Towards Unveiling the Interplay of Occupant Health, Comfort and Building Energy Consumption

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ABSTRACT

Promoting healthy indoor environment conditions for office workers, in line with reducing building energy consumption, requires thoughtful design choices. While researchers have been attentive to workers' comfort in the built environment, health-comfort relationship has often been overlooked and the energy consequences of meeting well-being and comfort needs are not well understood. We aim to investigate the complex interplay between an office worker's health and comfort, and their relationship with building energy consumption. As a preliminary investigation, we analyzed the data collected from an office worker over a 16-week period using two different types of data streams: worker's perceived physical and mental health symptoms through hourly Ecological Momentary Assessments (EMAs), and continuous indoor air temperature measurements in their office spaces. We first identify healthy temperature ranges that support worker's health, and we then evaluate the impacts of these healthy setpoints on energy consumption. This paper is a preliminary attempt at investigating the interplay of occupant health, comfort, and building energy consumption.

INTRODUCTION

The intersection of occupant comfort, well-being, and energy efficiency is becoming a focal point within the field of Human-Building Interaction (HBI). Sick Building Syndrome (SBS) manifests with occupants who experience a broad spectrum of physical and mental illnesses because of extended exposure to suboptimal Indoor Environmental Quality (IEQ) factors. Symptoms range from skin rash, migraines, fatigue, stress, to musculoskeletal problems (Ghaffarianhoseini et al., 2018). Thermal comfort and its effects on occupant well-being has been extensively studied as well. SBS and thermal comfort are both influenced by IEQ factors such as indoor air temperature. With over 80% of our time spent indoors (Klepeis et al., 2001), it is important to support occupant well-being and comfort while understanding the impact on building energy consumption.

Building setpoints analyses provide an insightful approach into understanding the energy consequences of comfortable setpoints. An essential element of this discussion involves recognizing human behavior and thermal preferences as a pivotal factor influencing energy consumption (Alhorr et al., 2016). The existing body of research reveals a significant trend favoring larger temperature setpoints for enhanced energy savings, but often compromising on occupant comfort (Jafarpur & Berardi, 2021). However, much of this evidence is derived from thermal comfort models, lacking longitudinal empirical data that reflect real-world conditions. Additionally, understanding the relationship between SBS and energy consumption remains largely unexplored. The prevalence of SBS is notably higher in mechanically ventilated buildings (i.e., most energy demanding buildings) (Alhorr et al., 2016), emphasizing the need to address this issue for both environmental and well-being considerations.

Furthermore, we recognize there exist longitudinal real-world studies in understanding SBS, although their application remains somewhat limited (Nezis et al., 2022; Sarkhosh et al., 2021). These studies often missed capturing day-to-day nuances of SBS with continuous IEQ variations throughout the day, by asking participants to reflect on how they felt only at the end of the data collection period. This approach falls short in considering the duration, frequency, and range of environmental exposure that shape SBS experiences. Conducting longitudinal studies on thermal comfort, furthermore, is challenging due to economic and practical constraints. While some looked at providing non-intrusive sensing solutions with occasional human-sensor interaction (Quintana et al., 2021), it is important to consider more frequent granular data collection of thermal comfort and SBS to fully account for their variability throughout the day.

Motivated by this background, this study aims to explore the intricate interplay between occupant health, thermal comfort, and building energy consumption. This paper presents preliminary results from a longitudinal study that combines granular data collection of an office worker's SBS and thermal comfort, objective IEQ measurements (i.e., air temperature) of their office space, and the corresponding energy implications of these metrics.

METHODS

Study Design and Participants. This pilot study was conducted within one office space in the University of Southern California (USC). We gathered data pertaining to environmental and health conditions from August 26th to December 13th, 2023. This preliminary study included the participation of one healthy, adult male individual, aged 29. The participant was free to use the office whenever they wanted, and data was collected during working days. The participant was instructed to not answer Ecological Momentary Assessments (EMAs) unless they were present at their office for at least 30 continuous minutes. The earliest EMA was at 9:00 am, and the latest was at 7:00 pm. IRB approval was obtained for this study prior to its initiation.

Measures. During this study, we measured two different types of data, including: (1) IEQ factors, which were collected using an indoor environmental monitoring device, and (2) health conditions and comfort levels using EMAs. First, we employed the AWAIR Omni as an Internet of Things (IoT) device for the purpose of monitoring IEQ in a high-resolution, real-time mode (Demanega et al., 2021). We placed the IEQ monitoring device atop the desk of the worker at a height of 0.8 meters from the floor calibrated as per factory recommendations. The device records air temperature data every minute along with other IEQ metrics. Second, we developed an EMA tool consisting of two validated and standardized questions, which were administered via automated email every hour. The first question aimed to ascertain the participant's comfort levels with regards to indoor temperature using a 5-point Likert scale, ranging from 1, indicating "Extremely uncomfortable" to 5, indicating "Extremely comfortable." The second question assessed perceived physical symptoms (e.g., eye-, skin-, nose-related symptoms, headache, fatigue) and mental health symptoms (e.g., low motivation, anxiety, trouble concentrating) that may arise due to IEQ factors. The participant was asked to indicate whether they had experienced any of these symptoms over the past hour.

Healthy and Comfortable Temperature Setpoints. The investigation aimed to examine the influence of temperature on health and comfort. Temperature was segmented into several ranges, each containing an equal quantity of data points, which later constituted our setpoints. We selected these ranges to ensure even temperature data distribution across. For each category, the frequency of the participant's reports of thermal comfort, discomfort, or neutrality (4-5, 1-2, and 3 points on 5-point Likert-scale, respectively) was evaluated. Additionally, the occurrences of SBS versus their absence were systematically coded. These metrics were then calculated as a percentage of time they occurred within a specific temperature range.

Building Energy Modeling. The U.S. Department of Energy (DOE) provides commercial building references as a benchmark for energy efficiency and design standards. We used the DOE reference for medium-office buildings, updated with ASHRAE's 90.1 2013 standards (ASHRAE, 2013). This reference is representative of the participant's office building, and it also provides an easily reproducible experimental setup. The medium-office reference is a three-story 4,982 m^2 office building with 15 thermal zones, modeled for 268 occupants with various occupancy levels throughout the day. The building uses a multi-zone Variable Air Volume (VAV) Heating, Ventilation, and Air Conditioning (HVAC) system for both its cooling and heating operations. The HVAC system is linked to a dual temperature thermostat, which we later modified to meet the setpoints of each simulation. We conducted simulations using EnergyPlus; we set the simulations in ASHRAE's 3B climate (i.e., warm dry, Los Angeles) and we used an .epw weather file from USC. We defined the run period for each simulation from August 26th to December 13th, 2023, to match the data collection period. For each simulation, we changed the thermostat setpoints (both heating and cooling) and kept all other parameters constant. We first ran a simulation with the baseline DOE medium-office building. We then performed simulations for each healthy and comfortable temperature ranges, by modifying the thermostat temperatures accordingly. We only modified the highest heating and lowest cooling setpoints recommended by ASHRAE on working days (i.e., excluding Sundays and holidays) (ASHRAE, 2013).

RESULTS

Health and Thermal Comfort Setpoints. Table 1 below delineates the temperature ranges under consideration and the corresponding probabilities of experiencing SBS as opposed to not experiencing them. Additionally, the table details the likelihood of perceiving thermal discomfort, neutrality, and comfort for one participant at different temperature ranges.

Table 1. Probability of experiencing SBS and perceiving thermal discomfort, neutrality, and comfort.

Temperature range (ºC)	Prob. of having SBS	Prob. of not having SBS	Prob. of thermal discomfort	Prob. of thermal neutrality	Prob. of thermal comfort
15.6-18.9	0.20	0.80	0.20	0	0.80
18.9-20.0	0.38	0.62	0.14	0	0.86
20.0-20.6	0.30	0.70	0.09	0	0.91
20.6-21.1	0.43	0.57	0.08	0	0.92
21.1-21.7	0.43	0.57	0.15	0	0.85
21.7-22.2	0.38	0.62	0.13	0	0.87
22.2-22.8	0.39	0.61	0.26	0	0.74
22.8-23.3	0.46	0.54	0.15	0	0.85
23.3-23.9	0.52	0.48	0.11	0.04	0.85
23.9-24.4	0.36	0.64	0.08	0	0.92
24.4-27.2	0.38	0.62	0.31	0.08	0.61

Building Energy Consumption, Health, and Comfort Interplay. Figure 1 below shows the impact of the determined healthy and comfortable temperature setpoints on building energy consumption. We observe that building energy consumption decreases as setpoint temperatures increase. The lowest setpoint range (15.6-18.9ºC) is associated with the highest building energy consumption at 657.7GJ, whereas the highest setpoints (24.4-27.2ºC) is associated with the lowest building energy consumption with 507.8GJ highlighting a 22.8% decrease in building energy consumption between the two farthest setpoints.

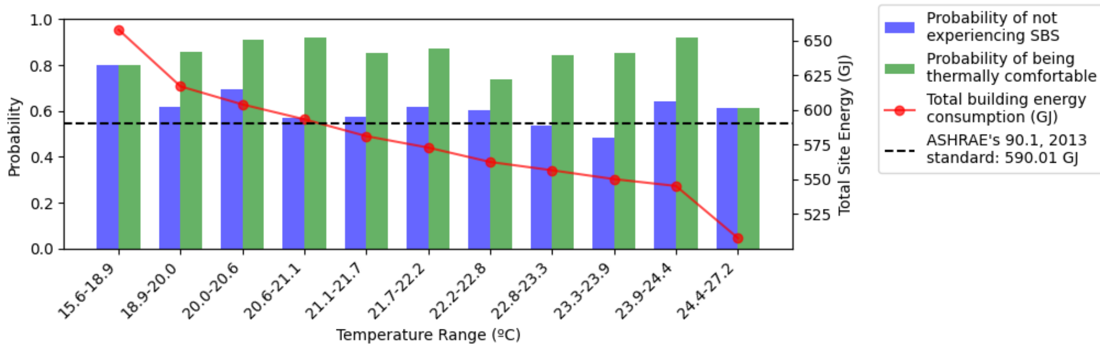

Figure 1. Prevalence of SBS and probability of perceived thermal comfort at different temperature setpoints, and corresponding building energy consumption.

We also observe that the remaining setpoints have narrower temperature ranges, with all but one employing half-degree intervals. As setpoints increase, there is a corresponding decrease in associated energy consumption. This relationship is, however, not strictly linear. We observe a more pronounced decrease in energy consumption for the initial lower setpoints, followed by a less abrupt decrease as setpoint temperatures increase. Finally, we note that setpoints with temperatures exceeding 21.1°C show an energy consumption below that of the baseline model recommended by ASHRAE (which had setpoints ranging from 21ºC to 24°C during work hours).

CONCLUSIONS AND FUTURE DIRECTIONS

Our results suggest that, for this one participant, the probability of being healthy (i.e., not experiencing SBS), on average, decreases with increasing temperature setpoints. While the probability of being thermally comfortable is somewhat inconclusive (Figure 1), the optimal range appears to be between 20ºC and 24ºC, with a notable outlier for temperatures in the range 22.5 ± 0.3ºC. We observe that although higher temperature ranges are associated with greater energy savings, they negatively affect thermal comfort as suggested by previous studies (Jafarpur & Berardi, 2021). These observations suggest that a moderate increase in operating temperatures would have a positive effect on building energy consumption without significantly compromising health and comfort.

The findings, however, cannot be generalized as the data was limited to one participant and one IEQ factor only. To ensure greater reliability, future research should consider incorporating a larger and more diverse cohort of participants. It is important to explore how healthy setpoints vary (or not) amongst diverse building occupants. Additionally, the effects of other IEQ and work-related factors remain unexplored. Environmental metrics such as air quality, relative humidity, as well as intensity and work type, all influence occupant well-being (Alhorr et al., 2016; Awada et al., 2023; Ghaffarianhoseini et al., 2018) and could ultimately play a role in building energy consumption. Future work should account for these metrics in subsequent simulations to study their interplay (e.g., coupling energy and contaminant simulations to investigate the interplay of IEQ factors on building energy consumption).

Furthermore, the study timeframe does not allow to fully represent the energy implications of healthy and comfortable setpoints. For instance, the significant decrease in building energy consumption with higher setpoints can be attributed to the mild Southern California climate and the limited simulation period. Simply put, the favorable weather conditions result in a substantial increase in cooling load when the building operates at lower temperatures. Year-long data collection should also be considered to provide more in-depth insights, and support more personalized, season-dependent setpoints. Future work could investigate the tradeoffs of healthy and comfortable environments on building energy consumption in different climates.

Finally, we note that narrow temperature bands may not align with practical operational practices adopted by building managers. Operating within such tight setpoints can strain HVAC systems, potentially yielding results that deviate significantly from real-world scenarios. Future research could investigate the impacts of varying building setpoints sizes and explore these effects and interaction with occupant health and comfort. We also note that the temperature setpoints used for this study were arbitrary, and future work will explore more accurate setpoints.

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