Control for the People: How Machine Learning Enables Efficient HVAC Use Across Diverse Thermal Preferences

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ABSTRACT

Occupants of commercial buildings tend to have restricted means of affecting HVAC operation. As a result, opportunities for energy efficient behavior change are limited to provisions over which the occupant has direct control. An occupant can turn off lights at night, unplug electronics, and other similar actions that they can adopt in their daily routine. However, these behavior changes fail to address HVAC energy consumption, a class of energy consumption that could benefit greatly from occupant feedback. A system for gathering thermal comfort preferences would create opportunities for energy savings, but how can occupants be incentivized to express their preferences?

Building Robotics has developed an application called Comfy that gives occupants the ability to immediately influence their thermal environment, and uses this feedback to optimize satisfaction and HVAC energy consumption. Comfy has been in operation for over three years and has thousands of users engaging with this new style of HVAC control every day. The usage data show important patterns in the daily thermal preferences of occupants. This data can be used to better understand the relationship between thermostat temperature setpoints and occupant preferences, improve thermostatic control, and inform energy-efficient HVAC operations.

Introduction

HVAC systems represent the largest portion of energy use in commercial buildings today (DOE, 2011). HVAC also represents the greatest opportunity for savings, as buildings wastefully over-condition spaces (Brager, 2015), operate with narrow thermostat setpoint ranges (Arens, 2012), and let faults go undetected. The Comfy system saves energy by addressing the errors mentioned above and makes spaces more comfortable by (1) initially widening thermostat setpoint ranges, (2) giving users the ability to influence their environment on-demand, and (3) using machine learning methods to continuously process user feedback and generate a thermostat setpoint schedule that varies throughout the day.

Comfy works with many different system types, but is designed for VAV systems, which are a common, actively commissioned system type (US Energy Information Administration 2012). VAV terminal units are ducted to a central Air Handling Unit (AHU) and modulate the amount of air entering a zone by controlling the position of a damper (Figure 1). Air entering the terminal units are usually cooled to a temperature between 55ºF and 65ºF. Because of this, VAV units deliver cooling by default. Some VAV terminals will have a reheat coil and can actively deliver warm air to the space. This temperature can be modulated and is typically between 75ºF and 100ºF. Comfy communicates with VAV controllers to modify thermostat setpoints, control the damper, and control the terminal's heating coil if present. When VAV units are commissioned, a thermostat setpoint range is usually fixed and does not change unless it is done by the building operator directly.

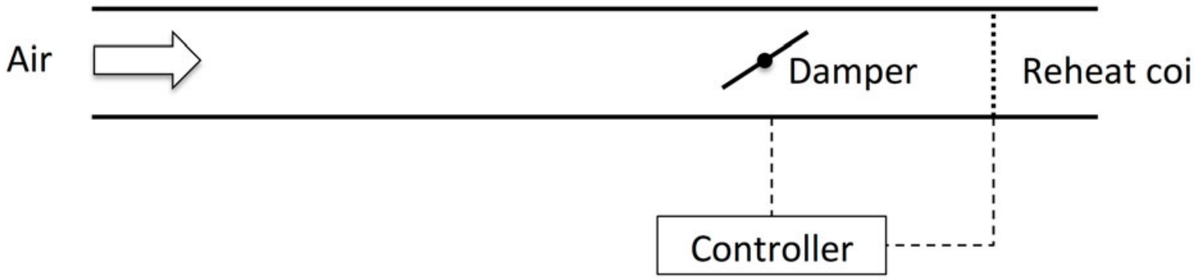


Figure 1. A simple VAV schematic diagram. Comfy sends BACnet commands to control the damper and hot water valve to the reheat coil to deliver warm or cool air to the space. Comfy also modifies the thermostat setpoints that the controller will attempt to satisfy.

Conventional wisdom in the HVAC design industry is that a narrow setpoint range that keeps a space at a strictly neutral temperature is ideal. However, it's been shown that a narrow setpoint range (1K) is not preferable to a wider setpoint range (2K), and that temporary warm and cool sensations can be perceived as pleasant (Parkinson, 2015). Even when the air temperature in a space is controlled to a strictly neutral range of 70-72 degrees, it would not take into account mean radiant temperature, shortwave solar radiation, or adaptation, which are all potentially important factors in thermal comfort (ASHRAE, 2013). Being in direct sunlight can cause a dramatic difference in perceived mean radiant temperature: the sun admitted by a small skylight can cause a 7ºF difference in perceived mean radiant temperature (Arens, 2015). After considering all of these factors impacting thermal comfort, neutrality in mechanically cooled buildings is neither desired nor possible (Arens 2010).

It has been shown in several studies (Hoyt 2014; Ghahramani 2015; Kazanci 2013) that widening thermostat setpoints results in significant energy savings. One such study claims that increasing the cooling setpoint in a VAV system from 72°F to 77°F results in a total HVAC savings of 27% on average, and that smaller incremental changes to the heating and cooling setpoints are also significant (Hoyt 2014). In the climate zone of Chicago, IL, reducing the heating setpoint by 1ºF saves 3.4% of total HVAC energy consumption, while increasing the cooling setpoint by 2ºF saves 7.2% (Center for the Built Environment, 2015).

While widening thermostat setpoint ranges is a promising means of saving energy, comfort can be impacted significantly without giving occupants a means of control. Comfy gives control to users by providing a stream of warm or cool air instantly upon occupant feedback, and learning optimal thermostat setpoint schedules. When a user clicks "Cool My Space" (CMS) Comfy's cloud server will remotely send BACnet commands to the VAV box serving the user's space, overriding the Building Management System's control sequence temporarily. It will decrease the cooling setpoint to insure that the heating coil is not active, and it will increase the airflow by means of damper position or airflow setpoint to deliver cool air into the space (Figure 2). After two minutes of high airflow, a rolloff airflow is enacted for the following eight minutes. After the ten-minute sequence is complete, control is relinquished to the BMS. Once the CMS sequence is complete, the user is free to submit more requests.

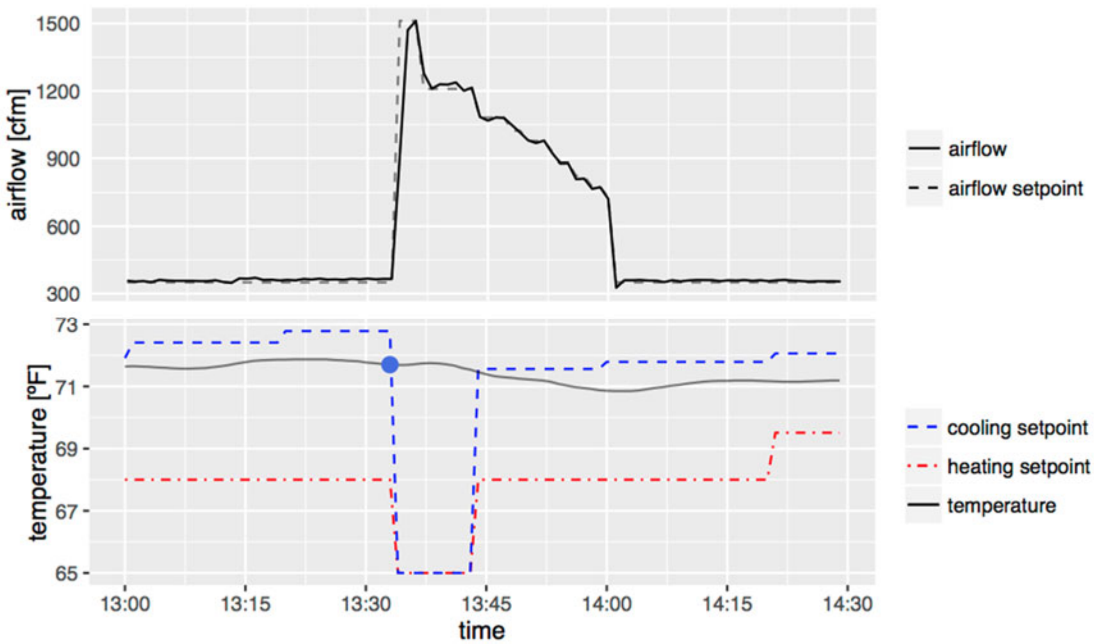


Figure 2. The blue dot indicates a user registering a CMS request. The airflow setpoint is increased, and the thermostat setpoints are set to 65 to induce cooling.

When a user clicks "Warm My Space" (WMS), the airflow is temporarily reduced to a small amount and the heating coil is activated. The control sequence then waits for the heating coil to warm up. By checking the discharge air temperature sensor, if available, we determine when the heating coil is fully active and increase the flow of warm air to the space (Figure 3). If the VAV terminal does not have a heating coil, the airflow is reduced for the duration of the blast, effectively heating the space by reducing the amount of cooling. As we do during the CMS stream sequence, the heating setpoint is increased temporarily to insure that heating mode is active. In the uncommon event that someone makes a conflicting CMS request in the same space, the warm stream will be stopped, and vice versa.

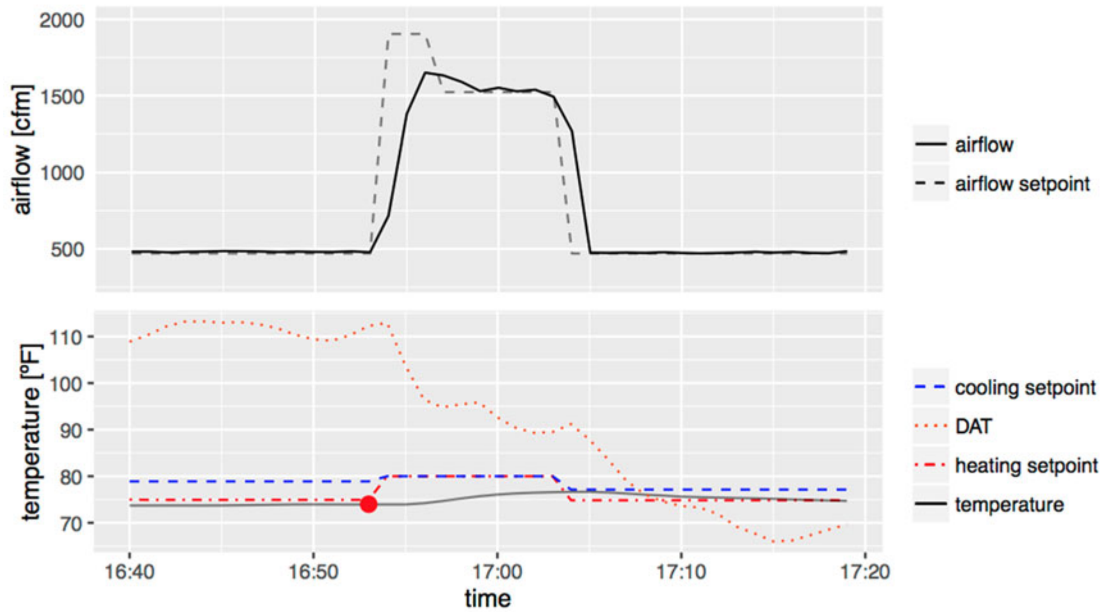


Figure 3. The red dot indicates a user registering a WMS request. In this case, the default control sequence failed to warm the space, but after the WMS request, Comfy increased the airflow and warmed the space.

Learning Thermostat Setpoint Ranges

The CMS and WMS stream sequences allow users to immediately influence their environment. Users may also opt to click “I Am Comfy”, which tells the thermostat setpoint optimizer that the temperature at that time is acceptable. In addition to the instant feedback that comfy provides, the thermostat setpoint ranges that will balance energy and comfort are calculated based on the preferences expressed by the CMS, WMS, and “I Am Comfy” votes. This strategy leverages the thermostat setpoint to act as a proxy for occupant thermal preferences, and computes thermostat setpoint temperatures that are specifically tailored to the individual thermostat. For example, if a thermostat is placed in a spot that is cooler than the rest of the zone, a conventional fixed deadband will result in a zone that is warmer than normal. By the same token, a south-facing zone that often has a high Mean Radiant Temperature (MRT) and direct solar radiation is likely to require more cooling, but will be conditioned to a fixed air temperature range that is probably the same as a north-facing zone. With Comfy, votes account for exposure or other time-of-day-based effects, as well as poor placement, poorly calibrated temperature sensors, or other biases.

In general, WMS votes will raise the heating setpoint if the heating setpoint is too low. This will result in heating being activated at a higher temperature using the learned setpoint schedule. If a WMS vote is made above the cooling setpoint, it will raise the cooling setpoint to prevent the space from cooling too much. Similarly CMS requests will lower the cooling setpoint when the cooling setpoint is too high, and lower the heating setpoint if the space is being heated too much. In this way, learned thermostat setpoint schedules will increase heating or cooling when it’s needed, and reduce it when it’s not. Figure 4a shows a space that has a thermostat setpoint schedule that has been heavily influenced by Comfy votes. Note that the y-axis represents room temperature, where the lower bound is 65ºF and the upper is 80ºF. The heating setpoint throughout the day has been raised due to the large number of votes. A small number of CMS requests have adjusted the cooling setpoints as well.

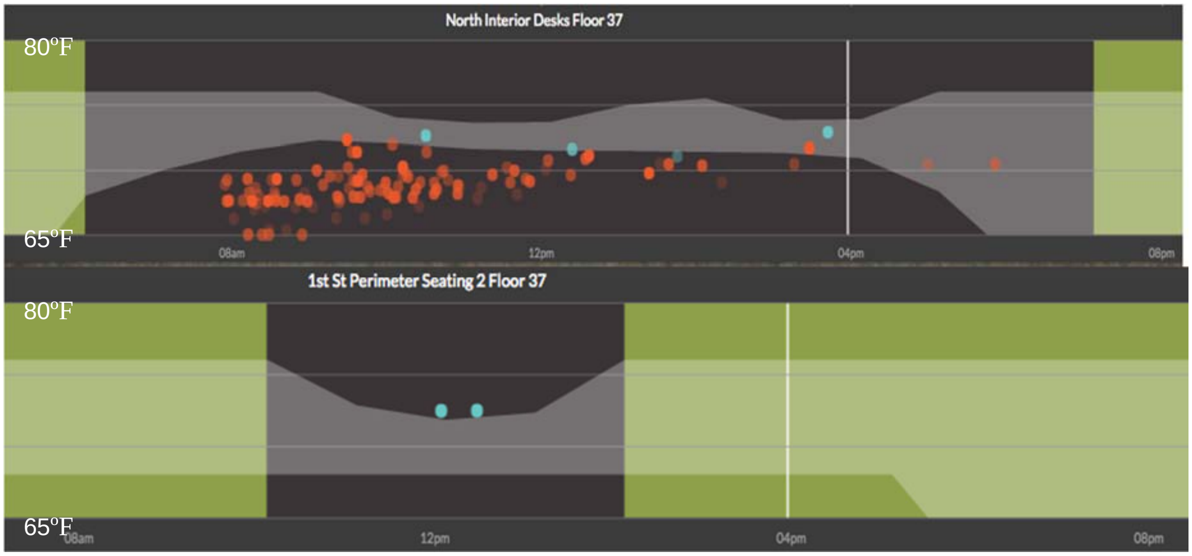


Figure 4a (top). A high occupancy, high usage zone results in a narrow thermostat setpoint range.
Figure 4b (bottom). A low occupancy zone enables Green Time, a period where the thermostat setpoint range can be widened. Note that the y-axis represents room temperature, where the lower bound is 65ºF and the upper is 80ºF

Zones that are not frequently occupied are likely to receive fewer CMS and WMS requests. This will result in what Comfy calls Green Time. Spaces that are not occupied do not need to be conditioned to meet specific occupant needs. Therefore, the thermostat setpoints can be widened significantly and the HVAC system will not waste energy conditioning the unoccupied space. This occurs commonly in conference rooms that are not used often, or only used in certain times of day. Green Time can span certain parts of the day, such as in the cases where a conference room is seldom used in the morning, or a recreational space that is only used at specific times of day. Figure 4b shows a low-occupancy space where green time occurs during operating hours. CMS requests have lowered the cooling setpoint in the early afternoon, but the morning and late afternoon setpoints are relaxed.

Comfy Requests Dataset

The Comfy system has been up and running in a variety of buildings for the past 3 years, and now is the firs time that it has been possible to aggregate and assess the data for trends in comfort and preferences. Given the unique access to occupants that this dataset provides, it can be used to triangulate and test chamber study research as well as smaller field studies. The dataset used for this paper was compiled from current installations of the Comfy software that allow for anonymized public use of data. This dataset represents 16 sites of varying size across the US and in India, and represents usage exclusively in office environments (including private and open office areas, conference rooms, break rooms and other similar spaces). Demographic information about users such as age, gender, and job type are not collected by Comfy and are therefore not known nor controlled for. All temperature values are taken from the existing room thermostats, and represent air temperature only.

Comfort preference diversity across populations

As existing research would predict, users request spaces to be warmed and cooled within a wide band of temperatures. Figure 5, for example, shows the average temperature for each user's CMS requests, showing that 10% of users have an average of below 69°F. Similarly, Figure 6 shows that almost 10% of users have an average WMS temperature above 74°F. Both of these facts may appear somewhat extreme, but show just how diverse preferences can be. Finally it is notable that the average WMS request is logged at 71.3°F, and the average CMS request is logged at 74°F.

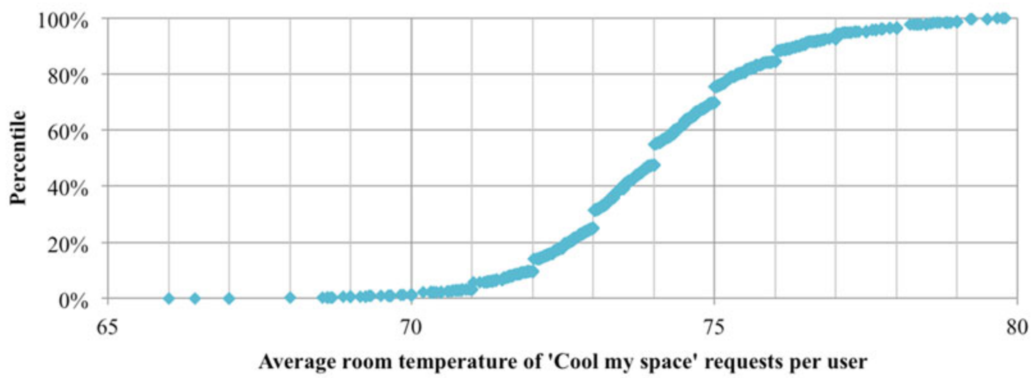


Figure 5. Cumulative distribution of average room temperature at the time of CMS requests by user.

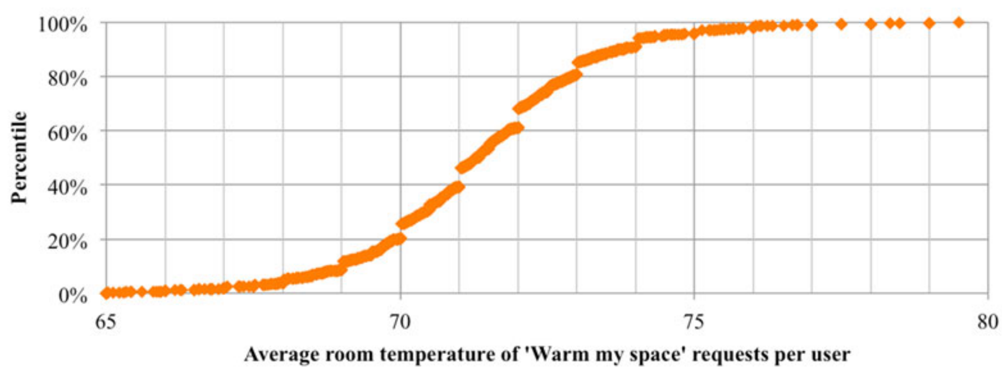


Figure 6. Cumulative distribution of average room temperatures at the time of WMS requests by user.

As noted above, this dataset does not include information on other aspects of the environments such as radiant temperature, clothing, humidity, air movement, or other factors. It is likely that some of the outlying request behavior (such as asking for a space to be warmer when the thermostat reads 75°F) is due to one or a combination of these conditions. In addition, miscalibrated thermostats may report that rooms have a different air temperature than they really have. And poorly placed thermostats may report a different air temperature from what the occupants feel. For all of these reasons and more, there is a great deal of Comfy usage that may not conform to thermal comfort models, but nonetheless represents operational realities of comfort and HVAC in buildings.

Comfort preferences by day and time

One pattern of note in aggregated Comfy user data is clear patterns of use that vary by day and time. As shown in Figures 7 and 8, the most popular time and request is the Monday morning WMS request, which may be partially due to building ramp-up from the HVAC system being off on the weekends, and may also have psychological or physiological causes relating to users transitioning from home to work. Future research is planned to assess whether these factors are indeed at play. WMS requests become less frequent as the week goes on, which suggest that the building mass is able to slowly warm up, resulting in warmer spaces.

CMS requests patterns exhibit consistent usage throughout the week, with the exception of Friday when there are fewer people in the office. It is possible that occupants' preferences for cooling are less driven by the temperature of the building mass, instead being affected by air temperature and shortwave radiation.

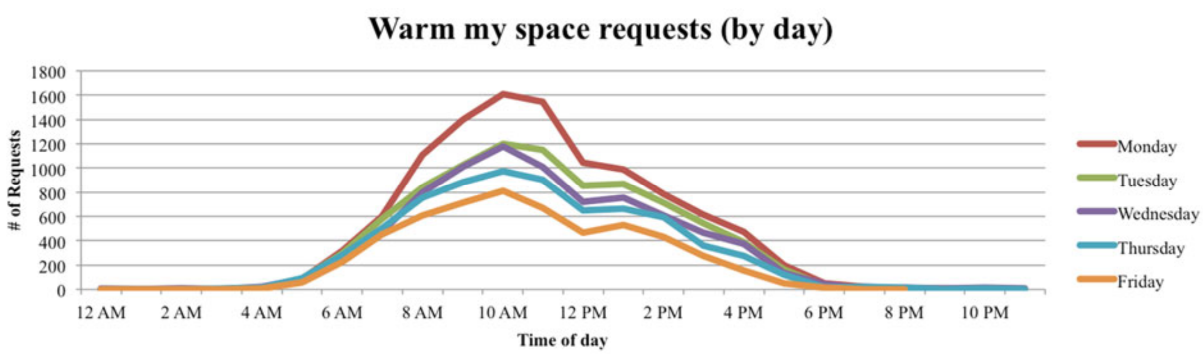


Figure 7. Warm my space requests

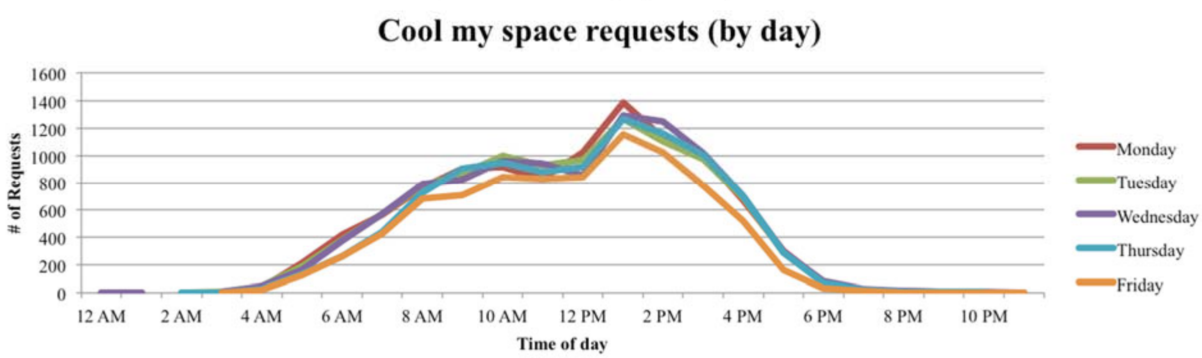
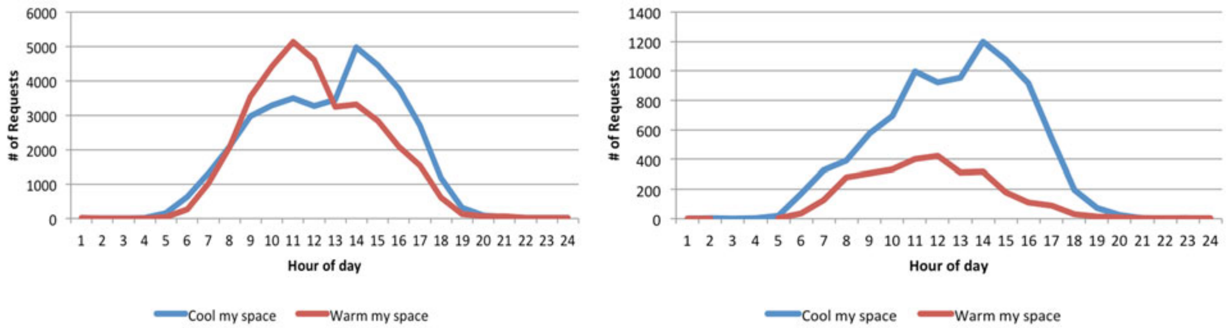


Figure 8. Cool my space requests

Additionally, Figures 7 and 8 show the clear distinction between WMS requests and CMS requests peaking at different times of day; WMS requests peak around 10am each morning, and CMS requests peak around 1:30pm, with clear morning and afternoon patterns. These trends are present across a wide range of space temperatures, and are present equally in interior and perimeter zones.

Comfort preferences and space types

Comfy is used in a variety of space types in typical office environments. Each zone is labeled with a space type during launch, and using that data, we are able to assess how Comfy is used differently in a variety of spaces. As can be seen in Figures 9a and 9b, requests are more



common in office areas (this graph shows both private offices and open offices) than in conference rooms.

Figure 9a (left) and 9b (right). These two graphs show all requests made in Comfy in office spaces (9a) and conference rooms (9b).

The volume of CMS requests is much higher in conference rooms than WMS requests. Conference rooms may get sporadically warm and stuffy with the ebb and flow of meetings. In this user behavior pattern, we see evidence that users may be requesting cool air for ventilation, not just cooling.

Engagement and persistence

Persistence of use is a common question raised in many behavioral programs and interventions in buildings; for many occupants, building systems are out-of-sight and out-of-mind. Without engagement, Comfy would gradually cause all active zones to be less conditioned, which would save energy but may risk uncomfortable occupants. However, Figure 11 shows that occupants stay engaged with the app well past the initial engagement period, albeit at slightly lower levels of use than the initial few months. This is healthy engagement, given that the machine-learning aspect of the software should be reducing the need for engagement somewhat over time.

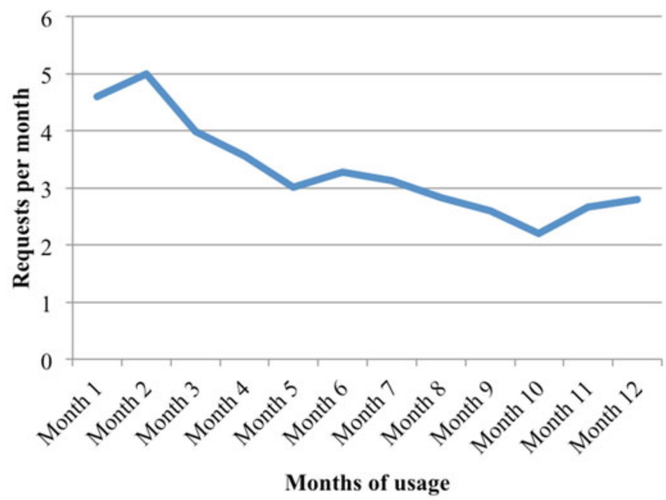


Figure 11. Average uses per month per user

There is also diversity among individual users, which is not reflected in this graph. On average, 20% of users use Comfy at least once per week, 40% use it at least once in 2 or 3 weeks per month, and 40% use it at least once per month.

Conclusion

The research community has long been aware of the diversity of thermal preferences across a variety of locations, individuals and other variables. Through data collected dynamically over the course of months and years in diverse communities in real life situations, we can gain a better understanding of how to design and operate work environments. This data analysis is just the beginning of understanding some of these dynamics, with many more questions to be addressed in future research.

References

Arens, E., Zhang, H., Hoyt, T., Kaam, S., Goins, J., Bauman, F.; et al. (2012). Thermal and air quality acceptability in buildings that reduce energy by reducing minimum airflow from overhead diffusers. UC Berkeley: Center for the Built Environment.

ASHRAE. Standard 55-2013: Thermal environmental conditions for human occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); 2013.

Brager, G., Zhang, H., & Arens, E.. (2015). Evolving opportunities for providing thermal comfort. Building Research & Information, 43(3), 274–287. doi: 10.1080/09613218.2015.993536. UC Berkeley: Center for the Built Environment.

Parkinson, T., deDear, R. (2015). Thermal pleasure in built environments: Physiology of alliesthesia. Building Research & Information, 43(3), 288–301. doi: 10.1080/09613218.2016.1140932.

Arens, E., Hoyt, T., Zhou, X., Huang, L., Zhang, H., Schiavon, S. (2015). Modeling the comfort effects of short-wave solar radiation indoors. Building and Environment, 88, 3–9. doi: 10.1016/j.buildenv.2014.09.004. UC Berkeley: Center for the Built Environment.

Arens E., Humphreys M., de Dear R.J., Zhang H. Are 'Class A' temperature requirements realistic or desirable? Building and Environment 2010;45(1):4–10.

Hoyt, T., Arens, E., Zhang, H. (2014). Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. Building and Environment. doi: 10.1016/j.buildenv.2014.09.010. UC Berkeley: Center for the Built Environment.

Ghahramani, A., Zhanga, K., Duttaa, K., Yanga, Z., Becerik-Gerber, B. (2015). Energy savings from temperature setpoints and deadband: Quantifying the influence of building and system properties on savings. Applied Energy. doi: 10.1016/j.apenergy.2015.12.115.

Kazanci, O. B., Olesen, B. W. (2013). The Effects of Set-Points and Dead-Bands of the HVAC System on the Energy Consumption and Occupant Thermal Comfort. 9th Windsor Conference: Making Comfort Relevant, At Windsor, UK.

Center for the Built Environment. (2015). CBE Setpoint Savings Calculator. http://comfort.cbe.berkeley.edu/energycalc/. Retrieved March 2016.

U.S. Department of Energy (2011). Buildings Energy Data Book. https://catalog.data.gov/dataset/buildings-energy-data-book. Retrieved May 2016.