces. The “personalized” HVAC control framework integrates environment data (obtained from sensors) with human physiological and behavioral data (obtained from wearable devices, polling apps) in a smartphone application we developed for human-building interaction. In the operation phase, occupants' thermal preferences are continuously predicted using the personalized comfort models, developed from the training data through the Random Forest classifier, when determining the optimum HVAC control strategies. Two case studies are conducted to demonstrate the capabilities of the developed framework to improve thermal comfort in single and multi-occupancy spaces.

## 1. Introduction

Thermal comfort of individuals is an important factor that affects occupant's overall satisfaction about the building indoor environment. According to a survey comprised of over 34,000 responses in 215 office buildings throughout North America and Finland, only 39% of respondents are satisfied with the thermal environment in their workspace [1]. People's thermal sensation and preference depend not only on the environmental factors such as temperature and humidity, but also multiple aspects from human perspective including physiological factors (e.g., gender, heart rate), psychological factors (e.g., stress, beliefs and attitudes), and behavioral factors (e.g., activity, clothing level) [2–4]. As a result, people's thermal sensation and satisfaction vary from one person to another. For example, gender has been proven to be closely related to thermal comfort where previous studies suggested that women prefer a relatively higher temperature than men in offices [5]. Considering the interactions with buildings (e.g., turn on a fan, open the window), occupants can have diverse thermal sensations within the same room [6]. Even for the same person, his/her thermal sensation and preference may vary significantly with temporal and spatial variations [7].

In typical office buildings, a centralized HVAC setpoint is usually chosen by facility managers based on industry guidelines such as American Society of Heating, Refrigeration, Air-Conditioning Engineers Standard (ASHRAE 55). However, this conventional strategy of maintaining the room temperature at a static value is unlikely to meet the thermal requirements of occupants in single or multi-occupancy spaces for several reasons. First, air temperature is non-uniform across the room where occupants sitting near the air outlets or in direct sunlight may have a different thermal sensation compared to others. Second, using room temperature as the only indicator of thermal comfort is inadequate to reflect an occupant's thermal state. For example, people who are doing heavy physical work may prefer a cooler environment than people at resting state due to their different metabolic rates [8]. Furthermore, several studies suggested that even room temperature is set according to the recommended indoor conditions, there is still a high percentage of dissatisfaction among the occupants about the indoor thermal environment, which reveals the inconsistency of people's actual and predicted thermal sensations [9]. In some cases where occupants don't have control over the thermostat, facility managers have to painfully deal with the frequent hot/cold complaints and constantly adjust the system to meet occupants' diverse thermal requirements [10].

The most widely used approach to evaluate occupant's thermal

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comfort is the Predicted Mean Vote (PMV) model developed by Ref. [8] which is adopted by ASHRAE Standard 55. The PMV model considers four environmental factors: air temperature, relative humidity, air velocity and mean radiant temperature, and two human factors: metabolic rate and clothing level to predict occupants' mean thermal sensation in a seven-point scale from $-3$ (cold) to 3 (hot). Predicted Percentage of Dissatisfied (PPD) is associated with PMV index which quantitatively describes the percentage of dissatisfied occupants under any given thermal conditions [11]. However, Fanger's PMV model has several limitations. First, the PMV model is developed based on the feedback of a large group of people under steady state conditions in laboratory settings (influential factors maintain a constant condition over time). In addition, human factors in the PMV model are assumed the same across all human subjects without the consideration of personal variations. This can lead to discrepancies between the actual and predicted thermal sensation [12–14]. Second, the PMV model is originally developed for mechanically ventilated buildings and assumes the human body as a passive recipient of thermal stimuli (Yao el al. 2009). However, this approach doesn't truly reflect human conditions in naturally ventilated environments. For example, several field studies in naturally ventilated buildings suggested that occupants' adaptive behaviors (e.g., open the window) also play an important role in their thermal preferences. This behavioral adaption can result in a wider comfort range and indicates that the PMV model is not accurate for naturally ventilated buildings [2,15–17].

To improve thermal comfort in indoor environments given occupants' diverse thermal preferences, several researchers investigated the "human-in-the-loop" approach which allows for human-based adjustments of the HVAC system [18–28]. "Human-in-the-loop" denotes the incorporation of human actual thermal sensation in the operation of HVAC system. However, these prior studies have several limitations such as lack of automatic control, low comfort prediction accuracy due to limited data sources, absence of natural ventilation in the HVAC control strategy. To address these limitations, this study proposes a personalized HVAC control framework which is capable of dynamically determining the optimum conditioning model (mechanical conditioning or natural ventilation) and HVAC settings (thermostat setpoint) with reduced human participation. To achieve this, personalized comfort prediction models are developed based on the environment and human data collected from various sources to evaluate each occupant's thermal comfort level over time. In mechanical conditioning mode, occupants' net votes (i.e., the average voting), as well as, the predicted preference from comfort models collectively determine the temperature setpoint. If comfort models suggest thermal comfort can be maintained in naturally ventilated conditions, occupants will be notified to open the window.

The paper is organized to first provide a detailed review of existing research studies on the personalized control of thermal comfort, discuss their main limitations and outline the specific contributions of this work to this body of knowledge. Then the development of personalized HVAC control framework and comfort prediction model is explained in detail. Finally, two case studies (single occupancy and multi-occupancy) are presented to demonstrate the feasibility of the proposed framework and the results are discussed.

## 2. Related work

This section will present a review of relevant literature. First, we reviewed selected studies to illustrate the common approaches of personalized conditioning implemented thus far, as well as the limitations of each study. Then we discussed the findings from studies of thermoregulation which demonstrate the feasibility of predicting thermal comfort using human bio-signals. Third, we introduced the influences of natural ventilation on thermal comfort and the difficulties of selecting conditioning mode. In this study, we incorporate human bio-signals and conditioning model selection in the personalized HVAC control framework to address the limitations of prior studies as discussed in the first subsection.

### 2.1. Personalized conditioning through human participation

With the rapid development of wireless sensor network, mobile devices and ubiquitous computing, researchers have explored various approaches to implement personalized control of indoor climate using various forms of human feedback [18–25,27–30]. In these studies, indoor environment data and human feedback on the ambient conditions are used to assess the indoor thermal comfort level and thus adjust the HVAC system using different decision algorithms.

In general, these prior studies can be divided into two categories: the PMV-based approaches and non-PMV-based approaches. In the PMV-based approaches (e.g., [20,22,23,26], researchers collected occupants' actual thermal sensations from phone applications to adjust the setpoint according to the PMV model. For example [20,22], and [23] developed participatory sensing applications to collect occupant's thermal vote. The decision algorithms allowed real-time correction of setpoint based on occupants' overall thermal votes. However, these studies have the limitations inherited from the PMV model, such as the assumption of steady state conditions, lack of personal variations, and often times researchers have to estimate some parameters in the PMV model (e.g., mean radiant temperature, metabolic rate) which may significantly deviate from the real situation.

In the non-PMV-based approaches (e.g., [18,19,21,24,25,27–30], researchers usually aimed to model occupants' thermal sensation using data collected from the indoor environment. For example [21], used a wrist-worn sensor to measure environment conditions such as ambient temperature, humidity and collect occupant's comfort state (hot, cold, and neutral) through voting. In this study, the authors trained a Fisher Discriminant classifier using two features (room temperature and humidity) to find the boundary of hot and cold sensations. Ref. [25] developed a smartphone application to collect occupants' thermal preferences (from cooler to warmer) under different ambient temperature conditions in mechanically conditioned offices. In this study, the fuzzy controller only applied the ambient temperature to predict comfort levels. Similarly [28], developed a complaint-driven control system which collects occupants' complaints (hot or cold) and environment conditions (air temperature and relative humidity) to determine their comfort state under both transient and steady state conditions [30] compared two HVAC control strategies (i.e., user satisfaction based control and empirical setpoint based control) and concluded that involving user feedback in the control loop can achieve a satisfied thermal environment. However, considering the diverse influential factors of thermal comfort from the human perspective, the lack of human data (e.g., skin temperature, activity level) in these studies may cause the model to be less representative under some circumstances (e.g., people with different workload can have diverse thermal comfort levels under the same room temperature).

[27] proposed a "model-free" approach which used only temperature data from the building management system (BMS) as environment inputs and avoided the cumbersome data collection required in the PMV model. For each control step, the temperature setpoint was directly changed by a fixed value according to occupants' overall net vote. However, as room temperature is the only factor collected to evaluate thermal comfort, this "model-free" approach is unable to predict thermal comfort if any factor from human or environment perspective changes. Thus, such a model-less system heavily relies on human reports during its operation, which can be cumbersome for its users.

In the market, some commercial products such as Comfy, CrowdComfort, Keen and Wally also adopted the idea of continuously collecting occupants' thermal votes and indoor conditions to maximize thermal comfort in the workplace through the optimization of temperature setpoint and air flow. Although these products involve human participation in the control loop, they have the same limitation as the