Investigating Occupant Thermostat-adjustment Behavioral Patterns in Different Heat Pump Operation Modes: A Field Experiment

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ABSTRACT

The advent of smart connected thermostats and their capability of data collection have spurred many studies exploring how occupants adjust thermostat setpoints to achieve comfort, along with the various factors influencing their setpoint preferences. The objective of this study is to investigate thermostat-adjustment behavioral patterns in households with single-stage heat pumps coupled with backup heaters and smart thermostats. A field study was carried out in 30 houses within a newly constructed residential community. The experiments consist of two parts: 1) a baseline mode featuring a heat pump paired with an auxiliary heater controlled by default thermostat heuristic rules, and 2) a comparison mode where the auxiliary heater is activated to provide the majority of heating. The findings from the field study suggest that several occupants exhibit lower setpoint preferences during the winter season for the comparison mode that has higher supply air temperatures. Furthermore, four distinct setpoint-increasing behaviors are identified, contributing to the setpoint differences between the two modes. Among these, the behavior associated with staging the auxiliary heater and lower heat pump capacity during cold weather conditions is the primary difference between the two operation modes. A noticeable decrease in this behavior is observed in the comparison mode.

Keywords: Thermostat-adjustments Behaviors, Setpoint Preferences, Thermal Comfort, Heat pump

1. INTRODUCTION

For residential buildings in the United States, space heating accounts for about 43% of total end-use energy consumption, and natural gas consumption represents 45% of this total (U.S. Energy Information Administration, 2020a). As concerns about climate change intensify and the need for decarbonization gains prominence, transitioning away from fossil fuel-based heating systems (e.g., gas furnaces) through electrification is of paramount importance. Air-source heat pumps offer a promising option for heating. Nonetheless, the heating capacity of heat pumps, as well as their efficiency, are both negatively impacted by a decrease in ambient temperature. In contrast, furnaces maintain a consistent capacity and produce higher supply air temperatures due to their utilization of natural gas combustion for heat generation. Moreover, previous studies have pointed out comfort-related issues with reduced capacity, such as low supply air temperature and slow response of indoor air temperature (Paul W. Francisco et al., 2004). Even when a low supply temperature is warm enough to condition a room, it can be colder than skin temperature (e.g., 90°F), and thus occupants may feel cool and uncomfortable. Furthermore, Jal-Alzadeh-Azar et al. (2006) demonstrated that when occupants feel uncomfortable during heating, there is a tendency to increase the setpoint, resulting in improved comfort at the expense of higher energy consumption.

Early studies primarily relied on interviews or surveys to explore how individuals engage with their thermostats to improve their comfort (Baylon et al., 2005; Gram-Hanssen et al., 2012). In recent years, smart and programmable thermostats have surged in popularity, with 52% of U.S. households adopting them according to the 2020 Residential Energy Consumption Survey (U.S. Energy Information Administration, 2020b), enabling seamless thermostat operation and occupant interaction data collection. For example, Huchuk et al. (2018) analyzed occupant thermostat behaviors, revealing variations in setpoint preferences across different climate zones, seasons (cooling, heating, shoulder season), and households. Panchabikesan et al. (2021) identified that outdoor temperature, floor area, and house type influence thermostat setpoint preferences. Additionally, setpoint differences are influenced by residents' interactions with thermostats, such as their scheduling of setpoints and frequency of overrides. Huchuk et al. (2021) investigated users' schedule override behaviors, noting a higher frequency of overrides during evening hours and in colder outdoor temperatures. Deng et al. (2022) analyzed the "Donate Your Data" dataset using logistic regression models to explore the potential factors driving overriding behaviors. Their study revealed that indoor temperature, outdoor temperature, and system running time influence the increase in setpoints during winter.

Despite numerous studies exploring occupant thermostat setpoint preferences, as far as the authors are aware, none have investigated the setpoint differences between different heat pump operation modes. To this end, a field study was designed to gather data on occupants' thermostat adjustments under two distinct operation modes: 1) a baseline mode featuring a heat pump paired with an auxiliary heater controlled by default thermostat heuristic rules, and 2) a comparison mode where the auxiliary heater is activated to provide the majority of heating. The study aims to address the following two research questions:
Q1: Do occupants exhibit different setpoint preferences for different operation modes?
Q2: Are there observable thermostat-increasing behaviors and what are the potential drivers for those behaviors?

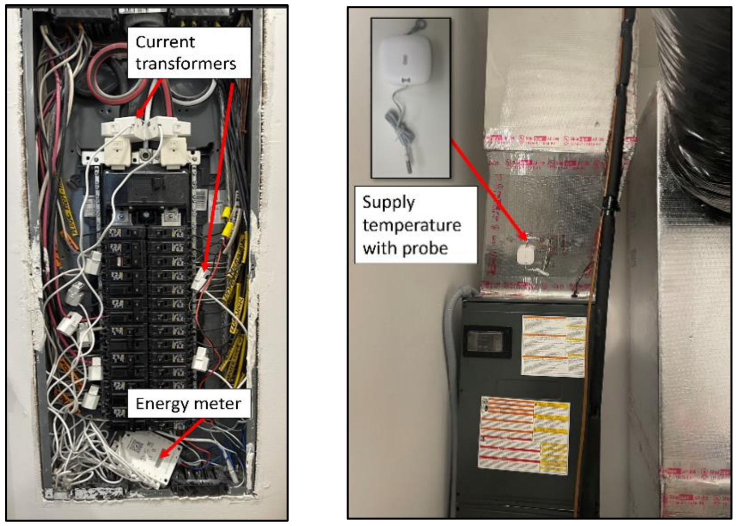
2. FIELD STUDY OVERVIEW

2.1 Research Testbed and Sensor Installation

The field study was conducted in 30 residences within a newly constructed residential community located in Indianapolis, IN (Figure 1). Most of them are two-story houses (total floor area 1,120 sq ft), and only three of them are single-story houses (1280 sq ft). Each house is equipped with a same single-stage heat pump with a backup heater, and residents are responsible for paying the utility bills. This field study was planned and carried out in compliance with Purdue’s Institutional Review Board (IRB Protocol #: 1702018811) to ensure all human subjects research was conducted ethically.

a) b)
Figure 1: a) Two-story and b) One-story single-family house.

Each household has an Ecobee thermostat that controls the heat pump and auxiliary heater. The thermostat collects operation data, such as the system setting (e.g., heating, schedule, off), temperature setpoint, indoor temperature, and occupancy status. Additionally, smart power meters and temperature sensors (range: -40°F to 221°F) have been installed to monitor disaggregated household energy consumption (e.g., heat pump and auxiliary heater) and supply air temperature respectively, as illustrated in Figure 2. All sensor data are collected via each vendor's web-based application program interface at 5-minute intervals and are stored in a MySQL database.



a) b)

Figure 2: a) An electrical panel with a smart power meter and b) a temperature sensor with a probe installed at the supply duct.

2.2 Experimental Procedure

The field experiments were carried out into two phases to gather data under two different modes: a baseline mode (December 23rd, 2023 to January 28th, 2024) and a comparison mode (January 30th, 2024 to March 1st, 2024). In the baseline mode, the heat pump and auxiliary heater were controlled based on thermostat default rules as shown in Table 1. The Ecobee thermostat will not activate the heat pump heating until the room temperature T_{in} drops 0.5°F below the setpoint T_{set}. Additionally, to save energy, the thermostat only triggers the auxiliary heater when the room temperature is 2.9°F below the setpoint. It turns off when the difference between room temperature and the setpoint is less than 1°F. While this default thermostat strategy is simple and intuitive, it may have some drawbacks in terms of thermal comfort, which will be discussed later. In the comparison mode, the heat pump and auxiliary heater were controlled by a modified thermostat operation rule as illustrated in Table 1. When the outdoor temperature T_{out} falls below 37°F, the auxiliary heater is activated to avoid potential discomfort issues such as low supply temperature and slow thermal response in cold conditions. Once the outdoor temperature is higher than 40°F, the auxiliary heater is deactivated and the heat pump is utilized to fulfill the heating load.

Table 1: Rules used in the baseline and comparison modes

Baseline (heat pump priority) mode thermostat rules	**Rules used in the comparison (auxiliary heater priority) mode**
If $\mathbf{T_{in} < T_{set} - 0.5}$ °F then	If $\mathbf{T_{out} < 37}$°F then
Heat pump heating until $\mathbf{T_{in} > T_{set}}$	Auxiliary heating.
Else if $\mathbf{T_{in} < T_{set} - 2.9}$°F then	Else if $\mathbf{T_{out} > 40}$°F
Auxiliary heating until $\mathbf{T_{in} > T_{set} - 1}$°F	Heat pump heating based on default rules

2.3 Household Data Analysis Approach

This study begins with baseline data analysis to understand the distinct thermostat settings for each unit. Subsequently, a subset of households showing active interactions with the thermostat to adjust setpoints based on their comfort needs is selected for further analysis. Using these selected units, a comparison of thermostat setpoint distributions between two modes was conducted to investigate potentially different setpoint preferences between the modes, aiming to address the first research question (Q1). Furthermore, to gain deeper insights into the underlying reasons for different setpoint preferences and address the second research question (Q2), various occupant behaviors associated with increasing setpoints were categorized and analyzed, and differences between the two modes were discussed.

3. RESULTS AND ANALYSIS

3.1 General Thermostat Settings

Figure 3 displays the thermostat settings selected by individual households during the baseline (heat pump priority) mode. The thermostat offers three distinct settings: 1) Schedule mode, where the thermostat is controlled by a schedule; 2) Off mode, in which the system is deactivated to conserve energy (e.g., residents turn off the system when they are about to leave home); and 3) Hold mode, allowing users to override the schedule and manually adjust the setpoint to meet their comfort needs. It should be noted that only 21 units were included in the data analysis due to data loss and residents moving out in some units.

The figure illustrates that each household has a distinct preference for thermostat settings. For instance, certain households (e.g., units 175 and 190) consistently utilize the hold mode instead of following a schedule. Conversely, other households maintain the systems in the off mode (e.g., units 166, 177, 163). In this study, we focus on the resident hold behaviors, aiming to understand the reasons behind setpoint-increasing actions and investigate if these actions are motivated by thermal discomfort.

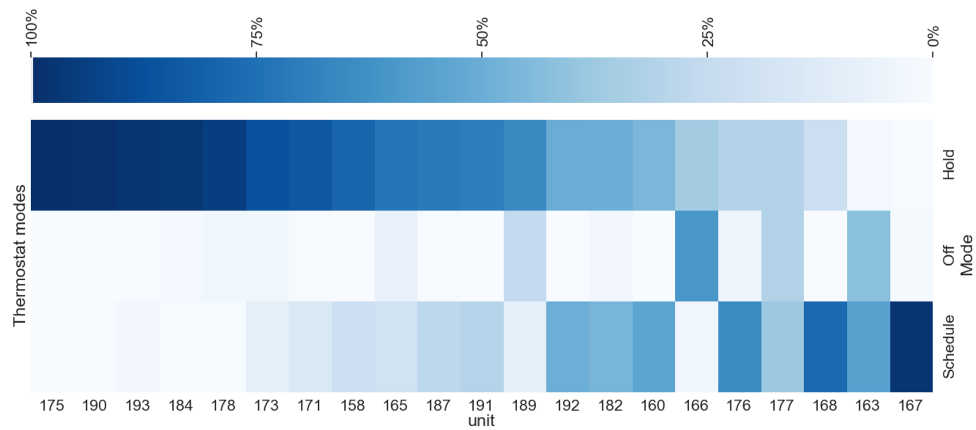


Figure 3: Each unit's thermostat setting in baseline mode (December 23rd, 2023 to January 28th, 2024).

3.2 Comparison of Thermostat Setpoint between Baseline and Comparison Modes

Figure 4 below illustrates the average daily actions of increasing setpoints for each unit in baseline (heat pump priority) mode. Certain units exhibit more frequent adjustments to increase setpoints (e.g., more than twice a day), while others display less interaction with thermostats (e.g., less than half the time each day). Thirteen households had frequent interactions with thermostats of more than 2 actions per day and were selected to evaluate differences in residents' setpoint preferences under the two modes.

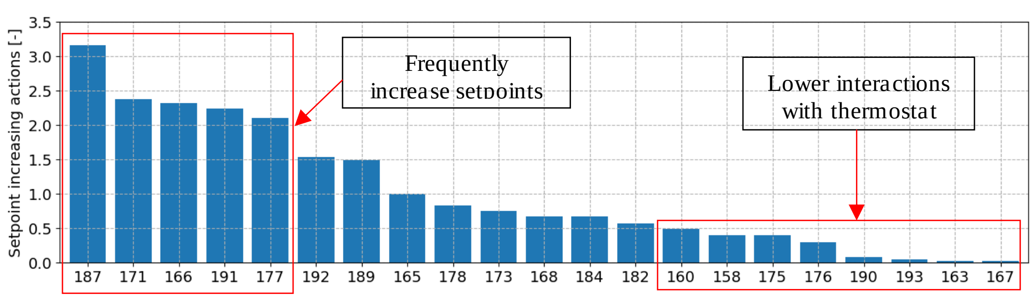


Figure 4: Average daily setpoint increasing actions for each unit in baseline mode (December 23rd, 2023 to January 28th, 2024).

To avoid the impact of varying outdoor conditions, the thermostat data from households were filtered to include only days with a daily average outdoor temperature between 19°F and 41°F. Subsequently, 21 days of data were analyzed for each mode. Figure 5a shows the boxplot of hourly outdoor temperature for the two modes. Figure 5b illustrates the change in occupants' setpoint preferences during the comparison (auxiliary heater priority) mode compared to the baseline (heat pump priority) mode. The boxplot represents the distribution of daily thermostat setpoints for each unit. The blue boxplot depicts the baseline, which utilizes default rules to control the heat pump and backup heater, while the red boxplot represents the comparison mode, where the backup heater primarily provides heating. Among these, 8 out of 13 units highlighted by the black dashed box show decreases in both the median setpoint and box in the comparison mode. For the remaining 5 units, 3 units exhibit similar median setpoints for both modes, while 2 units show slightly higher setpoints in the comparison mode. Therefore, the majority of units demonstrate lower thermostat setpoint preferences in the comparison mode. In the following sections, the behavior differences between the two modes and potential drivers are discussed to understand why occupants changed their setpoint preferences in the comparison mode.

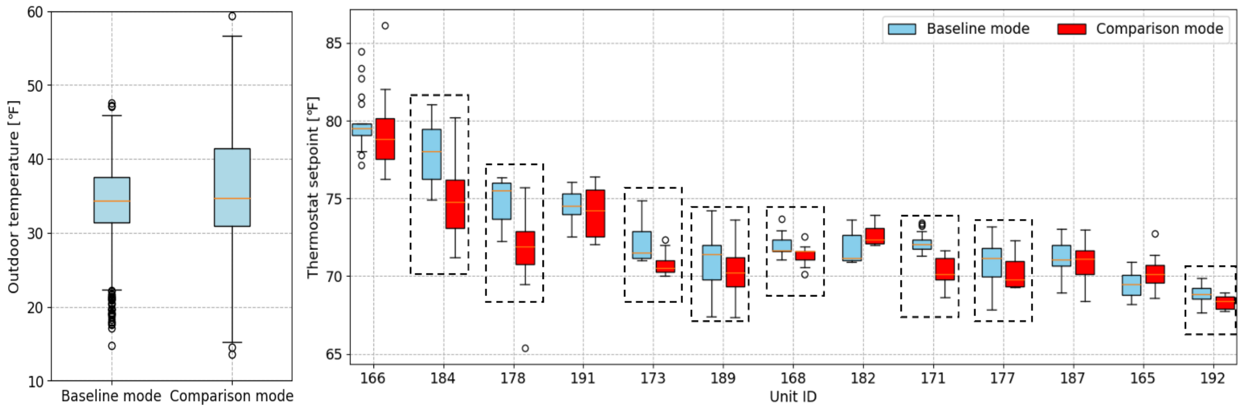


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Figure 5: a) Boxplot of hourly outdoor temperature for two modes; b) Thermostat setpoint distribution of baseline (heat pump priority) and comparison (auxiliary heater priority) mode.

3.3 Investigation of Occupant Setpoint-increasing Actions

3.3.1 Time-varying behaviors. Previous studies, such as Vellei et al. (2023), have highlighted the influence of time-of-day on human dynamic thermal perception and preferred temperature. The analysis of setpoint-increasing actions in the field data reveals correlations with time-of-day. Figure 6a displays the total number of increasing actions for unit 192 throughout the baseline. Interestingly, the residents exhibited a higher number of setpoint adjustment behaviors during the night period (e.g., 11 pm to 12 am) compared to other times of the day. Figure 6b displays the total number of increasing actions for unit 187 throughout the baseline. Compared to other times of the day, residents increased the setpoints more frequently during the 8 am to 9 am timeframe.

These behaviors are defined as time-varying behaviors and can be attributed to several factors. For example, Iyengar et al. (2015) have demonstrated that the thermostat schedule might not always align with occupancy patterns, leading to potential discomfort. Another study by Tamas et al. (2021) also reported that users often adjust the default nighttime setback settings to better suit their comfort preferences. Similar behaviors were observed in this study. Unit 192 has a default nighttime setback that begins at 11:30 pm, during which the temperature setpoint decreases from 70°F to 65°F. However, this schedule may not align with the resident's occupancy pattern. For instance, the resident may retire to bed later than the scheduled setback time. The significant decrease in setpoint during the nighttime setback period can greatly impact thermal comfort, prompting the resident to increase the setpoint. Secondly, these behaviors may be associated with human circadian variations. Vellei et al. (2021) have shown that core body temperature tends to be lower in the early morning and late night, while it peaks during the daytime. Furthermore, research by Vellei et al. (2022) discovered that occupants prefer warmer setpoints in the morning. This finding is based on an analysis of datasets including the Ecobee "Donate Your Data" dataset, ASHRAE I, and European Smart Controls and Thermal Comfort (SCATs) datasets. It is important to note that this analysis is entirely data-driven. In addition, other researchers have investigated thermal preference at different hours of the day by using chamber tests (Adam Shoemaker, 1996) or field experiments (Wang et al., 2022). Their experiment results also have similar observations. However, it should be noted that the experiments conducted thus far have primarily involved a limited number of human subjects or were conducted during specific periods of the day. As a result, it is challenging to draw definitive conclusions regarding the existence of a diurnal pattern of thermal perception. Lastly, the increased setpoint requirement in the morning or night may also be linked to the lower indoor mean radiant temperature (MRT). Kajjoba et al. (2022) have shown that indoor MRT tends to be lower in the morning due to the lower ambient temperature. This lower MRT may also prompt users to raise the air temperature for comfort.

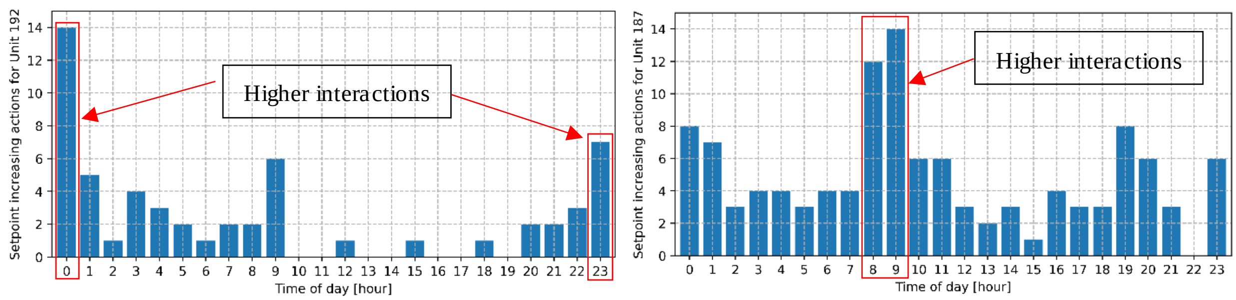

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Figure 6: a) Observed number of setpoint increasing actions in baseline (heat pump priority) mode (December 23rd, 2023 to January 28th, 2024) for a) unit 192 and b) unit 187.

3.3.2 System in off mode. The other instances of increasing actions are tied to the system operation mode. Some residents prefer to turn off the system when they are leaving home or simply to conserve energy even if they are still at home. Figure 7a shows the indoor temperature, setpoint and system operation profiles of unit 166 on Jan 1st 2024. It shows that this user often puts the system in "Off" mode, and the heat pump is not regulated according to the schedule. Despite the relatively high thermostat setpoint, the indoor air temperature remains low because the system is off. The resident irregularly activates the system to meet comfort needs. Figure 7b shows the thermostat setting of unit 166 in the baseline mode and the occupant turns off the system for about half the time.

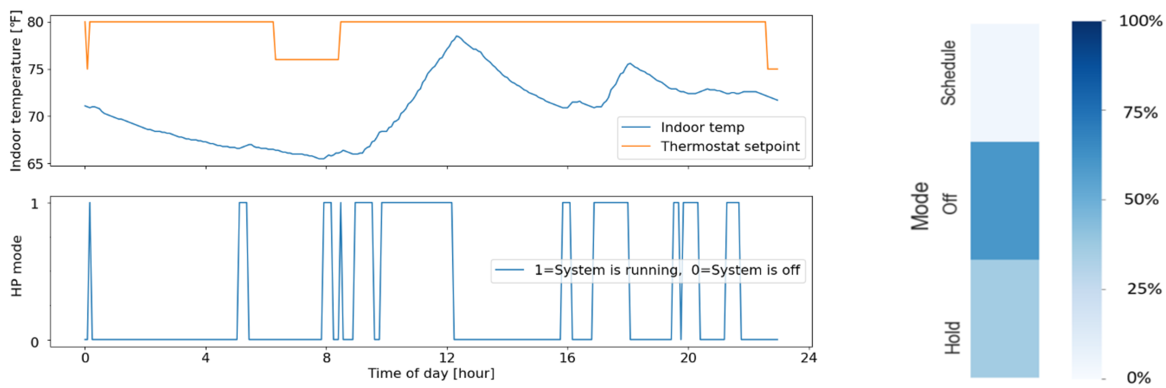

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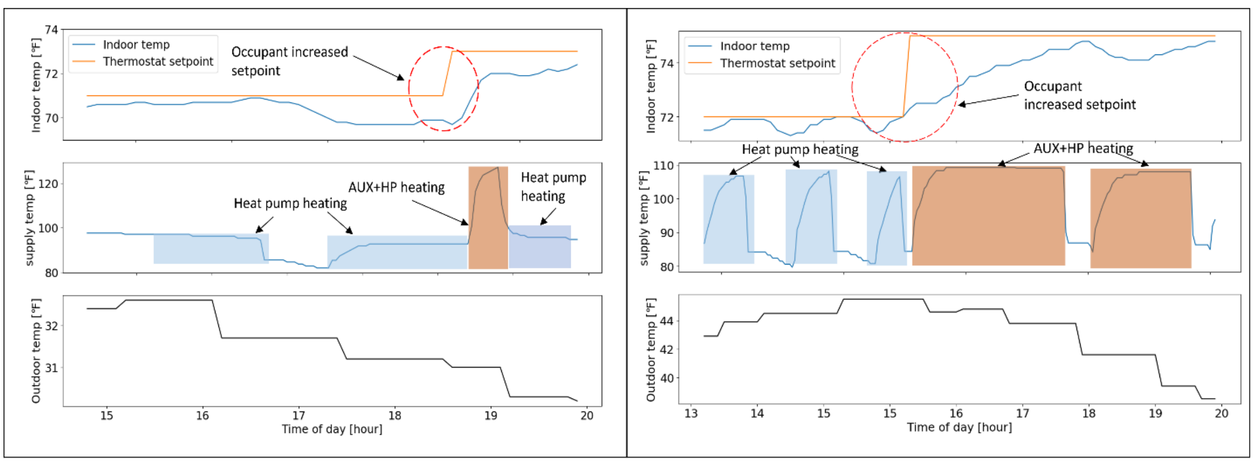
Figure 7: a) Indoor temperature, setpoint and system operation on Jan 1st, 2024; b) Thermostat setting during the baseline (heat pump priority) mode.

3.3.3 Auxiliary heater staging and decreased heat pump capacity. Figure 8a illustrates a scenario where the resident increases the thermostat setpoint when the room temperature fails to meet the setpoint. As the outdoor temperature decreases, the capacity of the heat pump also decreases. Consequently, the heat pump capacity becomes insufficient to meet the building load after 5 pm, leading to a decrease in indoor air temperature. However, according to thermostat rules, the auxiliary heater will not activate until the room temperature falls 2.9°F below the setpoint. The resident increased the setpoint from 71°F to 73°F when the room temperature was approximately 1.5°F lower than the setpoint around 7 pm. This increase in the setpoint triggered the backup heater. However, despite the heater activation, the room temperature still could not meet the setpoint because the heater was turned off when the difference between the room temperature and setpoint was less than 1°F. Instead, the heat pump was utilized to condition the space and conserve energy. It is evident that these thermostat heuristic rules result in some comfort penalties. Moreover, it is important to note that the supply air temperature is low (e.g., around 90°F) in this scenario due to the lower capacity. This factor may also influence the comfort and drive occupants to increase the setpoint.

During the data analysis of the decreased heat pump capacity scenario, some setpoint-increasing actions were observed when the system was undergoing defrosting. When frost accumulates on the coil due to low ambient temperature (e.g., 20°F to 40°F) and high relative humidity (e.g., > 65%RH), a defrost cycle is needed to remove the frost from the coil surface (Song et al., 2018). It is worth noting that the auxiliary heater is activated when defrost starts to maintain a high supply air temperature. Conversely, the heater deactivates and supply temperature drops when defrost cycles end. It has been observed that residents increased their thermostat setpoints multiple times during the defrost cycle. Nevertheless, it should be noted that no definitive conclusion can be made based solely on this observation. To confirm this finding and understand its implications for thermal comfort, further experiments in controlled environmental chambers are required and will be carried out by our team.

3.3.4 Other setpoint-increasing actions. Many actions remain challenging to interpret accurately solely through data analysis. Figure 8b depicts a scenario in which residents increased their setpoints despite the room air temperature already meeting the setpoint. The room temperature was well controlled around 72°F and the supply temperature was relatively high. Around 6 pm, the resident increased the setpoint from 72°F to 75°F. This scenario can also occur when the supply air temperature is low, but the heat pump has the capacity to heat the space. While a low supply air temperature may not be comfortable in many situations, occupants may not necessarily feel the supply air, as this depends on factors such as the location and design of the register (Paul W. Francisco et al., 2004). Therefore, those increasing setpoint behaviors could also be due to various factors such as individual preferences (e.g., clothing choices), specific activities of the residents, and other contextual factors not captured in the data. Further investigation and potentially additional data collection, such as surveys or interviews with the residents, may be necessary to provide deeper insights into these actions. Additionally, employing more advanced analytical techniques or incorporating contextual information could also help in better understanding and interpreting the observed behaviors.



a) b)

Figure 8: a) Temperature profiles of unit 182 on Jan 10th, 2024; b) Temperature profiles of unit 187 on Feb 12th, 2024

3.4 Thermostat-adjustment Behavioral Patterns for Baseline and Comparison Modes

Based on the behaviors described in previous sections, it can be observed that, aside from behaviors related to decreased Heat Pump capacity, the remaining behaviors do not show strong correlations with the system's operational characteristics in baseline (heat pump priority) and comparison (auxiliary heater priority) modes. To facilitate a better comparison of occupant behaviors in these two modes, the frequency of each behavior is calculated. Table 2 outlines the summarized rules utilized to differentiate various behaviors for data filtering. It is important to note that certain behaviors overlap. For instance, occupants may turn off their system during the daytime, then turn it on and raise the setpoint late at night when they feel uncomfortable. Similarly, increasing the setpoint due to decreased heat pump capacity may also occur during the late night or early morning. In such cases, these behaviors will not be categorized as time-varying behaviors.

Figure 9 below presents pie charts representing the percentage of each behavioral pattern for all 13 units that occurred in the two modes. The total number of increasing actions is nearly equal for both modes, with 404 actions against 401.

The majority of these actions are time-varying behaviors, which include both morning and night actions. Increasing setpoint behaviors related to the system being in off mode are comparable for both modes (14.1% vs. 17.2%). Other behaviors show a slight increase for the comparison mode. There is a notable decrease in behaviors related to decreased heat pump capacity in the comparison mode due to the advantages of using the auxiliary heater as the major heating source. However, solely comparing the overall increasing actions for the two modes makes it relatively challenging to determine why the occupants in the comparison mode have lower setpoints despite the lower occurrence of decreased heat pump capacity behaviors. In the next section, a detailed analysis of behaviors for each unit will be presented.

Table 2: Rules used to categorize thermostat-adjustment behavioral patterns

Behavioral pattern	Summarized rules
Time-varying	▪ Time: 23:00 to 11:00 ▪ Increase setpoint when the indoor temperature has reached setpoint ▪ Use "Hold" mode when increasing the setpoint
System in off mode	▪ Use "Hold" mode when increasing the setpoint ▪ The system is in "Off" mode when turning on the system and increasing the setpoint ▪ Indoor temperature is lower than the setpoint
Decreased HP (Heat Pump) capacity	▪ Use "Hold" mode when increasing the setpoint ▪ The auxiliary heater is not running when increasing the setpoint ▪ Setpoint is greater than indoor temperature plus the deadband
Other behaviors	▪ Does not meet the requirements for the behaviors above ▪ Increase setpoint when the indoor temperature has reached setpoint

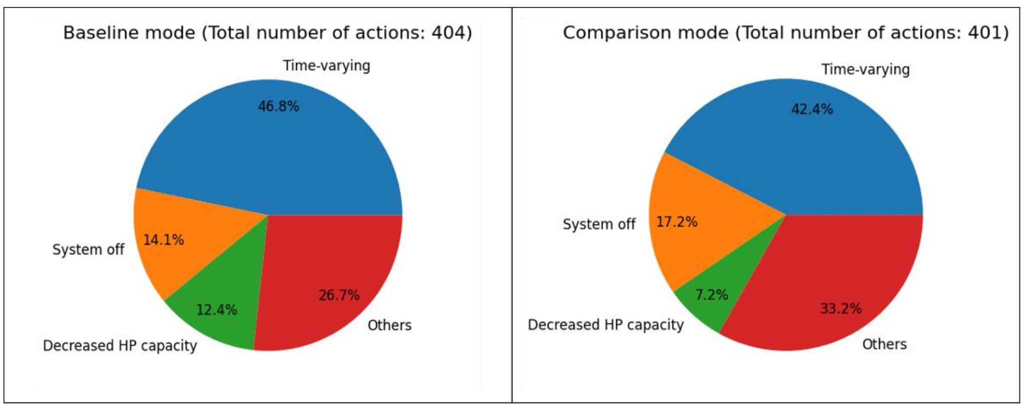


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Figure 9: Pie chart for thermostat-adjustment behavioral patterns for a) Baseline (heat pump priority) mode and b) Comparison (auxiliary heater priority) mode.

3.5 Analysis of Occupant Thermostat-adjustment Behavior for Individual Units

3.5.1 Unit with lower setpoints in comparison mode. Figure 10a illustrates the daily indoor temperature, thermostat setpoint, heating energy consumption, and outdoor temperature of unit 171 for the baseline and comparison modes. Each mode includes 21 days of operational data, with the daily average outdoor temperature ranging from 19°F to 41°F. Notably, the setpoint and indoor air temperature are lower in the comparison mode. Also, the energy usage demonstrates that the heat pump heating is primarily utilized in the baseline mode while the auxiliary heater serves as the primary heating source in the comparison mode.

Figure 10b illustrates the comparison of each increasing setpoint behavior. The total number of increasing actions is lower in the comparison mode (54 vs. 44), contributing to the decreased occupant setpoint in the comparison mode. The main reduction arises from actions related to decreased HP capacity, which results in the primary disparity between the two operation modes. Regarding the remaining behaviors, such as time-varying and other behaviors, they are not directly linked to the operational characteristics of the equipment. Instead, they reflect the occupant's individual living patterns, with a similar number of actions observed in both modes.

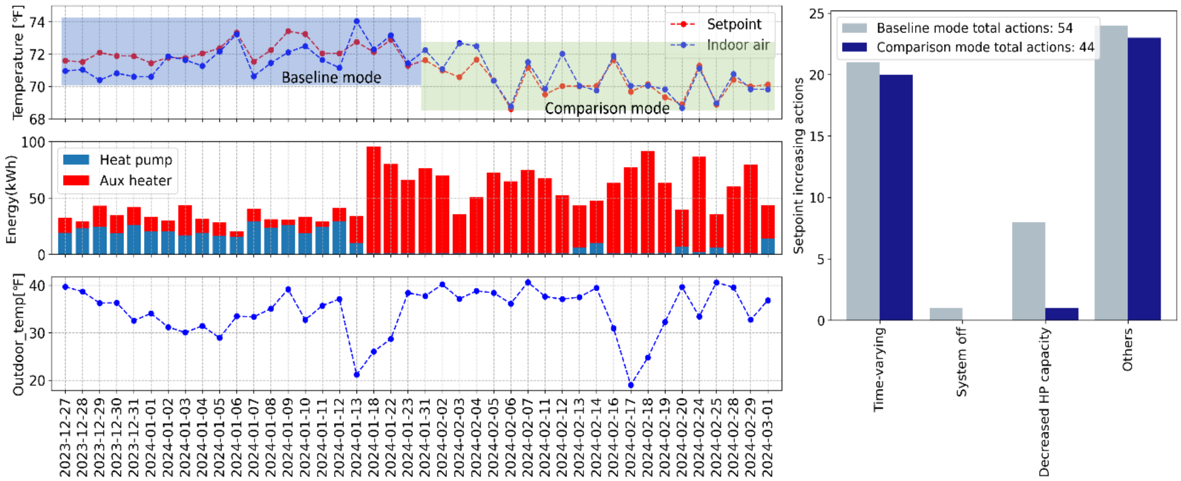

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Figure 10: a) Daily indoor temperature, thermostat setpoint, heating energy consumption and outdoor temperature for unit 171; b) Comparison of occupant thermostat adjustment behavioral patterns for baseline (heat pump priority) and comparison (auxiliary heater priority) mode.

3.5.2 Unit with higher setpoints in comparison mode. Figure 11a illustrates the daily indoor temperature, thermostat setpoint, heating energy consumption, and outdoor temperature of unit 187 for the two modes. Unlike unit 171, the setpoint and indoor air temperature in the comparison mode do not show a decreasing trend. Instead, there seems to be fluctuation in temperature, with some days showing higher setpoints while others display lower setpoint preferences. These fluctuations may be associated with specific activities of the occupants and the higher occurrence of other behaviors as depicted in Figure 11b. Furthermore, it is noteworthy that this unit relies more on the auxiliary heater in the baseline mode. This factor may also contribute to the similarity in setpoint preferences between the two modes.

Figure 11b shows the comparison of each thermostat-adjustment behavior. Similar to unit 171, actions associated with decreased HP capacity are lower in the comparison mode. However, due to the increased frequency of other behaviors, the total number of increasing actions is higher in comparison mode (65 vs. 72), thereby contributing to the high setpoint observed in comparison mode.

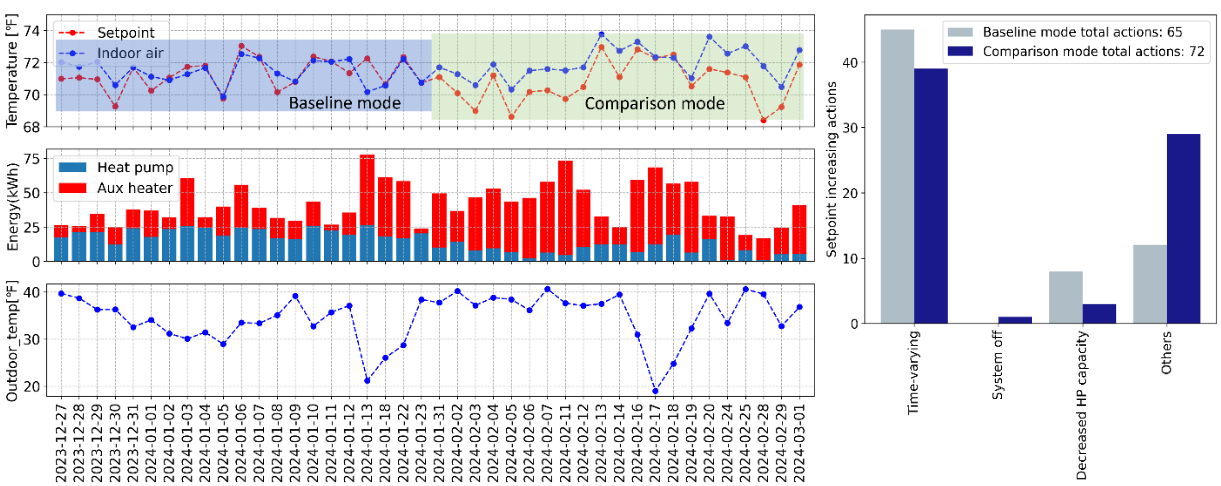

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Figure 11: a) Daily indoor temperature, thermostat setpoint, heating energy consumption, and outdoor temperature of unit 187; b) Comparison of occupant thermostat adjustment behavioral patterns for baseline (heat pump priority) and comparison (auxiliary heater priority) mode.

4. CONCLUSIONS

In this paper, a field study was carried out to investigate occupant thermostat adjustment behavior under two distinct operation modes: 1) baseline mode where a heat pump as the primary heating source with auxiliary electric heater backup, and 2) comparison mode where auxiliary electric heat is the primary heating source. The main findings from the field study are summarized below:

- Occupants have different thermostat setpoint preferences for different comfort delivery modes. For the selected units that have more active use and a higher number of interactions with thermostats, 8 of 13 units show lower median thermostat setpoints in the comparison (auxiliary heater priority) mode.
- Four distinct occupant behaviors for increasing the setpoint are identified. Among these, the behavior associated with staging the auxiliary heater and lower heat pump capacity is the primary difference between the two operation modes. There is a noticeable decrease in thermostat adjustment actions in the comparison mode. Aside from the behaviors related to the reduced heat pump capacity, the remaining behaviors do not show strong correlations with the system's operational characteristics in the two modes. Those behaviors are more related to individual preferences, specific activities of the residents, or other contextual factors not captured in the data.
- The investigation of individual units suggests that the total number of increasing setpoint actions impacts the overall setpoint preference (e.g., the median value of setpoint distribution). Occupants' specific activities may result in a higher frequency of other behaviors unrelated to the equipment's operation characteristics, thereby contributing to the overall preference for high setpoints.

While some behavioral patterns (e.g., other setpoint-increasing actions in Section 3.3.4) have been observed in the field study, drawing definitive conclusions solely from these observations and data analysis is challenging. Therefore, further investigations should be carried out, including additional data collection methods such as surveys or interviews with the residents and human subject experiments in controlled environmental chambers, and can offer deeper insights into these behaviors.

NOMENCLATURE

Abbreviation	Description	Subscripts	Description
HP	Heat pump	in	Indoor
AUX	Auxiliary heater	out	Outdoor
MRT	Mean radian temperature	set	Setpoint
SCATs	Smart Controls and Thermal Comfort datasets		
IRB	Institutional Review Board		

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