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Power to the people: personal control in offices for thermal comfort and energy savings

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Power to the People:
Personal Control in Offices for Thermal Comfort and Energy Savings

by
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Professor Edward Arens, Chair
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Abstract

Power to the People:
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by
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We have reached a point in which lowering building energy consumption and thereby reducing greenhouse gas emissions is an ecological imperative. Rethinking how we mechanically condition our buildings is an important means for substantially lowering building energy consumption. Rather than using large amounts of energy for space heating and cooling to condition the full volume of interior air to be within a narrow temperature range, people can be comfortable with a wider room temperature range as long as they have personalized control over local conditioning, which is similar to task-ambient lighting design already well understood in theory and practice. This field study tested low-energy footwarmers as one way in which occupants can personally control their own thermal environment.

During a six month winter period, participants in an office in Berkeley, California, were given a low-energy footwarmer with an easily accessible knob for adjusting the heat provided by the footwarmer to their desired level. The room heating set point was gradually lowered from 70F to 66F. The building management system and independent data acquisition recorded data from which the energy consumption data of the mechanical system and the individual plug loads of each workstation could be determined. Three times per day, participants took an online survey about their thermal comfort. The results show that the added plug load from the low-energy footwarmers was substantially less than the heating energy saved by lowering the heating set point. There was a 38-75% overall reduction in heating energy, which depended on the setpoint and outdoor conditions. Occupant surveys showed equivalent thermal comfort ratings when comparing the existing conditions to when people had the footwarmer and a lower heating set point.

From low-cost retrofits of sealed VAV offices to the design of new buildings, low-energy personal thermal control systems can effectively provide thermal comfort when set points are expanded. Rethinking the fundamentals of set points can lead to scalable impact in reducing building energy consumption and ultimately in lowering our ecological footprint.

1. Introduction

Despite the large amount of mechanical energy spent on space conditioning in offices, people still have their individual preferences when it comes to the thermal environment at their workspace. The heating and cooling setpoints have a large impact on the overall energy consumption of the mechanical system and they are chosen based on temperatures at which the most number of people are likely to be comfortable. Standards for indoor thermal environments such as ASHRAE Standard 55 assume that neutral is the most desirable thermal sensation and that the interior temperature should be uniform and steady-state. However, some thermal comfort research suggests that people may be comfortable in wider ambient conditions if there people experience localized heating and cooling of targeted body parts (Zhang 2003). Research also suggests that occupants like having personal control at their workstations to improve their thermal comfort and satisfaction (Aronoff and Kaplan, 1995; Heerwagen 2000).

Devices that provide personal control of thermal comfort address not only people's individual thermal preferences, but provide occupants with the opportunity to effectively benefit from localized heating and cooling. These devices have been previously studied in laboratory and field studies and have been referred to with different names: personal environmental controls, task-ambient conditioning, personal ventilation, task-ambient conditioning, and personal comfort system (PCS). While many of these are reviewed in the literature review, the thesis focuses on PCS which is designed to be low-power as opposed to some other energy intensive products and designed to provide localized conditioning. While there are several devices underdevelopment as part of PCS (footwarmers, fans, leg warmers, and heated and cooled desks and chairs), this thesis focuses specifically on the footwarmer device to assess its potential to maintain thermal comfort under cooler ambient temperatures during the winter.

Many of the past laboratory studies focus on testing how the devices impact comfort and whether they can maintain comfort under expanded setpoint conditions (Zhang, Arens, Kim, Buchberger, Bauman, and Huizenga 2010). Most of the past field studies either look at whether or not personal control improves comfort in the existing setpoint condition, or they measure or simulate energy savings from expanded setpoints (Brager, Paliaga, and De Dear 2004; Team-6% 2007; Davies, Holmes, Pau, and Collins 2008; Hoyt, Kwang, Zhang, Arens, and Webster 2009). There has only been one field study that looked at thermal comfort of people using devices providing personal control during expanded setpoint conditions, but the energy savings of the system was not reported (Bauman, Carter, Baughman, 2008). While that study, laboratory studies, and simulation studies suggest that there is a potential to save large amounts of energy by widening setpoints and maintaining thermal comfort through providing personal control, this thesis is the first field study that addresses personal control, thermal comfort, and measured energy savings. This thesis aims equally to provide effective ways to provide a thermally comfortable work environment and to easily and substantially reduce energy consumption in offices.

2. Literature Review

2.1 Overview of Thermal Comfort

This section is not meant as a comprehensive review of thermal comfort, but as a brief introduction to how thermal comfort is defined in the current ANSI/ASHRAE Standard 55-2013, how local thermal sensations impact whole-body thermal sensation, and how thermal comfort relates to indoor environmental quality (IEQ).

ANSI/ASHRAE Standard 55-2013, hereafter referred to as ASHRAE Standard 55, defines thermal comfort as “that condition of mind that expresses satisfaction with the thermal environment” (ASHRAE Standard 55-2013 2013). The goal is to provide design guidance to create steady-state thermal environments in which people have a neutral thermal sensation and in which at least least 80% of people are thermally comfortable. Variables for the thermal comfort calculation include metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity and the calculation method is based on laboratory research by Fanger to compute the percent mean vote (PMV) for thermal sensation and the predicted percentage of dissatisfied (PPD) people for the given conditions (Fanger 1982).

Before 2004, the calculation method for determining thermal comfort for naturally ventilated buildings was the same as mechanically ventilated buildings in ASHRAE Standard 55. The 2004 revision first included an adaptive model of thermal comfort applicable for naturally ventilated buildings that calculates the range of acceptable operative temperatures as a result of outdoor temperatures (ASHRAE Standard 55-2013). This was based on the development of the principle of adaptation and extensive field research. Humphreys and Nicol were early thought leaders in thermal adaptation and defined the principle of adaptation as follows. “If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” (Humphrey and Nicol, 1998). In other words, people will modify their environment to adapt to the current conditions. Subsequent extensive field data analyzed by Brager and de Dear shows that an adaptive model of thermal comfort is appropriate for naturally ventilated buildings because outdoor conditions influence the thermal comfort of occupants who have control over operable windows (de Dear and Brager 1998). At the time when the adaptive model was incorporated into ASHRAE Standard 55, Brager and Olesen wrote, “While the standard specifies conditions that will satisfy 80% of the occupants, that still may leave 20% dissatisfied. The best way to improve upon this level of acceptability is to provide occupants with personal control of their thermal environment, enabling them to compensate for inter- and intra-individual differences in preference” (Brager and Olesen 2004). While the adaptive model focused on operable windows as a form of personal control, this statement suggests greater levels of personal control may help further improve the overall percentage of thermally comfortable occupants beyond the current minimums specified in the standard. Even today, ASHRAE Standard 55 does not account for devices allowing for the personal control of the thermal environment.

Zhang developed a thermal comfort model specifically for non-uniform and transient conditions based on lab tests that revealed how local thermal sensation and comfort can influence overall thermal sensation and comfort (Zhang 2003). The model shows that the head and hands experience the warmest local thermal sensations in warm environments and that hands, arms, and feet experience the coolest local sensation in cool environments (Zhang 2003). Further, targeted cooling and heating of these local body parts was found to help improve someone's overall perception of comfort and satisfaction even if ambient temperatures fall beyond the traditional comfort range (Zhang 2003). This led to the development of energy-efficient footwarmers and handwarmers for heating occupants in cool environments, and facial air movement devices for warm environments (Zhang, Arens, Kim, Buchberger, Bauman, and Huizenga 2010; Pasut, Zhang, Kaam, Arens, Lee, Bauman and Zhai 2012).

In addition to these thermal comfort models, the literature also shows that post-occupancy evaluations are a valuable way of assessing occupant perception of thermal comfort. Analysis of the Center for the Environment's occupant satisfaction database found that only 11% of 215 buildings surveyed had at least 80% of occupants satisfied with their thermal comfort (Huizenga, Abbaszadeh, Zagreus, and Arens 2006). Among IEQ variables, thermal comfort is uniformly one of the top two sources of dissatisfaction in buildings (Huizenga, Abbaszadeh, Zagreus, and Arens 2006).

2.2 Theory of Personal Control for Thermal Comfort in Offices

There is generally consensus that giving occupants personal control of the thermal comfort at their workstations is a good practice favorable to occupants. In a broad overview of best practices for the design of offices, Aronoff and Kaplan (1995) argue that it is important to give occupants personal control of the IEQ at their workstation. In large buildings, HVAC systems can be limited in providing comfortable environments in some areas. Perhaps more importantly, they write, "Because the thermal conditions that individuals find comfortable are so variable, the ideal solution would be to allow everyone to set the conditions that they find comfortable." Not only does personal control allow people to make adjustments to their individual preferences, but people are generally more satisfied when they perceive that they have control over their environment and find that personal control features enhance the quality of the work setting. Further, "People's perceived ability to control their environment decreases stress and improves satisfaction, even if the control is never exercised" (Ibid).

Heerwagen also identifies many benefits to having personalized control over IEQ as part of a more general look at strategic benefits of green buildings (Heerwagen 2000). She writes that there are multiple personal control studies that show personal control can lead to increased perceived productivity, fewer illness symptoms, less absenteeism, enhanced work performance, improved comfort and acceptability, reduced time to achieve comfort, fewer coping behaviors, and fewer complaints to building managers. She echoes Aronoff and Kaplan by saying that personal control also has the simple yet powerful benefit of accounting for individual differences in preferences for IEQ.

The effectiveness of these concepts relies on the ease and clarity of the personal control system itself. A major barrier to the use of personal controls is that there is often poor design of the user interface, which demonstrates a need for the design of the controls themselves to be improved (Bordass et al. 1993). While there have been many advances in technology, complex systems can cause problems if no one knows how they work, they are ambiguous in intent, are poorly labeled, and fail to show if the adjustment has led to any change. Six usability criteria for control include clarity of purpose, intuitive switching, usefulness of labeling and annotation, ease of use, indication of system response and feedback, and a fine degree of control (Bordass et al. 2007). If personal controls lack these criteria, then installing the controls are unlikely to produce desired results. This problem was identified in a study by Brown and Cole comparing post-occupancy survey responses from a green office building to a conventional office building. In their report, they found that "Results suggest that while the availability and use of personal controls were higher in the green building, the quality of personal controls in terms of responsiveness, the absence of immediate and relevant feedback, and poor user comprehension may have led to sub-optimal indoor environmental conditions" (Brown and Cole, 2009). This shows that both good design of controls and occupant knowledge of how controls work are key to improving satisfaction.

2.3 Precedents of Testing Personal Control Devices

There have been several lab and field studies of how having personal control of IEQ impacts occupant thermal comfort. The studies reviewed here focus primarily on personal control of heating and cooling at the workstation under typical setpoint conditions, with some evaluating expanded setpoint ranges.

A lab study was done by the International Center for Indoor Environment and Energy at the Technical University of Denmark to assess the thermal comfort of 48 participants with and without an individually controlled system (ICS) that included personalized ventilation, an under-desk air terminal device supplying cool air, a chair with convectively heated backrest, an under-desk radiant heating panel, and a floor-heating panel (Melikov and Knudsen 2007). Occupants expressed more satisfaction with whole body thermal sensation when they had the ICS than the baseline. Even when people were using the ICS in a case when the set point was lowered two degrees Celsius and another case in which the set point was raised by six degrees Celsius, the percentage of people satisfied with whole-body thermal sensation was still higher than the baseline case (Melikov and Knudsen 2007).

A lab study at the Center for the Built Environment also found that providing 18 people with individual control maintained the roughly equivalent thermal comfort and perceived air quality ratings even when expanding set points to 18 and 30 degrees Celsius (Zhang et al. 2010). In this lab study, people were given a palm warmer, a heated keyboard, a footwarmer, a head ventilation device, and a hand cooling device. This study speculates that using these devices and allowing for an 18 – 30 degree C deadband could lead to 44% annual HVAC energy savings in the climate of Oakland, California (Zhang et al. 2010).

In another study at the Center for the Built Environment, study participants sat in chairs in which they could adjust the seat and backrest surface temperatures (Pasut, Zhang, Arens, Lee, Bauman and Zhai 2012). The study found that the low-power chairs (20-45W) strongly impacted occupant perception of thermal sensation and comfort even when the ambient temperature was as high as 84.2F (29C) and as low as 60.8F (16C). This study reinforced similar conclusions found by a previous study conducted jointly between South China University and the Technical University of Denmark in which 90% of subjects with personal control of their seat temperature were thermally comfortable when ambient temperatures ranged from 60F (15.6C) to 82.4F (28C) (Zhang, Wyon ,Fang, and Melikov 2007).

The main difference between previous lab studies and field studies on such personal control devices is that the lab studies focus on occupant comfort under expanded setpoint ranges and the field studies typically focus on the impact of the devices on comfort without changing setpoints. One exception is a field study in three Bank of America buildings in San Francisco that found that giving people task-ambient control at their desks led to 100% satisfaction with temperature, temperature control, and air movement when the setpoint ranged from 69.8F (21.0C) – 76.8F (24.9C) (Bauman et al. 1998). While this study did not report the overall energy savings and occupant surveys were only collected on six days during the summer, it nonetheless is a unique precedent for this thesis by demonstrating that people in real offices with personal control of their thermal environment can be satisfied when the setpoints are expanded beyond the typical conditions (Bauman et al. 1998).

Other field studies have shown that improved personal control leads to improved satisfaction even when the personal control strategies are as simple as easy access to operable windows or even the ability for each person to adjust and personalize his or her own workstation. In an extensive field study, Brager et al. analyzed occupant surveys and workstation microclimate measurements in a naturally ventilated municipal office building in Berkeley during the warm and cool seasons (Brager et al. 2004). The results showed that people who had more control of opening window, meaning that they had a desk directly next to a window or a private office with a window, accepted a wider comfort range and that this was preferable (Brager et al. 2004).

A research team at the Institute of Millennium Environmental Design and Research at Yonsei University also did a field study that included an analysis of the impact of personal control without introducing any new devices into the office building analyzed for the study (Lee and Brand 2005). This team surveyed people in five buildings in the United States that included an auto supplier, a government building, a telecommunications firm, a marketing firm, a manufacturer. As part of a larger survey, people were asked to rate their degree of control over the organization and appearance of their work area, their ability to adjust and rearrange their workstation furniture, and overall level to which they can personalize their workspace. This study found that people with higher control over their physical workspace reported higher levels of job satisfaction when compared to people with minimal control over their physical workspace (Lee and Brand 2005).

2.4 Personal Control and Energy Savings.

A large amount of energy is consumed by buildings to maintain a uniform indoor temperature in a specified range to maintain thermal comfort. Both outdoor weather and the setpoint temperatures greatly impact the amount of energy that the building consumes for heating and cooling. A seminal simulation study by Hoyt et al. used a large office EnergyPlus prototype model developed by the U.S. Department of Energy to estimate energy savings from widened air temperature setpoints in several different climates (Hoyt et al. 2009). Of specific relevancy to this thesis, this paper projects approximately 10% HVAC energy savings for each degree Celsius that the setpoint is raised or lowered (Hoyt et al. 2009).

The most examples of previous studies on measured energy savings from expanding setpoints in existing office buildings focus on the impact of raising the cooling setpoint during summer months. Japan launched the Cool Biz campaign to save on air conditioning energy bills in public buildings by requiring a cooling setpoint of 82.4F (28C) while encouraging a relaxed dress code (Team-6% 2007). In the United Kingdom, the British Council for Offices (BCO) released a report that calculated a 6% cooling energy savings and less than 10% thermal dissatisfaction when raising the cooling setpoint from 71.6F (22C) to 75.2F (24C) assuming people were allowed to dress more lightly (Davies et al. 2008). In a field study in an air conditioned office building in London, the cooling setpoint was raised from 71.6F (22C) to 75.2F (24C) in the summer with no significant difference in thermal comfort and satisfaction as reported by occupant surveys (Lakeridou et al. 2012).

While these studies focus on the impact on energy and comfort from expanded setpoints, these investigations do not provide occupants with ways to personally control the thermal environment at their workstation to provide a more comfortable local environment compared to ambient conditions. This thesis aims to combine the research on the physiological effectiveness of localized conditioning on thermal comfort, the commonly accepted principle that people prefer to have personal control of their environment, and the studies that show energy savings from expanding setpoints. The literature suggests a lack of studies that consider both occupant comfort and energy savings as a result of changing setpoints and providing occupants personal environmental controls. It is exactly this gap of knowledge that this research aims to address through a field study.

3. Problem Statement and Objective

3.1 Problem Statement

Many office buildings have no operable windows and use HVAC systems to keep the interior temperature within a narrow range to create a thermally comfortable interior environment for their occupants. While there are many different HVAC systems and office layouts, a typical and profuse design is to have a variable air volume (VAV) system condition the full volume of interior air, while knowledge workers stay stationary at their desks working from a computer. This is an inherently inefficient system as people's thermal comfort is dictated by the conditions immediately around themselves. While task-ambient lighting levels are well understood and applied in design, task-ambient conditioning offers similar potential for energy savings, but has seen minimal application beyond lab studies.

Personal control of conditioning and indoor environmental quality (IEQ) at large allows people to adjust settings to their desired levels, which directly impacts both energy consumption and people's experience inside buildings. It is widely understood that people are willing to accept, and may even prefer, a broader range of IEQ characteristics if they have personal control even if they do not use the controls. While standards allow for a wider interior temperature range when people have personal control over opening windows, standards currently dictate that all mechanically ventilated buildings must maintain a narrow deadband between heating and cooling setpoints, thereby preventing the potential energy savings of a task-ambient conditioning system with expanded setpoints. Not only are these savings a missed opportunity, but it is common for people in offices to bring in their own fans and space heaters for personal control of space conditioning. These fans, and especially the space heaters, exacerbate the office's energy consumption since they are typically high-power devices.

It is both intuitive and well-established that lowering the heating set point will lower heating energy consumption and raising the heating setpoint will lower cooling energy consumption. However, if people feel too cold or too hot, this can have a negative impact on comfort, productivity, and even health. Facility managers typically want to minimize complaints and aim for a steady state temperature within a narrow range. There are minimal cases in which mechanically ventilated office buildings have lowered the heating set point during the workday, though there has been some application of raising the cooling set point in the summer. While people can adapt to more extreme conditions over time, saving energy from expanded setpoints is problematic if people inside the space are uncomfortable.

While people prefer personal control and there is a large potential to save energy from expanded set points, there have been few field studies that combine these concepts to find the sweet spot between energy efficiency and thermal comfort. Though high-power fans and space heaters are available and sold frequently on the market, low-power conditioning devices have remained primarily in lab studies. While these low-power devices have shown potential to provide equivalent comfort with wider ambient temperatures in lab studies, little research has been done in the field to gain feedback from people in real offices while monitoring energy consumption with expanded setpoints.

3.2 Objective

The main objective of this study is to demonstrate that using a personal comfort system can reduce HVAC energy consumption while providing individual occupant thermal comfort. This project specifically field tests a low-power footwarmer given to 16 people in a VAV conditioned office in Berkeley, California, to determine if the device can provide equivalent thermal comfort at lower setpoints during the heating season, and to quantify the impact on the office's energy consumption.

Through HVAC monitoring, plug load measurements, surveys, and interviews, the field study was designed to (a) assess the thermal comfort of the occupants by analyzing occupant surveys during periods of time at lowered setpoints, (b) evaluate user feedback regarding the design of the footwarmer, (c) determine HVAC energy consumption through monitoring plug loads and heating, reheat, and cooling during the periods of time at lowered setpoints, (d) determine if the increase in plug loads was offset by HVAC savings from lowered setpoints.

This effort was part of a larger research agenda of the Center for the Built Environment at the University of California Berkeley to field test PCS devices, including low-power fans and low-power chairs that provide heating and cooling. The footwarmer used in this study was developed by CBE and tested in lab studies. Through field testing the footwarmer in a small office building during the winter months, this study developed a useful method for combining quantitative analysis of the HVAC system at different setpoints with qualitative feedback from occupants through surveys and interviews. This study therefore has a secondary contribution that is the development of field study methodology applicable to those interested in field testing PCS devices in other buildings and climates.

3.3 Significance

The results of this study have both short-term, medium-term, and long-term implications for building energy consumption and thermal comfort. A short-term goal is to learn from this first application of field study methodology with regards to the methodology itself and the analysis of the comfort and energy results. A medium-term goal is to use the results from this small field study as a stepping stone to arranging similar field studies in larger offices in various climates to help substantiate the conclusions. While this field test was in a VAV conditioned building, the technology would also work well in naturally ventilated buildings or radiantly cooled buildings to improve comfort. Additionally, field testing low-power devices could lead to technology refinement and commitment from a commercial manufacturer, which is an important step in scaling up these efforts to have an impact in society at large. A long-term vision for widespread implementation of low-power personal comfort systems is significant given the potential to substantially reduce building energy consumption and lower our carbon footprint. As a relatively low cost and low tech solution, low-power personal comfort systems are a noninvasive and relatively simple energy conservation measure that is feasible for both retrofit projects and new construction. Another long-term goal of this emerging field of research is for thermal comfort standards to allow for expanded setpoints in mechanically ventilated buildings with personal comfort systems, following a similar path as the research on personal control of operable windows that led to the adaptive comfort standard for naturally ventilated buildings. Ultimately, as buildings are for people, this research aims to make offices more comfortable for workers by providing them with the ability to control their own thermal environment.

4. Methods

In order to assess the impact of a low-power personal control system, this project combines occupant thermal comfort surveys and interviews with measurements of plug loads and HVAC energy consumption during periods of time at different temperature setpoints in a mechanically ventilated office building. This approach was designed to evaluate occupant thermal comfort and energy consumption at different temperature setpoints. The below sections thoroughly describe the personal comfort system, office, measurements, and surveys used for this field test as well as the project timeline.

4.1 Description of Personal Comfort System for Field Test

While several low-power devices developed for personalized control of localized conditioning are described in the literature review, this study tested two specific devices developed by the Center for the Built Environment at the University of

California, Berkeley. The fan and footwarmer units tested in this project are part of a suite of devices under development at CBE known as Personal Comfort System (PCS). While many fans and space heaters are designed commercially, a large innovation of the PCS fan and footwarmer is they have a low power draw. The industrial design of the PCS fan and footwarmer has been under development since 2009 and their technologies have been refined through lab tests. The PCS fan and footwarmer are shown below.

Figure 4.1-1 PCS Fan and PCS Footwarmer

Left – PCS fan; Center – PCS footwarmer; Right – PCS fan and PCS footwarmer installed at a workstation

The PCS fan is a desktop fan with an occupancy sensor and an air temperature sensor. An energy efficiency feature of this fan is that its occupancy sensor ensures that the fan remains off when no one is at the desk. There is no audible noise when the fan is running. The fan has a flexible neck so that it can easily be adjusted to directly target the air movement towards the user's head.

The fan has a knob at the base of the fan that controls the fan speed, which can be set anywhere between 0 – 100% power. The power of the fan at different settings was tested and Figure 4.1-2 suggests a linear relationship between the fan setting and power consumption with a maximum power less than 3.0 W. Given that conventional desktop fans are typically 200 W, the PCS fan is clearly a low-power device [provide source]. When the fan sits on an occupant's desk, 2.5 m/s is the maximum air speed measured at the head of an occupant sitting at his or her workstation. The maximum air volume delivered through the fan is 10 liters/second.

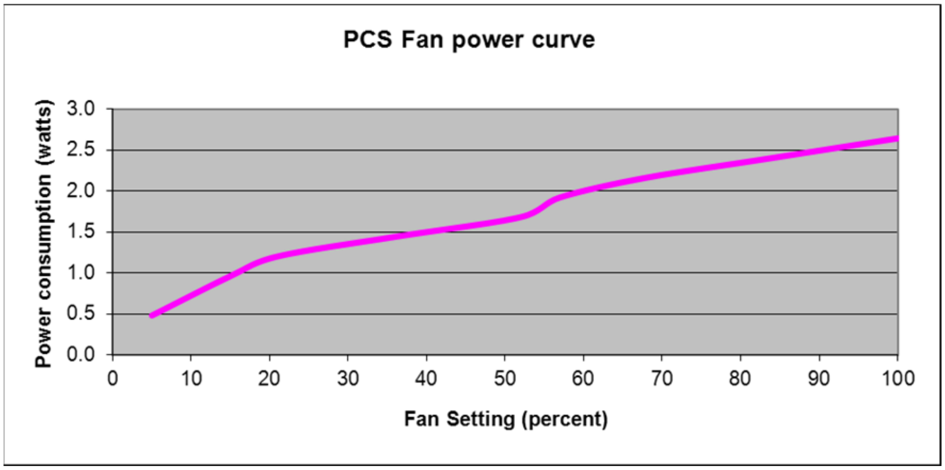


Figure 4.1-2 PCS Fan Power

The PCS fan and footwarmer have a microprocessor and USB connection to the user's computer so that software can monitor usage, power levels, and air temperature from the fan's sensor. While this software can upload this information to a database, the software did not work at all workstations in this project due to factors beyond the control of the research team. The fan and footwarmer use was monitored using alternate means described in 4.6 Physical Measurements.

The PCS footwarmer is a piece of equipment that sits under the desk. Similar to the fan, the power of the footwarmer can be controlled from 0 – 100% by a knob on the fan. The footwarmer is a well-insulated metal box with reflective material as the inside finish. It has two main characteristics that contribute to its energy efficiency. Unlike space heaters that operate continually as long as they are plugged in, the footwarmer has a pressure sensitive footplate that activates the heating when someone puts their feet on the footplate. Additionally, reflector light bulbs inside the footwarmer heat feet through directed longwave and shortwave radiation, which means that the footwarmer (0 – 160W) uses substantially less energy than spaceheaters are typically 1500 W (EnergyUseCalculator.com 2013). In the footwarmer, feet are also heated by the warm air inside the footwarmer, which is approximately 90F when the footwarmer is at full power.

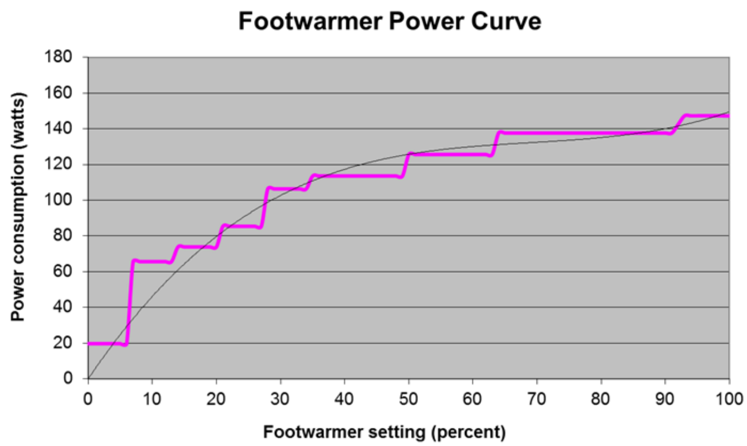


Figure 4.1-3 PCS Footwarmer Power

4.2 Building Selection Criteria

There were several criteria important for selecting an office building for this field test. These criteria included preferences for the location of the building, the mechanical system, layout of the office, and occupant characteristics.

Regarding building location, it was favorable for the test site to be nearby the UC Berkeley campus to allow for easy installation of the personal comfort system, the ability to troubleshoot potential problems during the study, site visits for any needed observations, and interviews at the conclusion of the study. Additionally, close proximity of the research team to the test site could also lead to perceived reliability of the team in the eyes of the study participants who would know that the team is nearby if any issues arise. Further, building a trusted relationship with the office leader is important in approving the study and sustaining occupant participation. While having a test site close to campus limited the study to a temperate climate, the proximity was still desirable given that this project was first of its kind and involved the development of new field study methods.

There were several requirements for the mechanical system. We sought a mechanically ventilated building that used a single-duct VAV reheat system with separate setpoints for heating and cooling to maximize the energy savings of setpoint changes. We needed to be able to have access to the building management system (BMS) with a control system that allows remote access for setpoint adjustments and the ability to lockout the thermostats to prevent occupants from changing settings. The BMS system needed to have data logging capabilities for the VAV box and air handling units (AHUs) that serve the office space for the field study. Another requirement for the HVAC system was that it had to be capable of maintaining specified setpoints and be compatible with an overlying database system that recorded variables needed to calculate HVAC energy consumption of the VAV system, namely airflow, room temperature, supply air temperature, and discharge air temperature.

Spatially, if the test site was a portion of a larger building, it needed to be an enclosed zone so that setpoint adjustments only affected the area participating in the study and that its energy flows could be isolated and its energy balance determined. This also allows for maximum control of the conditions in the test site. While we preferred to have a gender balance, a significant characteristic of the test site was to have an office in which occupants spend the majority of time at their desk. Since the study is about task-ambient conditioning, it is an approach most likely to have the greatest effect in offices in which task conditioning could be effective.

4.3 Description of Field Test Building

The Doe Annex of the Bancroft Library at UC Berkeley met the above criteria and was therefore selected as the office space for this field study. The Doe Annex currently houses the library services department and is an isolated office space that was renovated in 2006. Taylor Engineering was the mechanical engineering firm for the 2006 renovation of the space and we were fortunate to be able to meet several times with the lead engineers to better understand how the system operates and is controlled, which is described in detail in 4.3.2 HVAC System Description.

4.3.1 Workspace Description

The Doe Annex has an open office plan with two private offices, as well as a conference room and copy / kitchen area that were both excluded from the study since they are more transient spaces separate from where people primarily work. Table 4.3-1 provides the square footage of the office.

Type of Space	Area (ft^2)	Included in the Study?
Copy Room / Kitchen	432	No
Conference Room	265	No
Private Office	420	Yes
Open Office	2,957	Yes
Office Area in the Study	3,377	--

Table 4.3-1 Areas by Space Type in Doe Annex

The office is on the ground level and is primarily comprised of cubicle workstations, except for the two private offices. The cubicles each have partitions, two worksurfaces, desktop computers, shelves, and filing cabinets. Interior and exterior photographs of the office are shown below:

Figure 4.3-1 Photographs of Doe Annex
Left – Exterior; Center – Interior View; Right – Typical Cubicle

The main façade of the office faces north, which minimizes solar gain. There is one window on the west façade, 10 windows on the north façade, and three windows on the east façade. None of the windows are operable nor do any of them have interior or exterior shading devices. Half of the people sit in the perimeter close to windows and the other half are more removed from the windows. Each workstation was assigned a number, though not all workstations were occupied. Only occupied workstations were of interest for this study and the labeled occupied workstations are shown in Figure 4.3-2. While having only sixteen occupants and participants for the study is limiting, it is a manageable number for individual analysis and the development of the field study methods. All employees participated in the study and the office leader enthusiastically supported our study, which helped sustain participation from all employees throughout the study. The green highlighted area in Figure 4.3-2 shows the Doe Annex office space located within the Bancroft library. The white circles show the workstation location of the occupants and their Workstation ID numbers, which will be further explained in 4.4 Experimental Methodology.

Figure 4.3-2 Doe Annex Floor Plan: Area Included in the Study and Occupant Locations

While a survey would later be used to establish a basecase for the occupants' opinions of the indoor environmental quality of the office, the research team walked through the office several times to observe whether people used their own devices for localized conditioning at their workstations. The research team noted that there were two air filters installed in the office and that a few people were using personal fans, but there were no space heaters in use. When asked, occupants confirmed that space heaters were not used in the office. As a basecase condition, the occupants in the Doe Annex did not have personal control over the heating and cooling at their workstations with the exception of just a few people who used small, desktop fans.

Other desirable aspects of using this building for a case study included that there was an even gender balance in the office, but more importantly that occupants spend the majority of their workday at their computer at their workstation. The occupants are primarily programmers who are generally at their desk, or occasionally at meetings in the conference room in the office. Very few occupants have meetings outside of the office. Table 4.3-2 provides the gender of the participants as well as their own estimation of the percentage of time they spend at their desk.

Workstation Number	Gender	Estimation by participant of percentage of time spent at his/her workstation
WS1	Female	80 – 85%
WS2	Female	Some whole days at desk, but typically 1 day/wk in conference room, 2 days/wk 80% outside the office
WS3	Male	"almost always"
WS5	Female	80 – 85%
WS6	Male	95%
WS7	Female	"almost always"
WS8	Female	"almost always"
WS9	Female	90%
WS11	Male	85 – 90%
WS12	Female	98%
WS13	Male	80 – 90%
WS14	Female	90%
WS15	Male	"most of the time"
WS17	Male	85%
WS20	Male	95%
WS24	Male	95%

Table 4.3-2 Description of Study Participants

The Doe Annex was seen as a good fit for this study as it is an isolated office space, no operable windows, a gender balance, a high percentage of time spent at desks by the occupants, a supportive office leader, and a manageable number of occupants for the first field study of this kind. While these criteria are important, it was also necessary to assess the mechanical system of the office to ensure that we could control and measure setpoint adjustments and energy consumption.

4.3.2 HVAC System Description

The office is conditioned by a variable air volume (VAV) mechanical system with an Automatic Logic (ALC) control system and chiller-based cooling. This type of system varies the volume of heated or cooled air supplied into a room in order to maintain its air temperature (T_{rm}) between the heating and cooling setpoints. Rooms (or zones) are conditioned separately through dedicated VAV boxes that vary the airflow from the central system and which may also add heating or cooling to the central supply air. The control system specifies the heating and cooling setpoints, which for this office were 70F and 72F, respectively.

The chiller cools air in the central plant, which is then delivered to the VAV boxes in the Doe Annex. The temperature of the air supplied to the VAV boxes is called the Supply

Air Temperature (SAT), which was on average 56 F. When the VAV box is in cooling mode, the SAT is typically equivalent to the Discharge Air Temperature (DAT) since none of the VAV boxes have a cooling coil. When the VAV is in heating mode, valves in the VAV open to allow the flow of hot water through a heating coil in the VAV. When the DAT does not need to be conditioned to maintain T_{rm} between the heating and cooling setpoints, the VAV boxes deliver the volume of air needed to meet the minimum ventilation requirements. In all cases, the return air from the occupied zone is delivered to the central plant, some of which may be exhausted to limit pressurization of the building that would otherwise happen because of the intake of outside air. Figure 4.3-3 is a schematic diagram of the office's HVAC system showing the temperatures monitored by the control system, including SAT, DAT, and T_{rm}. The formula used for calculating the heating energy consumption of this system can be found in 5.4.3. Since the energy cannot be metered since the study only looked at one zone connected to a central HVAC system, the energy use was calculated through an airside energy balance from these recorded temperatures and calibrated airflow.

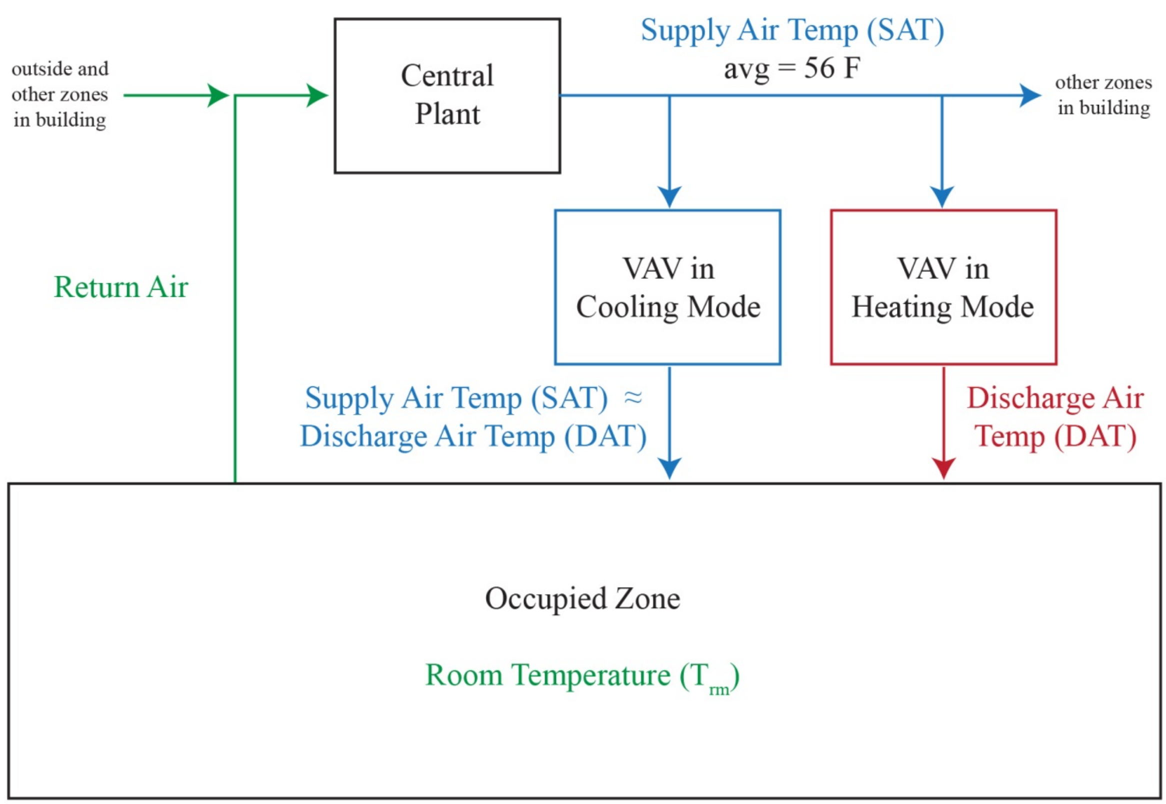


Figure 4.3-3 Schematic Diagram of Doe Annex HVAC System

The HVAC system has an Automated Logic (ALC) control system. It is BACnet compatible and its data can be accessed and exported through the UC Berkeley Simple Measurement and Actuation Profile (sMAP) software. sMAP makes it possible to record and remotely access numerous streams of climate and building performance data for calculating the energy consumption of the mechanical system. A further description of sMAP can be found in 4.6 Physical Measurements.

Figure 4.3-4 shows a map of the areas served by the VAV boxes monitored in this study. We were primarily interested in the VAV boxes serving the workstation area, which were VAV 2.8, VAV 2.10, VAV 2.13, VAV 2.14, and VAV 2.18. Since there is often a discrepancy between BMS airflow and actual airflow, it was important to calibrate the airflow to make sure that the existing system and controls would be conducive to the PCS experiment. A short experiment was done to test whether the flow specified in the BMS system for VAV 2.8, VAV 2.10, VAV 2.13, VAV 2.14, and VAV 2.18 matched the actual flow from these boxes. Knowing the correct air flow is important in calculating energy savings and evaluation indoor air quality issue

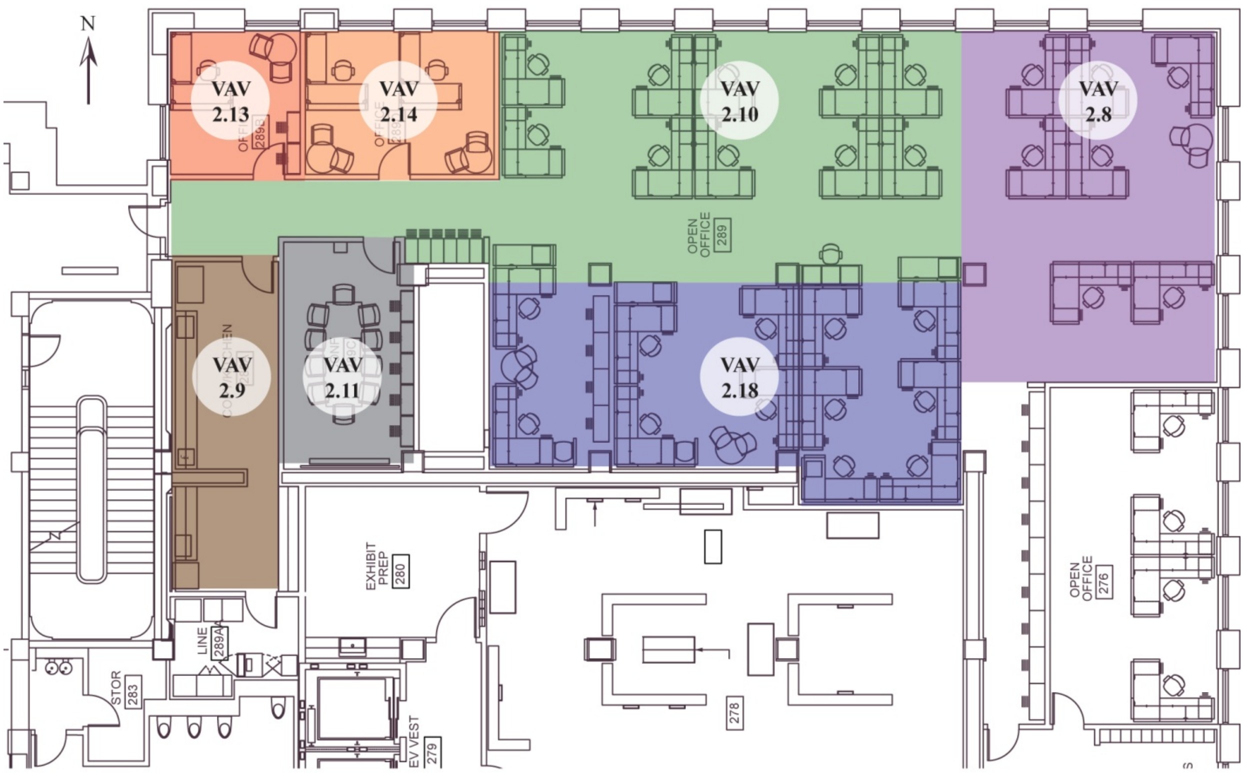


Figure 4.3-4 Doe Annex Plan of VAV Boxes

For each of these VAV boxes, the calibration procedure involved recording the airflow specified by the BMS and measuring the sum of the actual airflow from the box's diffusers. This was done at three different flows by varying the damper positions. The goal of the calibration experiment was to measure the airflow actually being delivered to the space compared to the value that the BMS system trended. Figure 4.3-5 is a photograph of the apparatus used to measure the airflow of the diffusers. A flowhood was held over a diffuser so that all the air from the diffuser went into the flowhood, which was connected to a duct blaster on the ground. The flowhood could only connect to one diffuser at a time so the process was repeated for every diffuser in the office. When a VAV box had multiple diffusers, it was important that the fan speed in the duct blaster be adjusted to overcome the airflow resistance added to the diffuser to which the apparatus was attached. The duct blaster adjusts the airflow so that there is no pressure difference between inside and outside of the hood. Since the joint between the flowhood and the diffuser is not pressurized, small leaks at this joint cannot impact the airflow measurement. This apparatus is a research tool developed by Darryl Dickerhoff at Lawrence Berkeley National Labs (LBNL). It has an accuracy ±3% of the reading, which is mostly bias type error. It is similar to the FlowBlaster Capture Hood Accessory commercialized by The Energy Conservatory (TEC 2013).

Figure 4.3-5 Apparatus for Measuring of Actual Airflow from Diffusers

For each VAV box, the BMS airflow and actual airflow for the 3 damper positions was graphed in Excel with a linear regression, with the assumption that the line would pass through (0,0) signifying no actual flow when the BMS airflow is set to 0 cfm. This assumption is made for two reasons. First, the actual zero is measured every day and used. Second, the offsets from the regressed data were lower than the accuracy of the calibration device. The slope of the regression line represents the accuracy of the actual airflow compared to the BMS airflow and should therefore be equal to 1 if the system is perfectly calibrated. Table 4.3-3 shows a comparison of the airflow given by the BMS and the actual measured airflow for each VAV box, which is a sum of their respective diffusers, as well as the slopes of the regression lines for all VAV boxes. An example of a regression graph showing the slope is shown in Figure 4.3-6.

VAV Box	Damper Position	BMS Airflow (cfm)	Actual Airflow (cfm)	Slope of linear regression of actual vs BMS airflow
2.8	55	1163	1169	1.01
	33	627	647	
	15	143	194	
2.10	55	834	796	0.95
	40	560	525	
	25	282	258	
2.13	55	569	559	0.94
	35	358	309	
	25	206	178	
2.14	55	259	236	0.90
	35	119	109	
	30	88	71	
2.18	55	632	682	1.06
	35	413	432	
	20	227	225	

Table 4.3-3 VAV Calibration Measurements

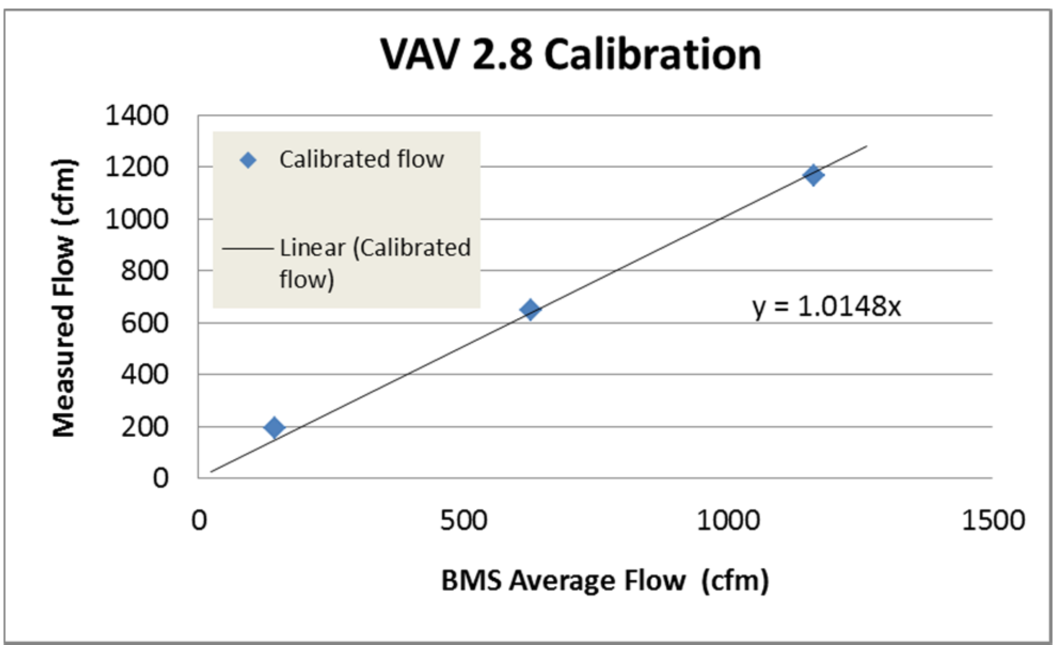


Figure 4.3-6 Regression of VAV 2.8 Calibration Results

The closeness of the values of the actual airflow and the values given by the BMS gave us confidence that that the system was performing as indicated by the BMS. In the example above, VAV 2.8 has a slope of 1.015, which means that the measured flow was roughly 1.5 % different than the airflow specified by the BMS system. This 1.5% difference was even less than the specifications of the duct blaster. Given that the slopes of the regressions were on average within 6% of perfect calibration and the standard error of the regression is about 4%, these results proved that the BMS system would be accurate for our needs in measuring the energy consumption of the HVAC system. The calibrated flows are used in all the heat flow calculations.

The mechanical system in the Doe Annex was a good candidate for the needs of this study because the system was designed with separate heating and cooling setpoints, sMAP could automatically access data from the well-regarded ALC control system, and the actual airflow from the diffusers was consistent with the values given by the BMS system,

4.3.3 Outdoor Climate Context

The time period available for this study, October 2012 through April 2013, is heating dominated in Berkeley, which is characterized by ASHRAE Climate Zone 3 and California Climate Zone 3. While humidity is low and temperatures are fairly moderate, buildings with minimal internal loads will typically be in heating mode during this timeframe as shown in Figure 4.3-7. The weather file from the nearby Oakland International Airport (OAK) reveals that there are typically 2909 heating degree days (base 65) and 128 cooling degree days (base 80F) annually (Pacific Energy Center 2006).

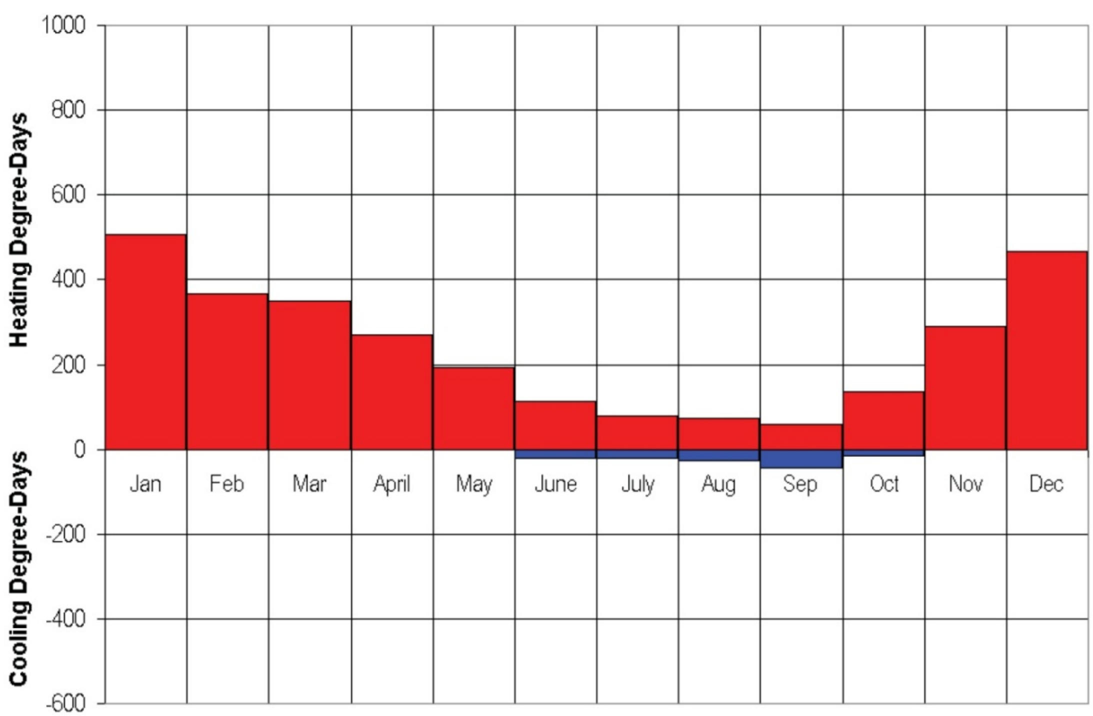


Figure 4.3-7 Heating and Cooling Degree Days: Oakland Int'l Airport (Pacific Energy Center 2006)

Figure 4.3-7 shows that there are typically only heating degree days during the timeframe of the study from October through April. A closer look at the TMY3 weather file from the Oakland International Airport below shows hourly temperature and relative humidity data for a typical year, with the study months highlighted again by dashed black boxes in Figure 4.3-8. While the Oakland International Airport is 16 miles from the field study site and has a different microclimate, the below graph provides a rough idea of annual temperature and humidity for the region.

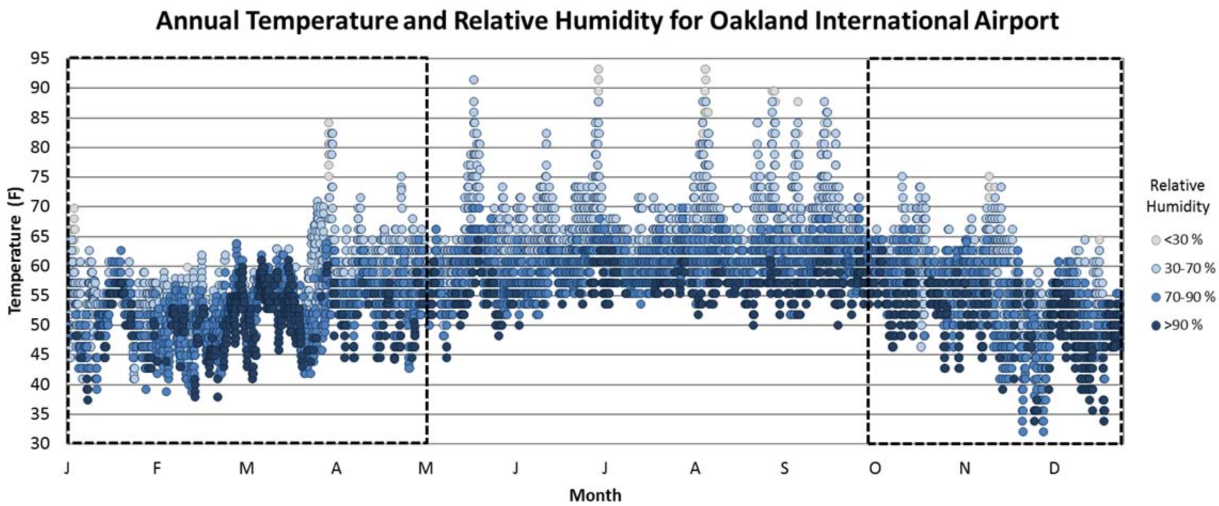


Figure 4.3-8 Annual Temperature and Relative Humidity of Oakland International Airport TMY Data

Given the time constraint of the study from October through April, the study focusing on evaluating the impact of PCS during wintertime conditions. This study therefore focuses on the use of the footwarmer and evaluates both energy and comfort when changing the heating setpoint, not the cooling setpoint.

4.4 Experimental Methodology

Since this research was the first field demonstration testing PCS devices and under adjusted setpoint conditions, it was necessary to develop an experimental methodology that would include subjective (surveys and interviews) and physical (HVAC and plug load monitoring) data. The different kinds of data collection are summarized below.

Data Collection Type	Frequency	Goal
Right Now Survey	3 times/day	Evaluate occupant comfort at specific setpoints
Exit Interview	1 time	Evaluate occupants' opinions of PCS after study
Plug Load Monitoring	Every 15 min	Determine PCS use and consumption
HVAC Monitoring	Every 15 min	Determine HVAC energy consumption at specific setpoints

Table 4.4-1 Field Experimental Methodology

The research team sent an email to the 16 employees working in the Doe Annex inviting them to participate in this study about the quality of the thermal environment of the office. They were told that participation would involve one minute long online surveys three times per day for specific weeks, referred to as "survey periods," over the following months. This survey, referred to as the "Right Now Survey," is further described in 4.5 Subjective Measurements. Participants were offered $25 gift certificates to a location of their choice for each of the weeks in which they submitted at least 10 surveys per week during a survey period. All 16 employees consented to participate in the study. Every participant's workstation was assigned a number, known as their "Workstation ID." Participants were given a candy box for their desk with their Workstation ID so they could easily find their Workstation ID number, which was needed every time they submitted a Right Now Survey. A plan showing the Workstation ID locations can be found in Figure 4.3-2.

Before any PCS units were installed and before the online survey link was sent out, the first step was to establish the basecase condition for both occupant comfort and energy consumption. Since the existing heating setpoint was 70F, the basecase condition was a heating setpoint of 70F and no access to PCS. In early September 2012, the research team installed power-metered powerstrips in each workstation and connected all workstation electricity consuming devices to this powerstrip (the computer, monitor, and later the PCS units). From this point onwards, the workstation plug loads and the HVAC energy consumption was monitored by the research team. 4.6 Physical Measurements further describes the method for monitoring plug loads and HVAC energy consumption.

At the end of September, Survey Period 1 began by sending an email three times per day over a period of six work days to the occupants with a link to the online survey, which recorded the survey votes in a database accessible for download by the research team. Survey Period 1 is an example of the basecase condition as the setpoint was 70F and no PCS units had been installed.

In mid-October 2012, the research team then installed 16 PCS units, one at each of desks of the participants. The research team met with each participant at his or her workstation to explain how to use both the fan and the footwarmer. The participants were encouraged to email the research team at any point during the study if they had any questions or problem with the fan or the footwarmer.

Survey Period 2 began in late October about a week after participants received the footwarmers, so this survey period was intended to observe the impact on occupant comfort when occupants gained use of PCS under the same heating setpoint, 70F. The heating setpoint was then gradually lowered and then gradually raised over the next five months. Each of the survey periods during this time had a distinct heating setpoint ranging from 70F down to 66F, shown in Table 4.4-2 and Figure 4.4-1. Setpoints were typically changed late in the afternoon. Occupants did not know when the setpoints were changed and were never told that the research team was adjusting the setpoint as part of the study. The goal of gradually lowering and then raising the setpoint was to give occupants the opportunity to adapt to the slightly lower temperatures. The survey for each period continued for one to two weeks.

From mid-March 2013 onwards, the setpoint stayed at 70F. In April 2013, the PCS units were disabled. We waited for two weeks to let participants adapt to the conditions without the PCS units before another survey period was arranged under the basecase conditions for comparison against Survey Period 1. Later in the month, the PCS units were reinstalled to further build the database with survey responses with a 70F heating setpoint and access to PCS. Again, the survey was performed a week after the PCS units were reinstalled to let participants adapt to the conditions with the PCS.

Given the small number of study participants, a few adjustments were made to the dates of the survey periods for several individuals to accommodate their vacation schedules to provide the opportunity to everyone to complete at least 10 surveys per week in each survey period week. This accommodation is reflected in Table 4.4-2 in Survey Period 11 and Survey Period 12, which identifies occupants by their Workstation ID (ex. WS2 = Workstation 2).

After the last Right Now Surveys were sent in May, six months after the beginning of the study, each occupant was interviewed for roughly 15 minutes asking them to reflect about their comfort and experience using PCS during the study. These interviews, referred to as “Exit Interviews,” are further described in 4.5 Subjective Measurements.

Prior to beginning the study, this methodology was reviewed and approved by UC Berkeley's Committee for the Protection of Human Subjects (CPHS) to ensure that participants consented to join the study, participant confidentiality was respected, and that no aspect of the methodology posed any negative risks for the participants.

	PCS?	Set Point	Start Date	End Date
Period 1	no	70	September 28	October 5
PCS installed October 22nd				
Period 2	yes	70	October 25	November 2
Period 3	yes	68	November 5	November 16
Period 4	yes	67	November 26	December 7
Period 5	yes	66	December 10	December 14
Period 6	yes	67	December 17	December 21
Period 7	yes	66	January 7	January 18
Period 8	yes	67	February 4	February 15
Period 9	yes	68	February 25	March 1
Period 10	yes	70	March 18	March 22
PCS disabled March 28th				
Period 11	no	70	April 8	April 12
Period 11 [WS2 and WS8 only]	no	70	April 8	April 17
PCS reinstalled April 23rd				
Period 12 [WS 2, 3, 8, 9, 11, 12, 15, 17, 20]	yes	70	April 25	May 1
Period 12 [WS 5, 6, 7, 13, 14]	yes	70	April 29	May 3
Period 12 [WS_24]	yes	70	April 24	May 10

Table 4.4-2 Timeline of Setpoints for Survey Periods

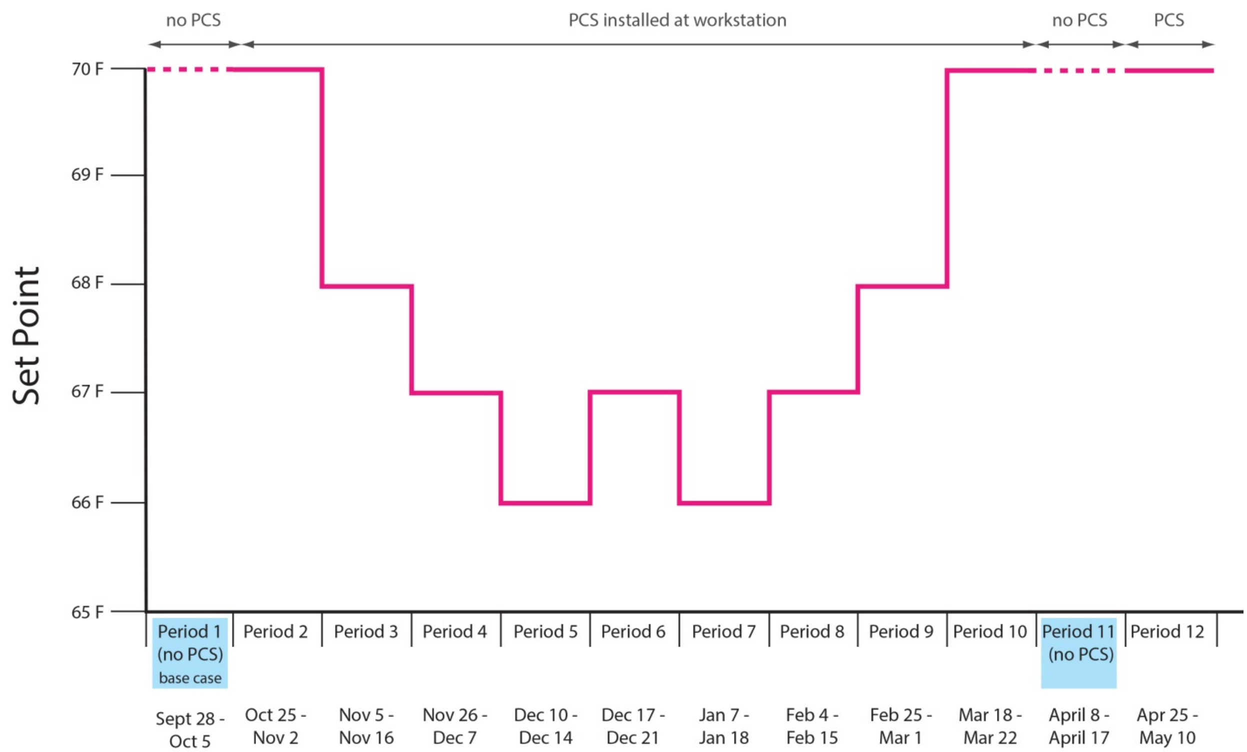


Figure 4.4-1 Timeline of Setpoints for Survey Periods

4.5 Subjective Measurements

Right Now Surveys was one form of subjective measurement used in this research. The Right Now Survey was intended as a means to assessing occupant comfort throughout the day over periods of time at different heating setpoints. During survey periods, participants received an email reminder three times per day with a link to the online survey but they could take the survey at anytime during the day since the link was always active. While occupants could take the survey at anytime, they were encouraged to take it three times a day and only if they were at their workstation, had been at their workstation for at least 15 minutes, and had not submitted a survey within the last two hours. The email reminders with the survey link were typically sent around 9:00 am, 11:00 am, and 2:00 pm on every day during a survey period. Table 4.5-1 lists the Right Now Survey questions, which target thermal acceptability, thermal sensation, air movement, and PCS use. There were 11 questions in the Right Now Survey, which is shown in Appendix A: Right Now Survey. The Right Now Survey took about 30 seconds to complete.

Response Type				Right Now Survey Question
7 Point Scale	Continuous Scale	Yes, No, Not In Use	More, Less, No Change	
X				Right now, how acceptable is the thermal environment at your workspace? (“Very acceptable” to “Not At All Acceptable”)
	X			You feel: (Cold / Cool / Slightly Cool / Neutral / Slightly Warm / Warm / Hot)
			X	You would prefer to be: (Warmer / No Change / Cooler)
X				Right now, how acceptable is the air movement at your workspace? (“Very Acceptable” to “Not At All Acceptable”)
				The air movement feels: (Imperceptible / Slightly Perceptible / Clearly Noticeable / Strong / Very Strong)
			X	You would prefer: (More Air Movement / No Change / Less Air Movement)
X				Right now, how acceptable is the air quality at your workspace? (“Very acceptable” to “Not At All Acceptable”)
	X			Your feet feel: (Cold / Cool / Slightly Cool / Neutral / Slightly Warm / Warm / Hot)
		X		Right now, does the desk fan provide enough cooling? (Yes / No / Not in Use)
		X		Right now, are you using another fan (in addition to our fan)? (Yes / No)
		X		Right now, does the footwarmer provide enough heat? (Yes / No / Not In Use)

Table 4.5-1 Right Now Survey Questions

In order to submit the survey, occupants needed to enter their Workstation ID so that all submitted survey responses were associated with the Workstation ID of the person who submitted them. Survey responses were also time stamped in the database, which could be downloaded at any point by the research team. Using an online based system automated the data collection process. The occupants considered the process easy and convenient in that it gave them some flexibility to take the survey at times that worked best with their schedules.

The Exit Interviews were conducted with each participant individually and were meant to gain people’s opinions regarding the PCS design and effectiveness after having it at their workstation for the previous six months. The responses were intended as complementary insight that would provide valuable context when evaluating each individual's Right Now Survey Responses and workstation power consumption. The interviews typically lasted around fifteen minutes and participants were encouraged to email any further comments that they preferred not to discuss in person or did not think of during the interview.

The same Exit Interview script was used for all of the interviews and it can be found in Appendix B: Exit Survey Interview Script. However, the interview script was more of a guide so that people could elaborate on and add topics about which they felt strongest. For both the fan and the footwarmer, occupants were asked questions addressing: whether or not they used the devices and why, what they liked and did not like about the devices, whether they changed their use of the devices during the study, whether there were specific or regular times in which the device did not meet their needs, and if they had any suggestions to change how they work and how they look. The interviews always ended with a series of general feedback about the thermal comfort at their workstation compared to elsewhere in the office, feedback about how the research team conducted the study, and any additional comments. A summary of each occupant's Exit Interview can be found in Appendix E: Individual Workstation Results.

4.6 Physical Measurements

To complement the simultaneous comfort study under changing setpoint conditions, it was necessary to develop a plan for complete energy measurement. In order to determine if there would be overall energy savings at specific setpoints, the physical data measurement plan was designed with the goal of later analyzing the change in plug load use and in HVAC energy consumption at distinct setpoints. PCS power usage and HVAC energy consumption were both continuously monitored throughout the study and a summary of the physical data acquisition is shown below.

Data	Source	Measurement Frequency	Application
PCS Power Usage	ACme Meter (one per workstation)	Interpolated to even 15 minute intervals from more frequent data captures	Needed to calculate change in plug load use
Room Temperature (T_{rm})	BACnet	every minute	Required for HVAC airside energy balance to calculate HVAC energy consumption
Discharge Air Temperature (DAT)	sMAP	every minute	Required for HVAC airside energy balance to calculate HVAC energy consumption
Supply Air Temperature (SAT)	sMAP	every minute	Required for HVAC airside energy balance to calculate HVAC energy consumption
Airflow from each VAV box	sMAP	every minute	Required for HVAC airside energy balance to calculate HVAC energy consumption
Return Air Temperature	PointSix wireless Sensors	every 30 seconds	Useful as a check for the accuracy of T_{rm} data trends
Outdoor Air Temperature	weather station	every 15 minutes	Useful for determining HVAC energy relative to outdoor weather conditions
Solar Radiation	weather station	every 15 minutes	Useful for determining if occupant comfort was influenced by solar radiation

Table 4.6-1 Summary of Methodology for Physical Data Acquisition

By continuously measuring PCS power usage at each workstation, it would help the research team to understand how people use the devices, compare individual differences, determine if individual and total PCS usage changed as a result of the setpoint adjustments, and compare the PCS energy use with the HVAC energy use. At every workstation, all electrical devices were plugged into wireless ACme power meters. These measure power usage and allow the data to be downloaded remotely since it is a wireless based system (Jiang, Dawson-Haggerty, Dutta, Culler, and Goto 2013). When post-processing downloaded data from the ACme meters, it was important to be able to distinguish the power usage profiles for the computer, monitor, and footwarmer. Since the fan was only 4 W, it would be unlikely to be able to distinguish the fan load from the other devices. Since the study was conducted in the winter and fan usage was expected to be minimal, this was not a barrier for this study, which focused on footwarmer use and the heating setpoint.

Figure 4.6-1 ACme Power Meter (Jiang, Dawson-Haggerty, Dutta, Culler, and Goto 2013)

In order to calculate the energy consumption of the HVAC system using an airside energy balance, it was necessary to continuously monitor the airflow through all VAV boxes in the study area, the supply air temperature reaching the VAV boxes (SAT), the diffuser discharge temperature entering the zone (DAT), and the temperature of the occupied zone (T_{rm}). Monitoring T_{rm} would also make it possible to confirm that changing the heating setpoint in the BMS was effective as T_{rm} should be equal to the heating setpoint in winter conditions. The SAT was consistently 56F, which was determined by other zones served by the same air handler. As the thermostats were locked out, the only way to change the setpoint was to request for the facilities manager to make the change in the BMS system.

Continuous monitoring of airflow, SAT, DAT, and T_{rm} was done using sMAP software, which had been developed in the Department of Electrical Engineering and Computer Science UC Berkeley as a research tool for web access to building energy data streams for optimizing energy supply networks (Blumstein 2013). sMAP allows users to remotely look at VAV box airflow and SAT, DAT, and T_{rm} trends to measure zone cooling and heating rates in real-time. sMAP archives the data in a time-series database that is readily examined and exportable in csv format for analysis.

The only independent sensors that were installed in the Doe Annex were PointSix data loggers with thermistors that recorded the return air temperature. The BMS did not record the return air temperature on a room by room basis so these sensors were the only way to collect this data in this building. PointSix sensors are battery powered devices that record data at specified intervals and can be connected to several types of sensors, including thermometers. The return air temperature was not needed for calculating the airside energy balance, but served as a useful check on the T_{rm} data recorded by the BMS. It would also be necessary if an attempt were to be made to calculate a total heat balance for the room.

A weather station at nearby Lawrence Berkeley National Laboratory (LBNL) records outdoor air temperature and solar radiation. Throughout the duration of the study, the research team accessed these data to determine the average daily temperature, maximum daily temperature, average temperature during workday hours, average daily solar radiation, and average daily solar radiation during workday hours. This information was useful for determining the energy performance of the HVAC system as well as comfort responses relative to outdoor air temperature. Recording solar radiation enabled the research team to consider whether or not radiation might be the cause of differing comfort votes between people at workstations by windows and those in the core, should such a difference be found in the analysis. Since the primary façade of the Doe Annex faces north, solar radiation was not expected to be an important factor in this project but remained part of the methodology as it might be more relevant in other PCS field tests.

5. Results

As this field study occurred during the winter months, the results are focused on assessing occupants' perceptions of their thermal comfort, use of the footwarmer, and heating energy consumption of the HVAC system. "Survey period" is a key term used throughout the following sections and refers to specified weeks during which occupants received the Right Now Survey at several different setpoint temperatures as recorded in Table 4.4-2 and Figure 4.4-1. As described in the methodology, the results encompass both qualitative and quantitative means to investigate the objectives set forth in this project.

The qualitative results begin with a general assessment of the Right Now Survey responses and then delve deeper by looking at the survey results of specific subsets of occupants. While the results include summary tables of key findings, additional graphs are provided in Appendix C: Right Now Survey Day by Day Results for Each Survey Period, Appendix D: For each Setpoint: Right Now Survey Results by Outdoor Temperature, and Appendix E: Individual Workstation Results. All of the Right Now Survey graphs report the number of votes (n value), statistically significance difference(based on p values of a t test at a 95% confidence level), and the percent of acceptability (applicable only to graphs for thermal acceptability). Each series of Right Now Survey graphs describes the method used for determining statistically significant difference and provides additional notes on other aspects of the graph.

After presenting the Right Now Survey Results of the office and occupant sub-groups, there is an assessment of each individual's Right Now Survey Results in combination with measurements of the average footwarmer power at his or her workstation. This is followed by a summary of people's thoughts on using the footwarmer and their overall impressions of their thermal comfort throughout the study as expressed in exit interviews after the study.

While measuring average footwarmer power reveals the added plug load, the quantitative analysis continues by assessing heating energy savings from setpoint changes for two different outdoor temperature ranges in order to quantify overall energy savings. All temperatures are in fahrenheit (F) and all power measurements are in watts (W) or kilowatts (kW).

5.1 Analysis of Thermal Response from Right Now Survey

In asking all 16 occupants in the office to take the survey at least 10 times per week during each survey period, there were a total of 2774 recorded surveys during the study. While links to the online survey were sent out three times per day during each survey period, most people submitted closer to 10 surveys per week as opposed to 15 surveys per week, which would have been the total if everyone took the survey just after receiving the link. Nonetheless, the responses are roughly distributed throughout the workday and each occupant tended to submit surveys throughout each survey period. While all 16 occupants contributed in the study, three occupants joined the study during Survey Period 2 and one occupant left her job at the beginning of Survey Period 10. As there is a relatively small number of participants in the study, each person's vote could impact the overall result much more so than if there were a large number of participants. However, the overall insights are still valuable to analyze general trends and the small number of participants allows for more detailed analysis of survey results of each individual.

Out of all the 11 questions in the Right Now Survey shown in Appendix A: Right Now Survey, the analysis focuses on thermal acceptability and thermal sensation. The assessment of thermal acceptability is based on the question, "Right now, how acceptable is the thermal environment at your workspace?" Participants had to choose discrete values ranging from 1 (not at all acceptable) to 7 (very acceptable). The analysis of thermal sensation is primarily focused on whole body thermal sensation, based on responses to the question, "Right now, you feel cold / cool / slightly cool / neutral / slightly warm / warm / hot." Where appropriate, the results for feet thermal sensation are analyzed based on responses to the question, "Right now, your feet feel cold / cool / slightly cool / neutral / slightly warm / warm / hot." As participants could choose any value on a continuous scale from cold to hot, the results are more granular than the thermal acceptability responses.

Graphs for thermal acceptability and thermal sensation present the votes using boxplots, a common graphing technique illustrated in Figure 5.1-1. IQR stands for interquartile range and equals the first quartile subtracted from the first quartile. Where applicable, information about additional layers of data on the graphs is provided at the beginning of the following sections of the Right Now Survey analysis.

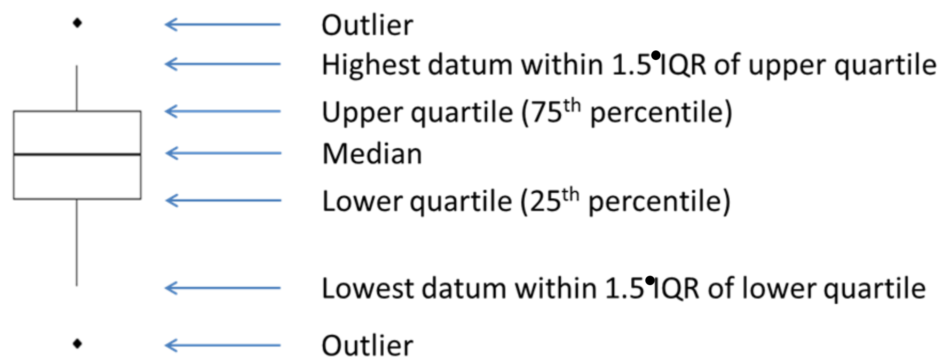


Figure 5.1-1 Boxplot Diagram

The Right Now Survey results begin by looking at the votes of all participants by survey period, followed by a summary of daily results to understand if there was any adaptation during each survey period, and then an analysis of the votes cast in different outdoor temperature ranges to determine if the weather impacted thermal acceptability and thermal sensation. There are then a series of graphs that look at the difference in votes between subsets of votes to better understand whether or not there are additional factors that impact occupant thermal acceptability and sensation. These subsets for comparison consider differences in votes between those satisfied and those dissatisfied with thermal acceptability, frequent footwarmer users and non-frequent footwarmer users, people whose workstation is along the perimeter and those who sit in the core of the office, votes cast in the morning and votes cast in the afternoon, and males and females.

5.1.1 Assessment of Overall Votes

A substantial finding in this study is that the thermal acceptability votes shown in Figure 5.1-2 reveal that there was no significant difference in thermal acceptability when occupants were given the footwarmer and the setpoint was gradually lowered. The thermal acceptability votes for the survey periods range from 86-94%, all of which are above the minimum requirements set forth in ASHRAE Standard 55, which states that spaces should be designed such that at least 80% of occupants are thermally comfortable. The basecase is considered Survey Period 1, which is the existing setpoint (70F) and before people were given footwarmers. In Survey Period 1 (70F), 89% of the occupants found their workstation thermally acceptable. Since there were 16 participants in the study, a single person changing his or her opinion from thermally acceptable to thermally unacceptable (or vice versa) would have changed the basecase value by 7% (1 person out of 16 total = 6.25%). As the thermal acceptability votes for Survey Periods 2 – 11 are never 5% greater or 3% less than the basecase, overall thermal acceptability was maintained throughout the wintertime study in which people had the footwarmer and the heating setpoint was gradually lowered to 66F and then gradually raised back to 70F.

Additionally, the mean and median of the boxplots are similar for the survey periods that have the same setpoint. The main difference, however, is that as setpoints lower, the range of votes increases. While the mean and median are fairly constant throughout the field study and there are no statistically different results, the colder setpoints have more votes towards the not acceptable side of the spectrum. While there were not enough votes to cause a statistical difference between the overall thermal acceptability results at the original setpoint (70F) and the lowered setpoints, this result suggests a slight broadening of the range of people's opinions about the thermal acceptability at their workstations.

Figure 5.1-3 shows that whole body thermal sensation votes are slightly cool in the existing conditions (Survey Period 1, 70F no PCS), improving mildly towards a neutral thermal sensation upon receiving the footwarmer at the same setpoint (Survey Period 2, 70F), gradually dipping back towards slightly cool as the setpoint is lowered (Survey Periods 3 – 9, 68 – 66F), and then returning towards a neutral thermal sensation when the setpoint is 70F again (Survey Periods 10 – 12, 70F with and without PCS) at the end of the study. The votes when the setpoint is 70F, with and without PCS, are closer to neutral than Survey Period 1 and are the survey periods that have votes closest to neutral thermal sensation. These results suggest that while whole body thermal sensation votes shift slightly cooler, this is not enough to substantially change their votes for how thermally acceptable they find their workspace in general. This also suggests that despite people having access to a footwarmer, they still feel slightly cool overall at lower setpoint temperatures.

The survey did not include a question about the thermal sensation in people's feet until Survey Period 2 (70F) after the footwarmers were installed. The responses to the question about feet thermal sensation are shown in Figure 5.1-4. For Survey Period 2, the majority of the votes were close to neutral, though there are quite a few outliers for both warm and cool feet thermal sensation. The warm outliers are likely due to the use of footwarmers. As the setpoint temperature was lowered, the median and mean for the feet thermal sensation in each survey period remained quite close to neutral, but there were a wider range of responses in each survey period both towards the warm and cool side of the spectrum. Similar to the whole body thermal sensation, this suggests that there is less agreement about feet thermal sensation at lower setpoints.

However, the mean and median of feet thermal sensation stay at a neutral thermal sensation throughout the field study while the whole body thermal sensation votes dip towards slightly cool. In other words, the footwarmer could consistently generally keep most people's feet at a neutral temperature even if their whole body thermal sensation was slightly cool.

The survey also asked people whether or not the footwarmer provided enough heat; the responses are shown in Figure 5.1-5. This was only a relevant question when the footwarmer was in use. Throughout the winter, there were consistently 2 – 4 % of votes in each survey period saying that the footwarmer did not provide enough heat. This is a very low number of votes and shows that this sentiment was felt equally when the setpoint was 70F, 68F, 67F, and 66F. This survey question was also a chance for people to self-report whether or not they were using the footwarmer. While people may have used the footwarmer at times when they were not taking the survey, these results give a general idea of the footwarmer usage in the office, which was also monitored directly using an ACme power meter at each workstation. These results show that footwarmer usage increased as the setpoint lowered and that footwarmer usage diminished as the setpoint became closer to the existing setpoint (70F). Additionally, this self-reported footwarmer reveals that only 42% of occupants were using the footwarmer even at the lowest setpoint (66F). It also shows that 10 – 17% of occupants used the footwarmer when the setpoint was at its existing setpoint (70F), which suggests that people thought the footwarmer was beneficial even when no adjustments were made to the HVAC system.

Key to graphs in this section:

- • = mean
- ✳ = statistically significant difference
    - o For the Thermal Acceptability graph: This symbol occurs for each survey period whose votes are significantly different from the votes of Survey Period 1 (70F, no PCS), the first boxplot on the x axis.
    - o For the Whole Body Thermal Sensation graph: This symbol occurs for each survey period whose votes are significantly different from the votes of Survey Period 1 (70F, no PCS), the first boxplot on the x axis.
    - o For the Feet Thermal Sensation graph: This symbol occurs for each survey period whose votes are significantly different from the votes of Survey Period 11 (70F, no PCS), the second to last boxplot on the x axis.
- values above the x axis without "%" signs = n (number of votes in the survey period)
- values above the x axis with "%" signs = percentage acceptable (Thermal Acceptability only)

- o Percent acceptable (for Thermal Acceptability only) = (sum of "4," "5," "6," and "7" votes in the survey period) / (total number of votes in the survey period)

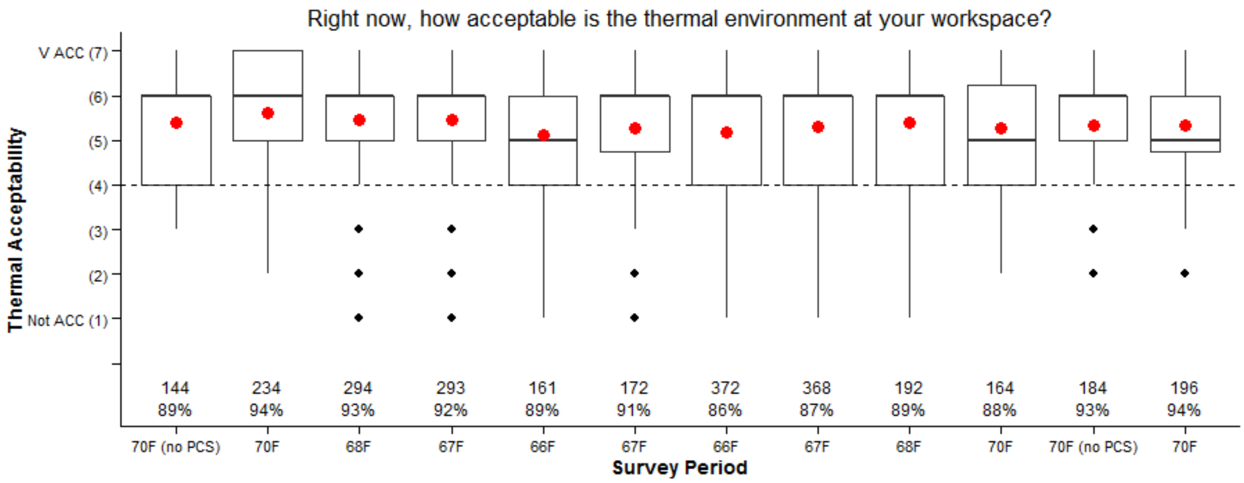


Figure 5.1-2 Overall Votes: Thermal Acceptability

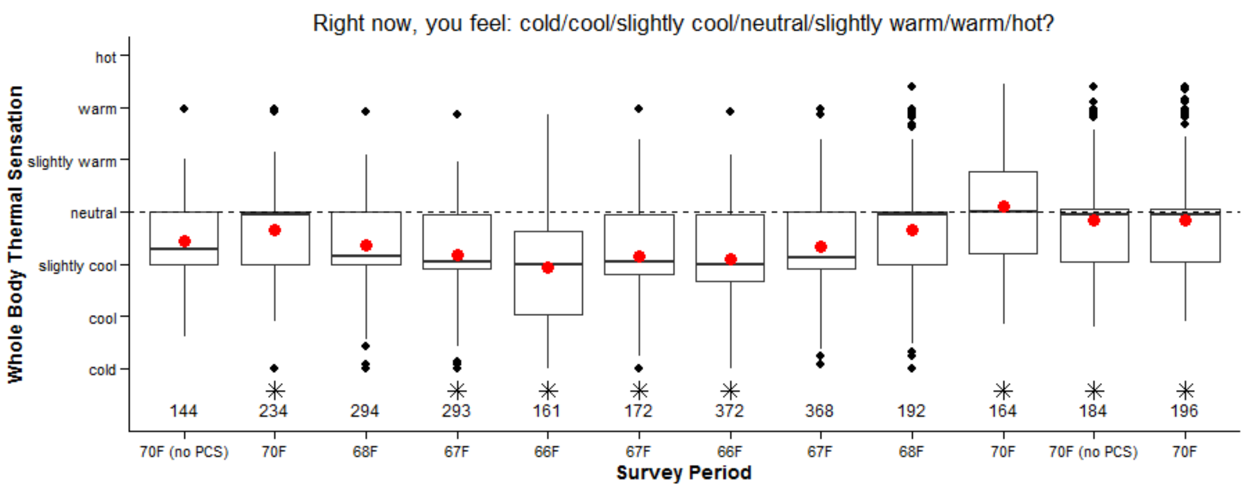


Figure 5.1-3 Overall Votes: Whole Body Thermal Sensation

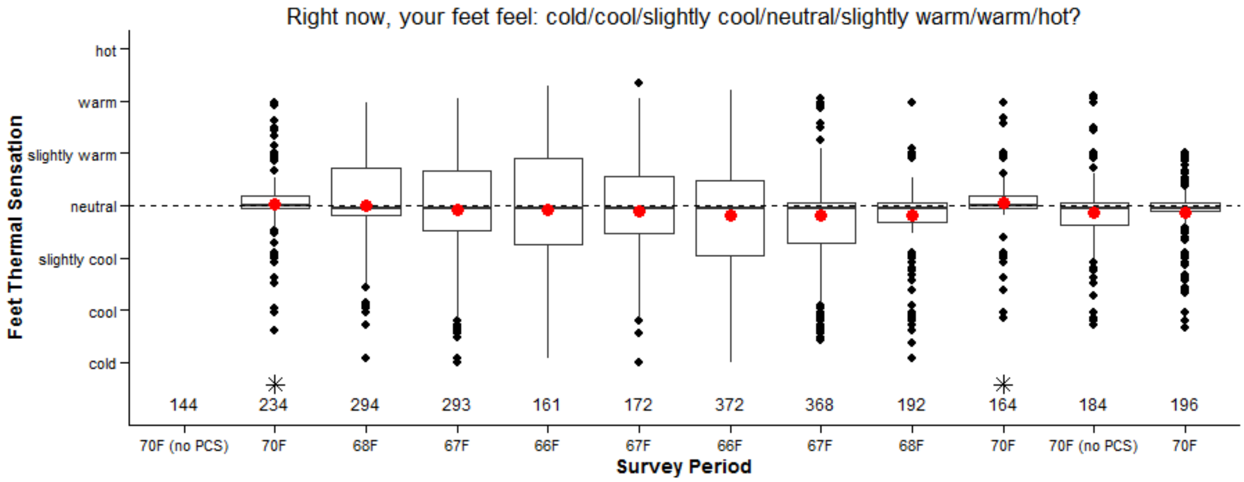
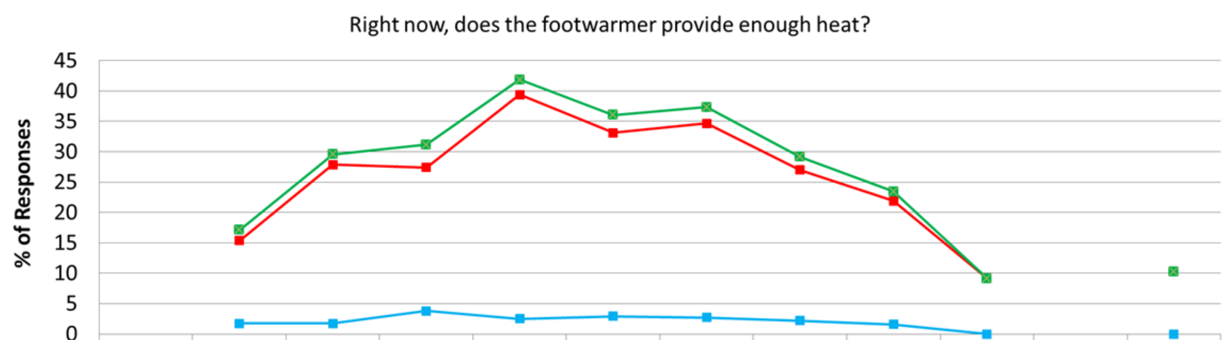


Figure 5.1-4 Overall Votes: Feet Thermal Sensation



	70F (no PCS)	70F	68F	67F	66F	67F	66F	67F	68F	70F	70F (no PCS)	70F
yes		15	28	27	39	33	35	27	22	9		10
no		2	2	4	3	3	3	2	2	0		0
in use		17	30	31	42	36	37	29	23	9		10

Figure 5.1-5 Overall Votes: Footwarmer Usage and Satisfaction

5.1.2 Votes Day by Day

Looking at the results of each day of the survey period allows for investigating whether or not people's votes changed from the beginning to the end of the survey period. While the setpoint was typically changed over the weekend so that the first day of experiencing a slightly altered setpoint was after two days out of the office, the altered setpoint was nonetheless a change from the previous thermal conditions experienced by the occupants. The hypothesis was that people might react negatively to slightly lower setpoints at first, but then adapt towards the middle or end of the survey period as they get used to the new condition. This is based on research that concludes, "thermal adaptation can be attributed to three different processes—behavioral adjustment, physiological acclimatization and psychological habituation or expectation" (Brager and de Dear 1998).

While the day by day results for every survey period for both thermal acceptability and whole body thermal sensation are in Appendix C: Right Now Survey Day by Day Results for Each Survey Period, Table 5.1-1 and Table 5.1-2 provide a general summary of the results of the day by day analysis. Table 5.1-1 shows that the percent acceptable for the last day of every survey period is always higher than the first day of the following survey period, with the exception of the last day of Survey Period 1 and the first day of Survey Period 2 both having 100% acceptable votes. None of the survey periods have days with thermal acceptability results that are significantly different and lower than the first day of the survey period, though three survey periods have days in which there are days with percent acceptable values 7% or lower than the first day of survey period. Three of the survey periods have days with thermal acceptability results that are significantly different and higher than the first day of the survey period and 9 survey periods have days in which the percent acceptable values are 7% or higher than the first day of the survey period. These results suggest that there was a slight level of adaptation throughout the survey periods but do not show substantial change in the day by day perception of thermal acceptability as the setpoint changed.

Table 5.1-2 summarizes the statistically significant differences of the day by day analysis of whole body thermal sensation. Out of the 72 days of the survey, only 7 days (9.7%) had whole body thermal sensation votes that were statistically different than the first day of their respective survey period. These 7 days occurred in 3 survey periods in which the significantly different days had a mean farther from neutral than the first day of the survey period, and 1 survey period in which the significantly different days had a mean closer to neutral than the first day of the survey period. Assuming that neutral is the ideal whole body thermal sensation, this suggests that 25% of the survey periods had one or two days in the middle of the survey period that were slightly worse than the beginning of the survey period and 8% of the survey periods had a few days in which the days in the middle of the survey period were slightly better than the begging of the survey period. However, the day by day whole body thermal sensation votes show generally that there is minimal significant difference in votes as each survey period progressed.

Key to tables in this section:

- Table 5.1-1 Day by Day Votes: Summary of Thermal Acceptability Percentages and Statistical Significance:
    - o Rows = Percentage acceptable and statistically significant difference for each day of the survey period specified in the beginning of the row. For example, each cell in the P1 row first row gives the Percent Acceptable

for each of the six days in Survey Period 1 when the setpoint was 70F with no PCS.

- Top half of each cell = percentage acceptable
  - Percent acceptable = (sum of "4," "5," "6," and "7" votes for that day of the survey period) / (total number of votes for that day in the survey period)
- Bottom half of each cell = statistically significant difference
  - If there is a "✳" in the bottom half of the cell, then there is a statistically significant difference between the thermal acceptability votes for that day compared to the first day of that particular survey period.
  - If there is not a "✳" in the cell, then there is not a statistically significant difference between the results for that day and those of the first day of the survey period.
- Cell shading:
  - Dark green = when the percent acceptable value is 7% or more higher than the first day of that particular survey period (representing the equivalent of one person changing his or her vote from unacceptable to acceptable)
  - Dark red = when the percent acceptable value is 7% or more lower than the first day of that particular survey period (representing the equivalent of one person changing his or her vote from unacceptable to acceptable)
  - Dark grey = when no surveys were solicited that day

- Table 5.1-2 Day by Day Votes: Summary of Whole Body Thermal Sensation Statistical Significance
  - Rows = statistically significant difference for the whole body thermal sensation votes for each day of the survey period specified in the beginning of the row. For example, each cell in the P1 row first row gives the statistically significant difference for each of the six days in Survey Period 1 when the setpoint was 70F with no PCS.
    - If there is a "✳" in the cell, then there is a statistical difference in the whole body thermal sensation votes for that day and those of the first day of that particular survey period.
    - If there is not a "✳" in the cell, then there is not a statistical difference in the whole body thermal sensation votes for that day and those of the first day of that particular survey period.
  - Cell shading

- Light green = when there is a "✳" and the mean of the results for that day is closer to neutral than the mean of the results for the first day of that particular survey period
- Light red = when there is a "✳" and the first day of the survey period, and the mean of the results for that day is farther from neutral than the mean of the results for the first day of that particular survey period
- Dark grey = when no surveys were solicited that day

		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
P1	70F (no PCS)	57%	94%	86%	91%	97 %	100 %				
P2	70F	100 %	89%	97%	91%	92 %	94%	96%			
P3	68F	76%	95%	91%	89%	93 %	93%	98% *	97%	100 %	
P4	67F	82%	97% *	91%	97% *	96 % *	83%	87%	89%	100 % *	96%
P5	66F	89%	81%	97%	92%	89 %					
P6	67F	88%	97%	86%	91%	93 %					
P7	66F	89%	88%	86%	84%	97 %	81%	83%	74%	91%	89%
P8	67F	79%	90%	83%	88%	96 %	89%	83%	92%	87%	90%
P9	68F	86%	89%	86%	84%	98 %					
P1 0	70F	82%	97% *	84%	89%	91 %					
P1 1	70F (no PCS)	88%	91%	95%	100 %	90 %					
P1 2	70F	92%	90%	97%	94%	97 %					

Table 5.1-1 Day by Day Votes: Summary of Thermal Acceptability Percentages and Statistical Significance

		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
P1	70F (no PCS)										
P2	70F										
P3	68F										
P4	67F			*			*	*			
P5	66F			*	*						
P6	67F				*						
P7	66F										
P8	67F										
P9	68F										
P10	70F										
P11	70F (no PCS)										
P12	70F				*						

Table 5.1-2 Day by Day Votes: Summary of Whole Body Thermal Sensation Statistical Significance

5.1.3 Votes by Outdoor Temperature

Looking at thermal acceptability and whole body thermal sensation votes during distinct outdoor temperature ranges allows for one to assess whether the worse results occurred during more extreme weather conditions. For both thermal acceptability and whole body thermal sensation, the votes at specific setpoints are considered during distinct outdoor temperature ranges. For example, the votes from Survey Period 1 and Survey Period 11 are combined in the first row since both survey periods had a setpoint of 70F and people did not have the footwarmers.

While the results for the votes by outdoor temperature for both thermal acceptability and whole body thermal sensation are in Appendix C: Right Now Survey Day by Day Results for Each Survey Period, Table 5.1-3 and Table 5.1-4 provide a general summary of the results of the analysis of votes at different outdoor temperatures for each of the setpoint conditions. For each day of the survey period, the average outdoor temperature was calculated as the average temperature during occupied hours. Table 5.1-3 shows that at under pre-field study conditions (Setpoint 70F, no PCS), there was up to a 12% difference in the percent acceptable votes during different outdoor temperature ranges, though only one day was statistically different than the 55-60F basecase outdoor temperature range. At lower setpoints, there is less of a range of the percentage acceptable values across different outdoor temperature conditions though the weather during these setpoint conditions was consistently cool. In general, these results show that there is minimal statistically significant difference in the percent acceptable results for different outdoor temperatures for each of the setpoint conditions.

In addition to the thermal acceptability votes, the whole body thermal sensation votes were fairly consistent at different outdoor temperature range at each setpoint as shown in Table 5.1-4. Only when the setpoint was 68F were the results for outdoor temperature ranges that were statistically different from the basecase 55-60F outdoor temperature range. Even for these two statistically different results, the results for those two days are simply closer to a slightly cool sensation while the results for the other outdoor temperature ranges at that setpoint are closer to neutral. In other words, there is not a large discrepancy between the boxplots for the whole body thermal sensation votes at different outdoor temperature ranges at that setpoint. Outdoor temperature does not have a substantial effect on whole body thermal sensation.

Key to tables in this section:

- Table 5.1-3 Votes by Outdoor Temperature: Summary of Thermal Acceptability Percentages and Statistical Significance
    - Rows = Percentage acceptable and statistically significant difference for votes that were recorded during specific outdoor temperature ranges during the days with the setpoint specified in the first cell of the row. As there were multiple survey periods at each setpoint, all votes for each setpoint are combined in this analysis.
    - Top half of each cell = percentage acceptable
        - Percent acceptable = (sum of “4,” “5,” “6,” and “7” votes for days at that setpoint during those outdoor temperatures) / (total number of votes at that setpoint during those outdoor temperatures)
    - Bottom half of each cell = statistically significant difference
        - If there is a “✳” in the bottom half of the cell, then there is a statistically significant difference between the thermal acceptability votes in that outdoor temperature range compared to the votes during the 55-60F outdoor temperature range. The basecase outdoor temperature range for this statistical analysis is 55-60F because the most number of responses throughout the whole field study were in this range, which it why it is used later in this report to normalize heating energy consumption.
        - If there is not a “✳” in the cell, then there is not a statistically significant difference between the thermal acceptability votes for that outdoor temperature range and those during the 55-60F outdoor temperature range.
    - Cell shading:

        - Dark green = when the percent acceptable value is 7% or more higher than the results at that setpoint during the 55-60F outdoor temperature range (representing the equivalent of one person changing his or her vote from unacceptable to acceptable)
        - Dark red = when the percent acceptable value is 7% or more lower than the results at that setpoint during the 55-60F outdoor temperature range (representing the equivalent of one person changing his or her vote from unacceptable to acceptable)
        - Dark grey = when there were no cases in which there were votes cast during that oudoor temperature range at the given setpoint

- Table 5.1-4 Votes by Outdoor Temperature: Summary of Whole Body Thermal Sensation Statistical Significance
    - Rows = statistically significant difference
        - If there is a "✳" in the bottom half of the cell, then there is a statistically significant difference between the whole body thermal sensation votes in that outdoor temperature range compared to the votes during the 55-60F outdoor temperature range.
        - If there is not a "✳" in the cell, then there is not a statistically significant difference between the whole body thermal sensation votes for that outdoor temperature range and those during the 55-60F outdoor temperature range.
    - Cell shading
        - Light green = when there is a "✳" and the mean of the results for that outdoor temperature range at that setpoint is closer to neutral than the mean of the results at that setpoint during the 55-60F outdoor temperature range
        - Light red = when there is a "✳" and the mean of the results for that outdoor temperature range at that setpoint is farther from neutral than the mean of the results at that setpoint during the 55-60F outdoor temperature range
        - Dark grey = when there were no cases in which there were votes cast during that outdoor temperature range at the given setpoint

	43-48F Outdoor Temp	49-54F Outdoor Temp	55-60F Outdoor Temp	61-66F Outdoor Temp	67-72F Outdoor Temp	73-78F Outdoor Temp	79-84F Outdoor Temp	85-90F Outdoor Temp
Setpoint 70F (no PCS)			84%	96% *	92%	97%		89%
Setpoint 70F			89%	94%	95%	97%	100%	
Setpoint 68F		91%	89%	97%		87%		
Setpoint 67F	90%	89%	91%					
Setpoint 66F	87%	84%	89%					

Table 5.1-3 Votes by Outdoor Temperature: Summary of Thermal Acceptability Percentages and Statistical Significance

	43-48F Outdoor Temp	49-54F Outdoor Temp	55-60F Outdoor Temp	61-66F Outdoor Temp	67-72F Outdoor Temp	73-78F Outdoor Temp	79-84F Outdoor Temp	85-90F Outdoor Temp
Setpoint 70F (no PCS)								
Setpoint 70F								
Setpoint 68F		*				*		
Setpoint 67F								
Setpoint 66F								

Table 5.1-4 Votes by Outdoor Temperature: Summary of Whole Body Thermal Sensation Statistical Significance

5.1.4 Comparison of Satisfied against Dissatisfied Thermal Acceptability Votes

The graphs in this section focus on the difference in results for every survey period between the “Dissatisfied Group,” defined as those who voted “1: not acceptable,” “2,” or “3” for the thermal acceptability question, and the “Satisfied group,” defined as those who voted “4: neutral,” “5,” “6,” or “7: very acceptable” for the thermal acceptability question. These same groupings of votes were maintained to look at the difference between the Dissatisfied Group and the Satisfied Group for whole body thermal sensation and feet thermal sensation. The goals of comparing these two groups include better understanding the severity of those dissatisfied and determining whether those who find the thermal environment uncomfortable are too warm or too cold.

As expected, Figure 5.1-6 shows there is always a statistical difference between the Dissatisfied Group and the Satisfied Group as far as thermal acceptability. It also shows that the number of people in the Dissatisfied Group is consistently much smaller than that of the Satisfied Group, which is also true in Figure 5.1-7 and Figure 5.1-8. The thermal acceptability graph shows at even for the existing setpoint, 70F (both with and without the footwarmer), there are still some people who find the thermal environment of their workstation slightly unacceptable (mostly "3" votes on the 7 point scale). As the setpoint decreases to 68F, 67F, and 66F, the level of unacceptability in the thermal environment does grow slightly (more of a mix of "2" and "3" votes on the 7 point scale). It is rare that someone votes "1: not at all acceptable" and the results of the Dissatisfied Group differ little between the 68F, 67F, and 66F setpoints.

Figure 5.1-7 shows that those dissatisfied with thermal acceptability, the Dissatisfied Group, consistently had a slightly cool to cold whole body thermal sensation when the setpoints were lowered to 68F, 67F, and 66F. Figure 5.1-11 shows that this same group of people had slightly cool feet thermal sensation were also slightly cool at the lower setpoints. Unlike Figure 5.1-6 which always shows a statistical difference between the Dissatisfied and Satisfied Group, Figure 5.1-7 and Figure 5.1-8 show that the statistical difference is mostly at the lower setpoint temperatures. A surprising result from this series of graphs is that Figure 5.1-7 shows a difference in whole body thermal sensation for the Dissatisfied Group between the results for the survey periods in which the setpoint was 70F at the beginning of the study and those at the end of the study. While the Dissatisfied Group was typically slightly cool at the 70F early on in the study, they were slightly warm towards the end of the study. Though this study focused on heating savings and footwarmer use during winter months, there is an opportunity to use low-power devices to provide personal control of cooling during hot moths. While occupants were given a PCS fan, an analysis of that device was outside of the scope of this thesis.

Key to graphs in this section:

- Dissatisfied Group (red) = results when someone voted "1: not acceptable," "2," or "3" for the thermal acceptability question
- Satisfied group (blue) = results when someone voted "4: neutral," "5," "6," or "7: very acceptable" for the thermal acceptability question
- ✳ = statistically significant difference
    - For the Thermal Acceptability, Whole Body Thermal Sensation, and Feet Thermal Sensation graphs: This symbol occurs for each survey period in

which the votes of the “Dissatisfied Group” are significantly different from those of the “Satisfied Group” for that same survey period.

- values in red and blue above the x axis = n (number of votes of the red group and the blue group for that particular survey period)
- values above the x axis with “%” signs = percentage acceptable (Thermal Acceptability only)
    - o Percent acceptable (for Thermal Acceptability only) = (sum of “4,” “5,” “6,” and “7” votes in the survey period) / (total number of votes in the survey period)
    - o For each survey period, two percent acceptable values are given. The left percent acceptable value represents the result for the red group and the right percent acceptable value represents the result for the blue group.
    - o

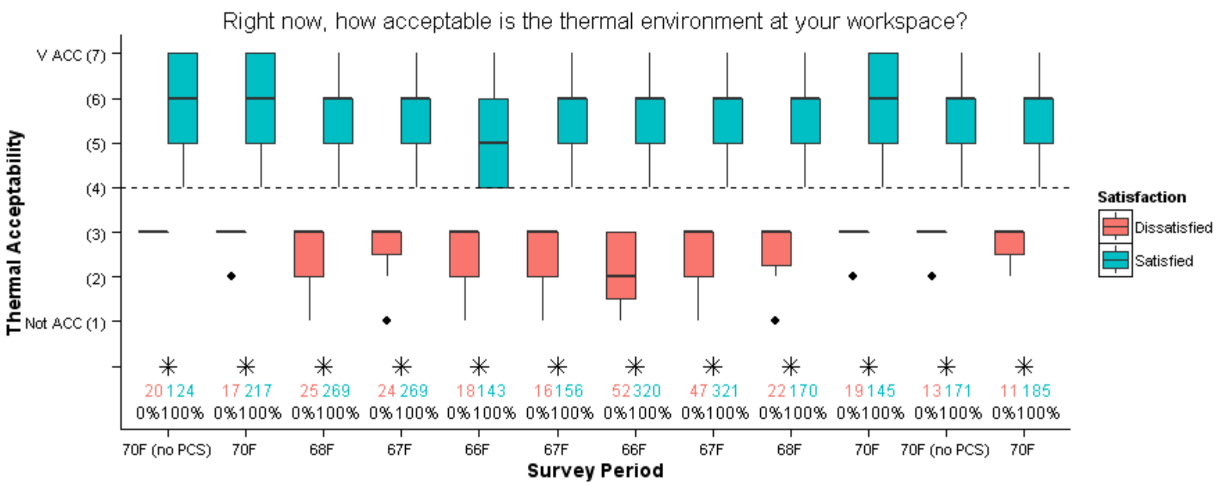


Figure 5.1-6 Satisfied vs Dissatisfied Votes: Thermal Acceptability

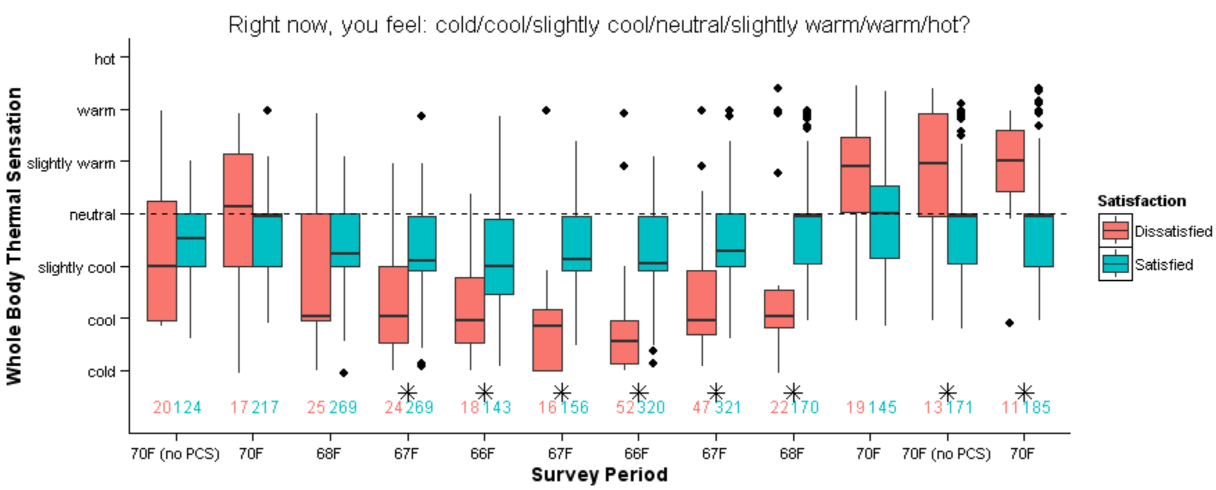


Figure 5.1-7 Satisfied vs Dissatisfied Votes: Whole Body Thermal Sensation

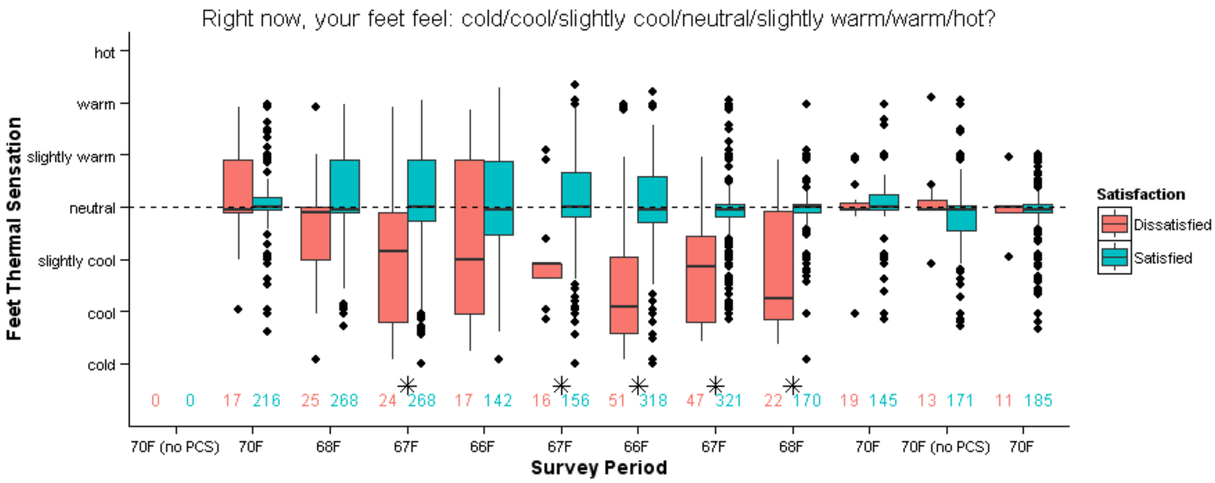


Figure 5.1-8 Satisfied vs Dissatisfied Votes: Feet Thermal Sensation

5.1.5 Comparison of Frequent Footwarmer Users against Non-Frequent Footwarmer Users

The graphs in this section focus on the difference in results between people who self-reported that they were using the footwarmer, the "In Use Group," and those who were not using the footwarmer, "Not In Use Group," at the time of submitting the survey. These results show that the Not in Use Group was always higher than the In Use Group, but that the number of votes in the In Use Group was highest at the cooler setpoint temperatures. Reasons why people did not use the footwarmer more were conveyed in exit interviews, which are summarized in 5.3 Insights from Exit Interviews.

When the setpoint was the existing setpoint, 70F, there was always a statistical difference between the thermal acceptability of the Not In Use Group and the In Use Group, shown in Figure 5.1-9. When this occurred in the beginning of the study, the In Use Group had slightly lower thermal acceptability responses but they had substantially higher thermal acceptability responses at the 70F setpoint towards the end of the study. There was only one survey period in which the setpoint was not 70F, Survey Period 8 (setpoint 67F), that had statistically significant difference for thermal acceptability and the In Use Group had slightly more acceptable votes. Statistical significance aside, the In Use Group always had a higher percentage acceptable with the exception of Survey Period 5 (same percentage as Not In Use Group, setpoint 67F) and Survey Period 2 (just 2% lower than the Not In Use Group, setpoint 70F). In general, this graph suggests that the thermal acceptability was slightly higher for those using the footwarmer, but that there was not a large statistically significant difference in these results and that there were always more non-users than users when the surveys were submitted.

When it comes to thermal sensation, Figure 5.1-10 shows that the In Use Group and the Not In Use group have fairly similar whole body thermal sensation responses that are rarely statistically significant. However, Figure 5.1-11 shows a substantial difference in the feet thermal sensation that is always statistically significant between the Not In Use Group and the In Use Group. While the Not In Use Group often reported slightly cool or neutral feet thermal sensation votes, the In Use Group typically cast their vote as slightly warm for feet thermal sensation. This suggests that people can have a slightly warm feet thermal sensation, a slightly cool whole body thermal sensation, and still find the thermal environment acceptable.

Key to graphs in this section:

- Not In Use Group (red) = Results when someone self-reported that he or he was not using the footwarmer at the time of submitting the survey
- In Use Group (blue) = Results when someone self-reported that he or he was using the footwarmer at the time of submitting the survey
- Grey boxplots = Results of all votes as the footwarmer was deactivated during those survey periods
- ✳ = statistically significant difference
    - For the Thermal Acceptability, Whole Body Thermal Sensation, and Feet Thermal Sensation graphs: This symbol occurs for each survey period in which the votes of the “Not in Use Group” are significantly different from those of the “In Use Group” for that same survey period.
- values in red and blue above the x axis = n (number of votes of the red group and the blue group for that particular survey period)
- values above the x axis with “%” signs = percentage acceptable (Thermal Acceptability only)
    - Percent acceptable (for Thermal Acceptability only) = (sum of “4,” “5,” “6,” and “7” votes in the survey period) / (total number of votes in the survey period)
    - For each survey period (except Survey Period 1 and Survey Period 11), two percent acceptable values are given. The left percent acceptable value represents the result for the red group and the right percent acceptable value represents the result for the blue group.

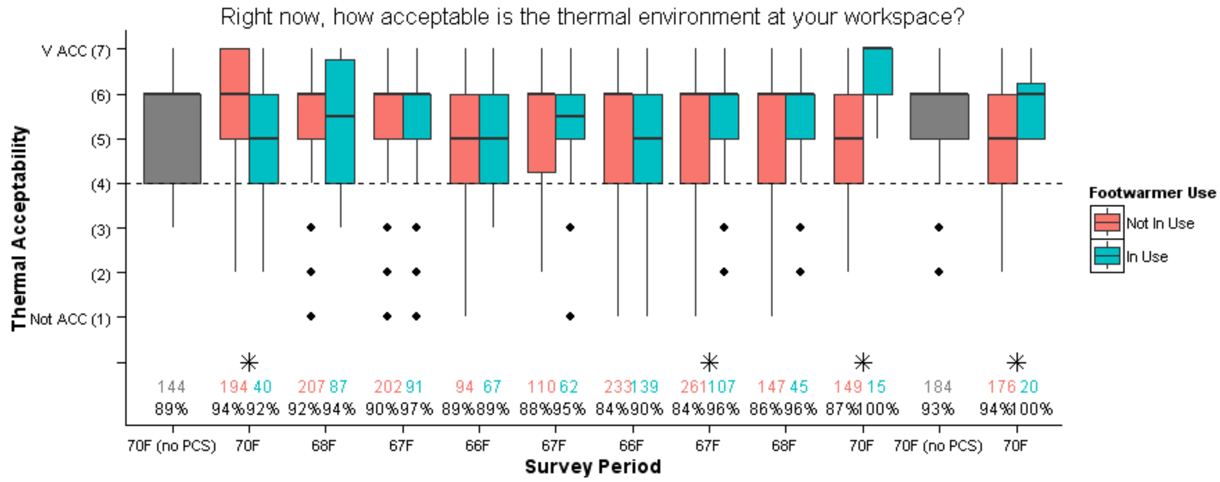


Figure 5.1-9 Footwarmer Users vs Non-Users: Thermal Acceptability

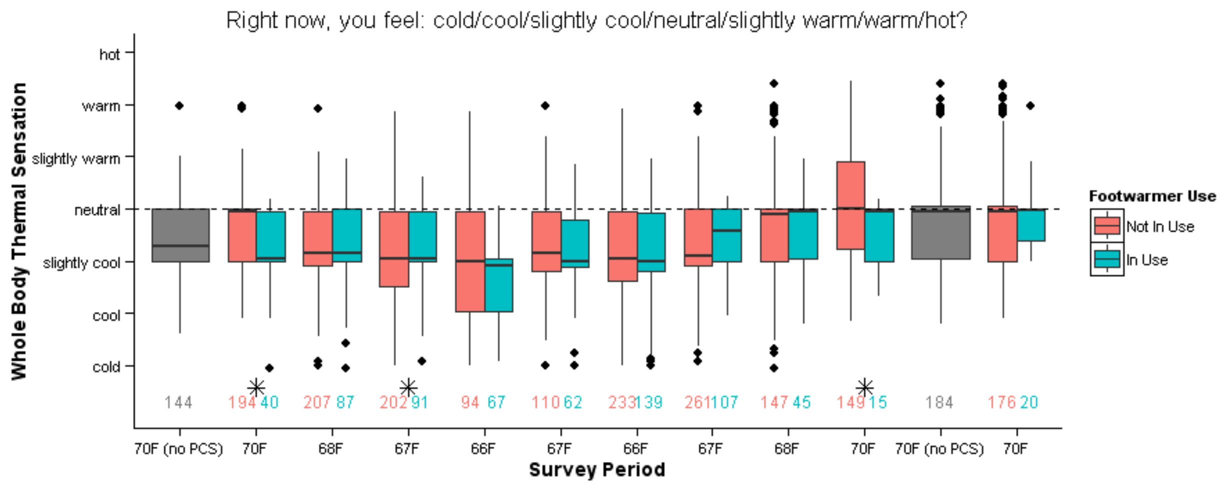


Figure 5.1-10 Footwarmer Users vs Non-Users: Whole Body Thermal Sensation

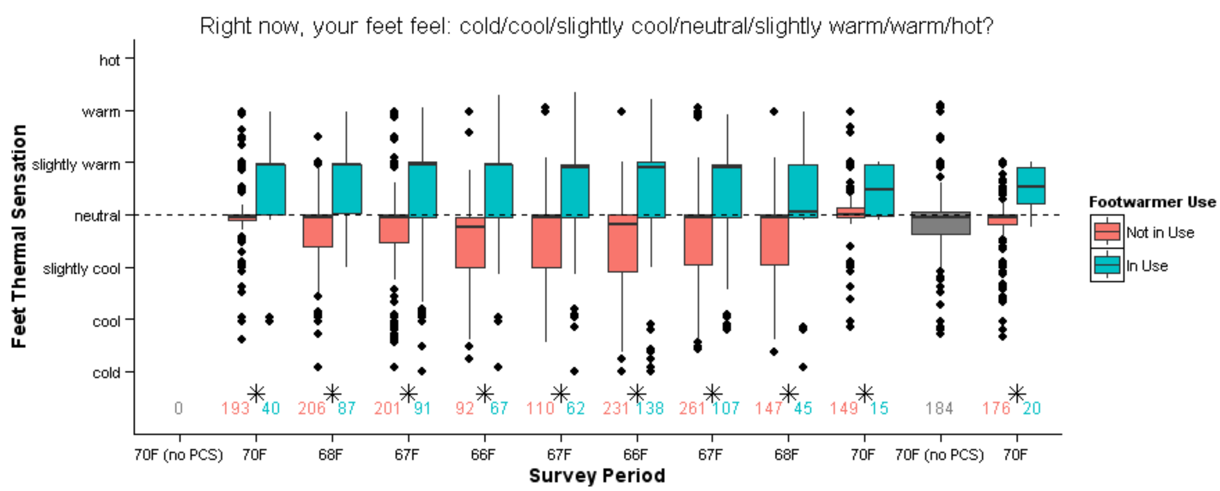


Figure 5.1-11 Footwarmer Users vs Non-Users: Feet Thermal Sensation

5.1.6 Comparison of Perimeter Workstations against Core Workstations

This section compares results between people who sit near the façade, the "Perimeter Group," and those who sit further from the façade, the "Core Group." Figure 4.3-2 shows a floor plan of the office and the location of all of the workstations, half of which are on the perimeter and half of which are not. This floor plan also shows that almost all of the windows in the office are facing north and photographs of the façade is shown in Figure 4.3-1.

Figure 5.1-12 shows that there was statistically significant difference between the Perimeter Group and the Core Group for thermal acceptability responses in half of the survey periods, mostly at lowered setpoints. There is not a clear pattern as to whether the Perimeter Group had higher or lower levels of thermal acceptability though there was often a larger range of thermal acceptability responses in the Perimeter Group. While Figure 5.1-13 shows that a third of the survey periods show a statistically significant difference between the groups for whole body thermal sensation, the means for each of the groups in these survey periods are often similar and the boxplots are not substantially different. Overall, there does not appear to be noticeable trends in the thermal acceptability and whole body thermal sensation between people who sit near the façade and those who do not.

Key to graphs in this section:

- Perimeter Group (red) = Results from those people sitting closest to the façade (Workstations 1, 2, 3, 5, 7, 9, 17, 20)
- Core Group (blue) = Results from those people sitting furthest from the façade (Workstations 6, 8, 11, 12, 13, 14, 15, and 24)
- ✳ = statistically significant difference
    - For the Thermal Acceptability and Whole Body Thermal Sensation graphs: This symbol occurs for each survey period in which the votes of the "Perimeter Group" are significantly different from those of the "Core Group" for that same survey period.
- values in red and blue above the x axis = n (number of votes of the red group and the blue group for that particular survey period)
- values above the x axis with "%" signs = percentage acceptable (Thermal Acceptability only)
    - Percent acceptable (for Thermal Acceptability only) = (sum of "4," "5," "6," and "7" votes in the survey period) / (total number of votes in the survey period)
    - For each survey period, two percent acceptable values are given. The left percent acceptable value represents the result for the red group and the right percent acceptable value represents the result for the blue group.

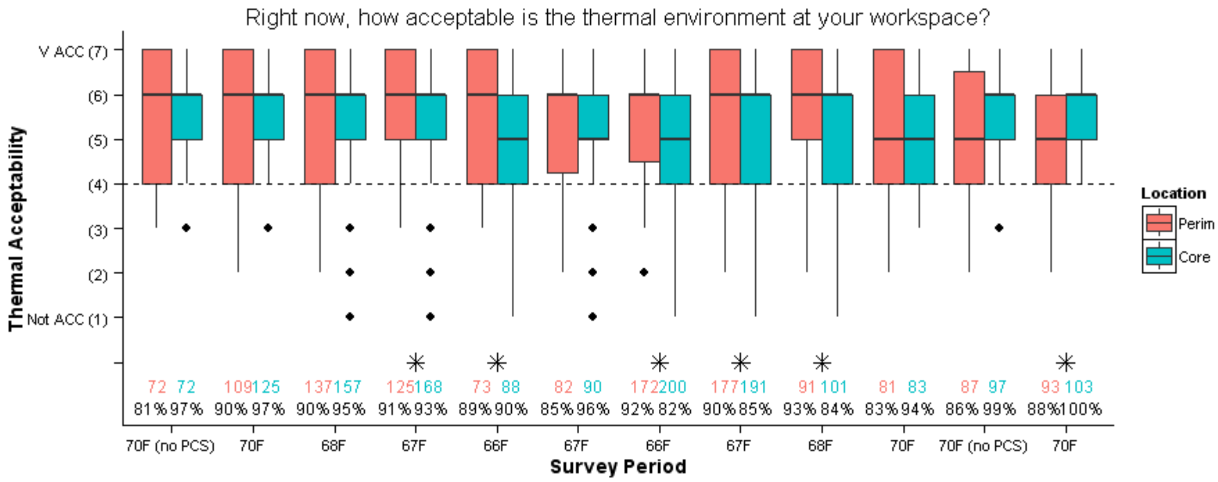


Figure 5.1-12 Perimeter vs Core Workstation Votes: Thermal Acceptability

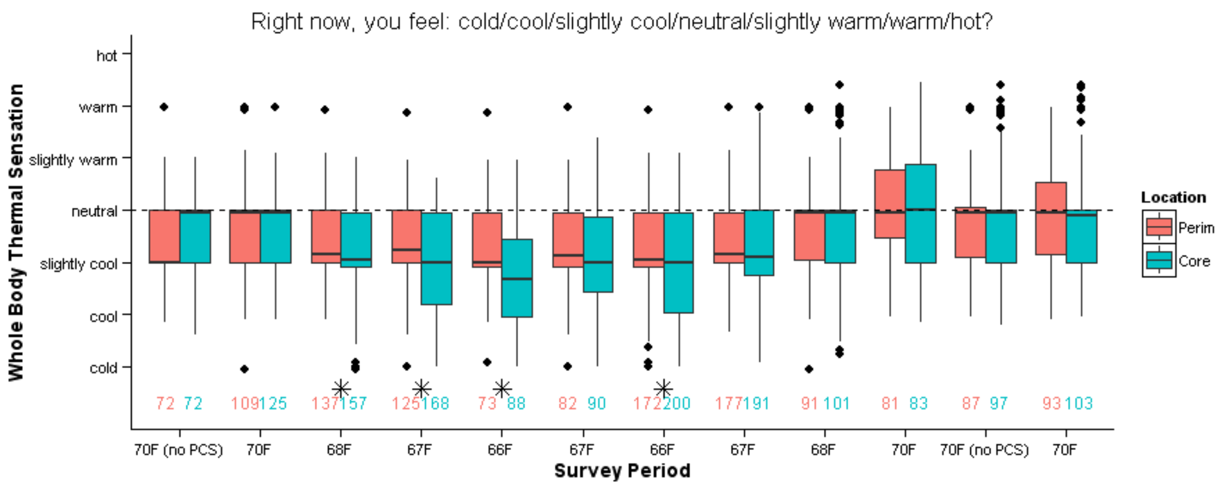


Figure 5.1-13 Perimeter vs Core Workstation Votes: Whole Body Thermal Sensation

5.1.7 Comparison of Morning Votes against Afternoon Votes

This section compares the thermal acceptability and whole body thermal sensation between the votes that were submitted before 12:00 pm, presented as the “Morning Group,” and those that were submitted after 12:00 pm, presented as the “Afternoon Group.”

Figure 5.1-14 shows that there were only 2 survey periods with statistically different results for thermal acceptability between the Morning Group and the Afternoon Group. There were no survey periods with statistically different results for whole body thermal sensation shown in Figure 5.1-15. For the two survey periods with statistical difference in thermal acceptability, the morning votes are slightly higher but there is not enough overall difference between the groups in Figure 5.1-14 and Figure 5.1-15 to conclude any particular trend. These graphs show that the results in any given survey were not dependent on the time of day in which they were submitted and that there was a roughly similar number of votes cast in the morning as in the afternoon during the study.

Key to graphs in this section:

- Afternoon Group (red) = Results from surveys submitted after 12:00 pm
- Morning Group (blue) = Results from surveys submitted before 12:00 pm
- ✳ = statistically significant difference
    - o For the Thermal Acceptability and Whole Body Thermal Sensation graphs: This symbol occurs for each survey period in which the votes of the "Afternoon Group" are significantly different from those of the "Morning Group" for that same survey period.
- values in red and blue above the x axis = n (number of votes of the red group and the blue group for that particular survey period)
- values above the x axis with "%" signs = percentage acceptable (Thermal Acceptability only)
    - o Percent acceptable (for Thermal Acceptability only) = (sum of "4," "5," "6," and "7" votes in the survey period) / (total number of votes in the survey period)
    - o For each survey period, two percent acceptable values are given. The left percent acceptable value represents the result for the red group and the right percent acceptable value represents the result for the blue group.

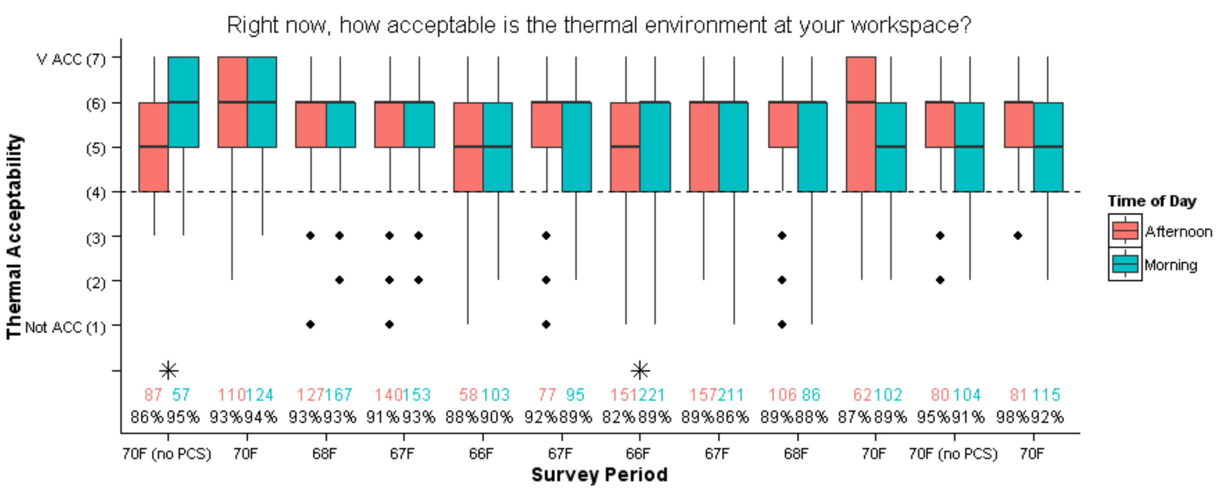


Figure 5.1-14 Morning vs Afternoon Votes: Thermal Acceptability

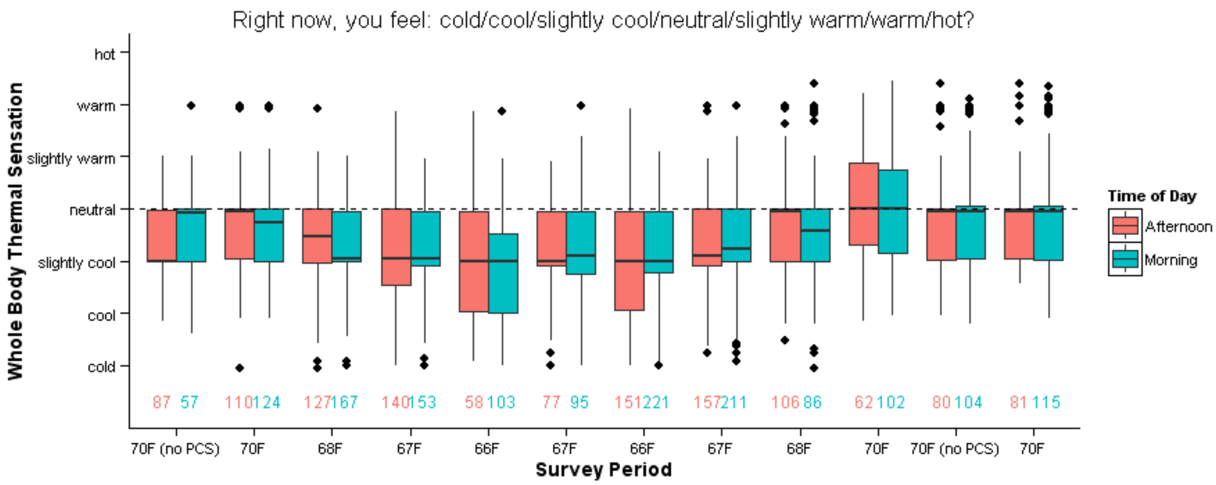


Figure 5.1-15 Morning vs Afternoon Votes: Whole Body Thermal Sensation

5.1.8 Comparison of Male Occupants against Female Occupants

This section compares the thermal acceptability and whole body thermal sensation between males and females. The gender and workstation number is given in Table 4.3-2, which shows that there are an equal number of males and females in the office. The group of people who rarely or never used the footwarmers is roughly evenly split between the genders.

Figure 5.1-16 shows that there is a statistical difference between males and females with regards to thermal acceptability at every setpoint. Males consistently had larger ranges of thermal acceptability and the female votes were always in a smaller range more concentrated towards the "very acceptable" side of the acceptability spectrum. Figure 5.1-17 shows that males were slightly cooler than females as far as whole body thermal sensation and that this difference was statistically significant about half of the time. In both Figure 5.1-16 and Figure 5.1-17, these patterns are always observed in the basecase condition of having the setpoint at 70F without the footwarmer. While the difference in responses between the genders is more pronounced than the differences in some of the other paired groupings presented in this analysis, the difference in opinion regarding thermal comfort between people of genders in this office appears to be a pre-existing condition not changed in any noticeable way by this study.

Key to graphs in this section:

- Males (red) = Results from workstations 3, 6, 11, 13, 15, 17, 20, and 24.
- Females (blue) = Results from workstations 1, 2, 5, 7, 8, 9, 12, and 14
- ✳ = statistically significant difference
    - o For the Thermal Acceptability and Whole Body Thermal Sensation graphs: This symbol occurs for each survey period in which the votes of

the males are significantly different from those of the females for that same survey period.

- values in red and blue above the x axis = n (number of votes of the red group and the blue group for that particular survey period)
- values above the x axis with "%" signs = percentage acceptable (Thermal Acceptability only)
  - o Percent acceptable (for Thermal Acceptability only) = (sum of "4," "5," "6," and "7" votes in the survey period) / (total number of votes in the survey period)
  - o For each survey period, two percent acceptable values are given. The left percent acceptable value represents the result for the red group and the right percent acceptable value represents the result for the blue group.

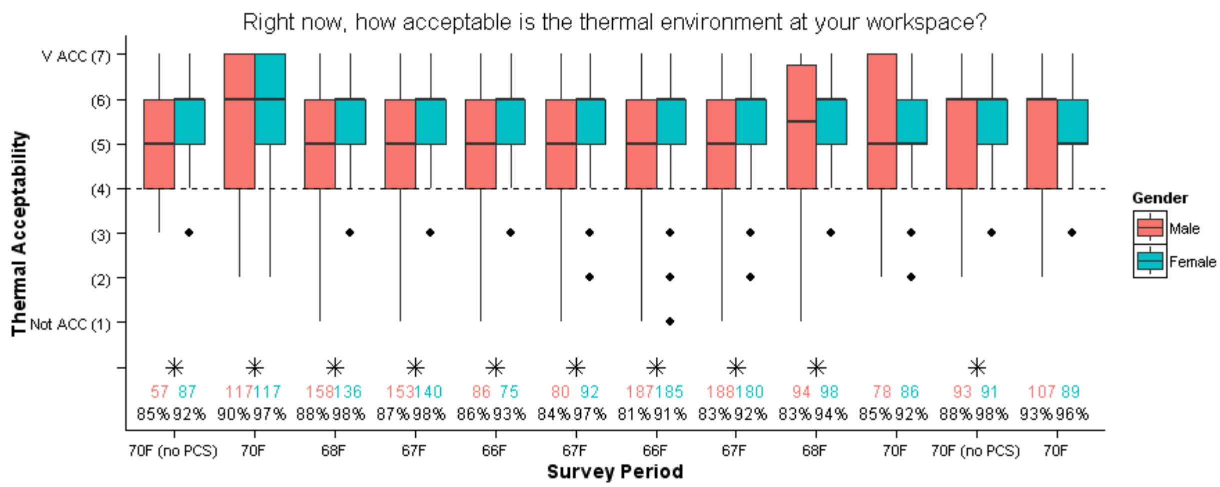


Figure 5.1-16 Male vs Female Votes: Thermal Acceptability

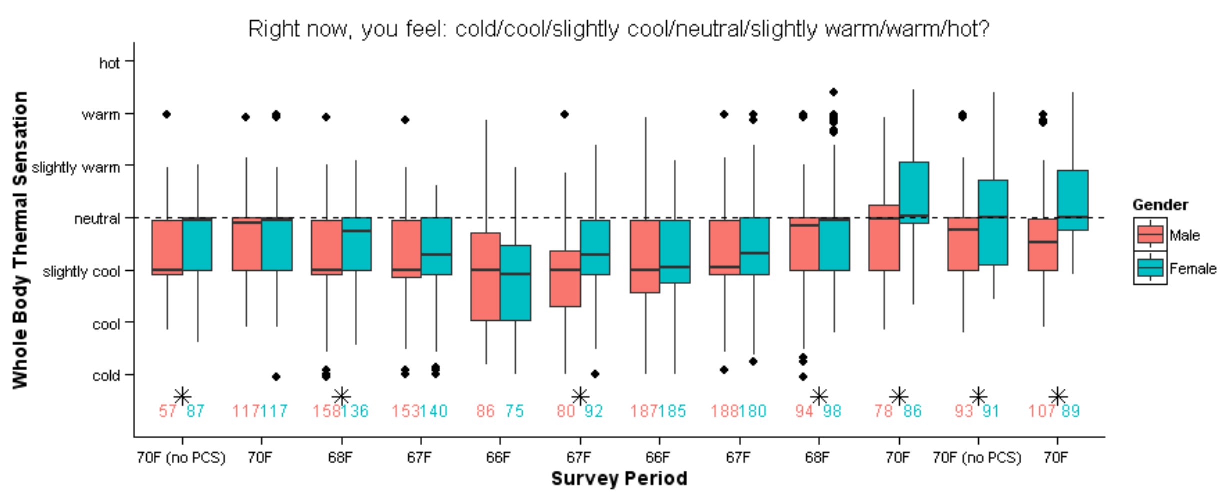


Figure 5.1-17 Male vs Female Votes: Whole Body Thermal Sensation

5.1.9 Summary of Thermal Response Votes from the Right Now Survey

The 2774 Right Now Survey responses were extensively analyzed by looking at overall trends in thermal acceptability and thermal sensation, as well as comparisons between groups of people within the study, including footwarmer users versus non-users, perimeter workstations versus core workstations, morning votes versus afternoon votes, and male votes versus female votes. While these analyses focused on the results between each of the survery period, the results also were analyzed by each day of the survey period to consider adaptation and also by distinct outdoor temperature ranges to consider the impact of weather. While the graphs for all of these are either in the previous section or in the appendices, the percent acceptable figures and statistical significance results for thermal acceptability and whole body thermal sensation are summarized below in Table 5.1-5, Table 5.1-6, and Table 5.1-7. The main findings from this analysis are:

- There was no significant difference in thermal acceptability between the existing conditions and when occupants were given the footwarmer and exposed to lower setpoints.

- While whole body thermal sensation votes shift from neutral to slightly cool at lower setpoints, this is not perceived as a change large enough to impact overall thermal acceptability.

- According to self-reported footwarmer use at the time of the submitting the survey, footwarmer use increased as the setpoint lowered.

- There is minimal evidence of thermal adaptation on the daily level though the setpoint was lowered very gradually over time

- The small number of people who are not satisfied with their thermal environment typically have a slightly cool whole body thermal sensation, though they had a slightly warm whole body thermal sensation at the end of the study.

- Thermal acceptability was slightly higher for those using the footwarmer, but there is not a large statistically significant difference in these results and that there were always more non-users than users when the surveys were submitted.

- The location on of the workstation and the time of day do not have a substantial impact on thermal acceptability and whole body thermal sensation votes.

- While males consistently found the thermal environment less acceptable and more cool than females, the study did not drive these gender differences as they also occurred during the existing setpoint during periods of time when people did not have the footwarmer.

In short, the Right Now Survey results show that people's perception of their thermal comfort stays at a similar level throughout the winter as setpoints are gradually lowered from 70F to 66F and people are given access to footwarmers, and then as setpoints are gradually raised back to 70Fr. Given that ASHRAE Standard 55 requires that only a minimum of 80% of people be satisfied with thermal comfort, people in this field study general have a high overall percentage of thermal acceptability with and without the footwarmer as well as at the existing setpoint and lower setpoints. While there was not widespread use of the footwarmer, it was available to occupants and those who used it had slightly better, though often not statistically different, votes for thermal acceptability and thermal sensation.

Key to tables in this section:

- Table 5.1-5 Summary of Thermal Acceptability Percentages
    - Rows = Percentage acceptable for each survey period for the category specified in the first cell of each row.
        - Percent acceptable = (sum of "4," "5," "6," and "7" votes for that category in that survey period) / (total number of votes for that category in that survey period)
    - Cell shading:
        - Dark green = when the percent acceptable value is 7% or more higher than that of the first survey period in that row (representing the equivalent of one person changing his or her vote from unacceptable to acceptable)
        - Dark red = when the percent acceptable value is 7% or more lower than that of the first survey period in that row (representing the equivalent of one person changing his or her vote from unacceptable to acceptable)
        - Dark grey = when that category is not applicable for a particular survey period

- Table 5.1-6 Summary of Thermal Acceptability Statistical Significance and Table 5.1-7 Summary of Whole Body Thermal Sensation Statistical Significance
    - Rows = Statistically significant difference for each survey period for the category specified in the first cell of each row. Table 5.1-6 is for thermal acceptability and Table 5.1-7 is for whole body thermal sensation.

- For the Overall Votes row: If there is a "✳" in the cell, then there is a statistically significant difference between the votes for that category in that survey period and the votes in that category from Survey Period 1.
    - Light green = when the results for that survey period are statistically significant and the mean of the results for that survey period has a higher thermal acceptability than the results for Survey Period 1.
    - Light red = when the results for that day are statistically significant and the mean of the results for that day is farther from neutral than the mean of the results for the first day of that particular survey period
- For all other rows: If there is a "✳" in the cell, then there is a statistically significant difference between the votes of the two groups in that survey period for the groups specified in the first cell of the row. For thermal acceptability (Table 5.1-6), the "✳" is placed in the cell at the height corresponding to that of the group specified in the first row of the cell that has the higher thermal acceptability for that survey period. For whole body thermal sensation (Table 5.1-7), the "✳" is placed in the cell at the height corresponding to that of the group specified in the first row of the cell that has a whole body thermal sensation closer to neutral.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Setpoint	70F (no PCS)	70F	68F	67F	66F	67F	66F	67F	68F	70F	70F (no PCS)	70F
Overall Votes	89%	94%	93%	92%	89%	91%	86%	87%	89%	88%	93%	94%
Satisfied	100%	100%	100%	100 %	100 %	100 %	100 %	100 %	100 %	100%	100%	100%
Dissatisfied	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Footwarmer In Use		92%	94%	97%	89%	95%	90%	96%	96%	100 %	NA	100 %
Footwarmer Not In Use		94%	92%	90%	89%	88%	84%	84%	86%	87%	NA	94%
Perimeter Workstations	81%	90%	90%	91%	89%	85%	92%	90%	93%	83%	86%	88%
Core Workstations	97%	97%	95%	93%	90%	96%	82%	85%	84%	94%	99%	100 %
Morning	95%	94%	93%	93%	90%	89%	89%	86%	88%	89%	91%	92%
Afternoon	86%	93%	93%	91%	88%	92%	82%	89%	89%	87%	95%	98%
Males	85%	90%	88%	87%	86%	84%	81%	83%	83%	85%	88%	93%
Females	92%	97%	98%	98%	93%	97%	91%	92%	94%	92%	98%	96%

Table 5.1-5 Summary of Thermal Acceptability Percentages

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Setpoint	70F (no PCS)	70F	68F	67F	66F	67F	66F	67F	68F	70F	70F (no PCS)	70F
Overall Votes												
Satisfaction (Dissatisfied vs Satisfied)	*	*	*	*	*	*	*	*	*	*	*	*
Ftwrmr Use (Not In Use vs In Use)		*						*		*		*
Location (Perimeter vs Core)				*	*		*	*	*			*
Time of Day (Afternoon vs Morning)	*						*					
Gender (Male vs Female)	*	*	*	*	*	*	*	*	*		*	

Table 5.1-6 Summary of Thermal Acceptability Statistical Significance

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Setpoint	70F (no PCS)	70F	68F	67F	66F	67F	66F	67F	68F	70F	70F (no PCS)	70F
Overall Votes		*		*	*	*	*			*	*	*
Satisfaction (Dissatisfied vs Satisfied)				*	*	*	*	*	*		*	*
Ftwrmr Use (Not In Use vs In Use)		*		*						*		
Location (Perimeter vs Core)			*	*	*		*					
Time of Day (Afternoon vs Morning)												
Gender (Male vs Female)	*		*			*			*	*	*	*

Table 5.1-7 Summary of Whole Body Thermal Sensation Statistical Significance

5.2 Individual Workstation Analysis: Right Now Survey and Footwarmer Power

To analyze each individual workstation, this section considers each occupant's Right Now Survey responses relative to everyone else in the office and their average power use by survey period. These results are presented in conjunction with comments made during the exit interviews, which are more thoroughly analyzed in 5.3 Insights from Exit Interviews.

The results of Workstation 14 are shown here to provide an example of the comfort and average workstation power of someone who typically used the footwarmer. While this workstation is analyzed in detail in this section, the graphs of the Right Now Survey results for the other workstations are found in Appendix E: Individual Workstation Results. The results of all of the individual analyses are summarized in this section by providing a summary by survey period of each workstation's percent acceptable, average power use, and statistically significant differences of thermal acceptability and whole body thermal sensation votes compared to their responses in the first survey period. These summaries are in Table 5.2-1 and Table 5.2-2.

Figure 5.2-1 shows that Workstation 14's thermal acceptability was consistently higher than that of the combined result of everyone else in the office. While Workstation 14's thermal acceptability votes were 100% in every survey period, the boxplot show that her thermal acceptability was improved when given a footwarmer in the existing setpoint of 70F (Survey Period 2), then decreased slightly as the setpoint lowered down to 66F (Survey Periods 3-5), then improved slightly as the setpoint was raised to 67F (Survey Period 6), and then stayed practically the same for the rest of the field study as the temperature was raised gradually back to 70F (Survey Periods 7 – 12). Overall, this graph shows that changing the setpoint had minimal impact on Workstation 14's thermal acceptability. While Workstation 14's thermal acceptability was initially slightly lower at lower temperatures, it remained constant during the second half of the study showing that the lower setpoint temperatures eventually had the same level of thermal acceptability as the existing conditions.

For most of the survey periods in the first half of the field study, Workstation 14's whole body thermal sensation was statistically significant and warmer compared to the votes of everyone else in the office as shown in Figure 5.2-2. Workstation 14's whole body thermal sensation was typically closer to neutral compared to the votes of everyone else in the office, which were typically closer to a slightly cool thermal sensation. This shows that even though the whole body thermal sensation was not neutral, Workstation 14 still considered the workspace environment to have a high level of thermal acceptability.

As temperatures dropped, Workstation 14 used the footwarmer more and more. Figure 5.2-3 shows Workstation 14's footwarmer power usage was 125W on average when the device was on, which was higher than the monitor and computer average power which were each close to 75W. In the exit interview, Workstation 14 said that the footwarmer was usually used at full blast, which is why the average footwarmer power is 125W for all survey periods when the device was on. However, while the device was used at full blast when it was on, it was not used consistently throughout the day.

Figure 5.2-4 averages the computer, monitor, and footwarmer power as averaged during occupied hours and shows that the footwarmer was definitely not used consistently throughout the day. Figure 5.2-4 shows the footwarmer never exceeded 30W on average per survey period when the average power is calculated for the occupied hours, not for only when the device is turned on. While the footwarmer use increased as the setpoint temperature decreased, the average power was relatively low (29.1W) in the survey period in which it was used most because it was only used as needed as opposed to being on constantly.

Key to graphs in this section:

- The "*" marks represent a statistically significant difference at a 95% confidence level between the particular workstation (red boxplots) and all other workstations in the office (blue boxplots) for each survey period.
- The red numbers are the n values of the boxplots for the particular workstation and the blue numbers are the n values of the boxplots for all other workstations.
- In each thermal acceptability graph, the percentages are votes that are acceptable (responses of "4," "5," "6," and "7") relative to the total number of votes for each boxplot ("1," "2," "3," "4," "5," "6," and "7").

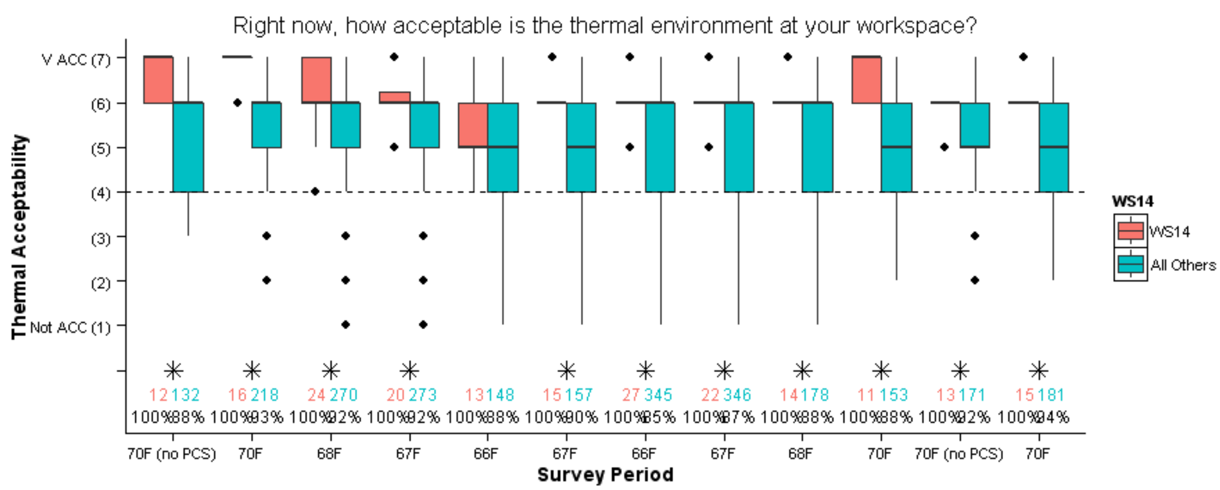


Figure 5.2-1 Workstation 14 Thermal Acceptability

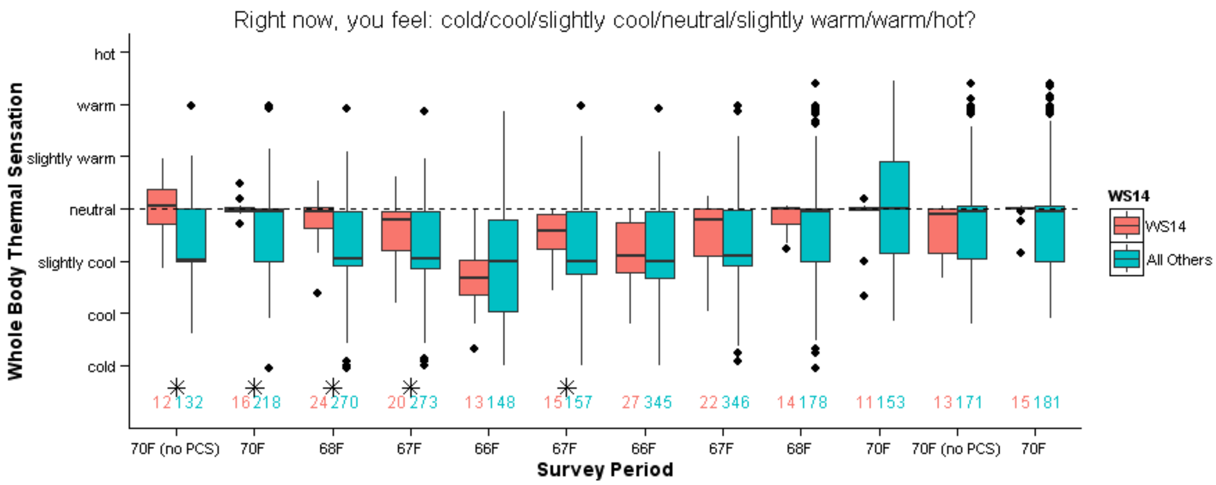


Figure 5.2-2 Workstation 14 Whole Body Thermal Sensation

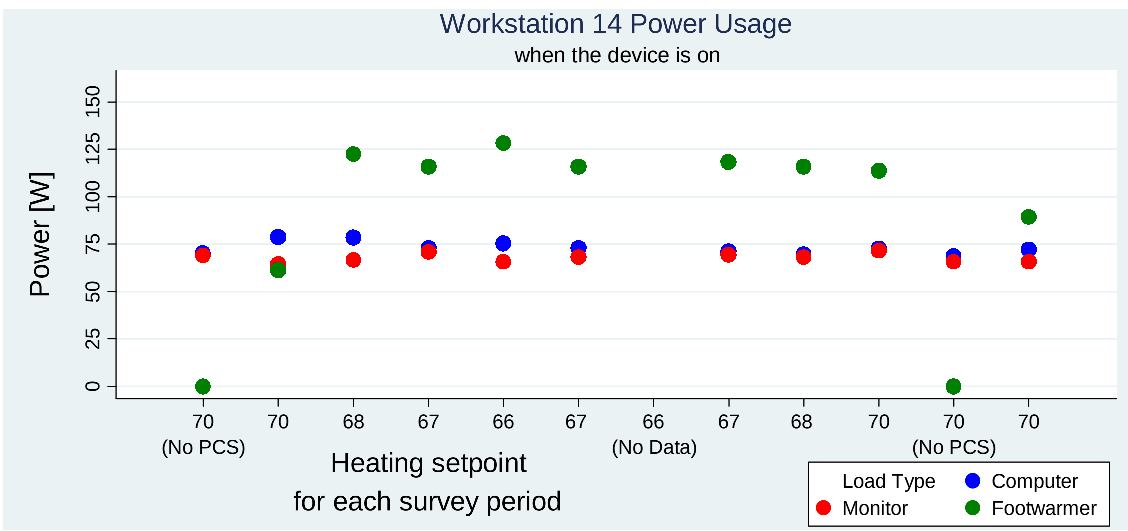


Figure 5.2-3 Workstation 14 Average Power (Footwarmer On)

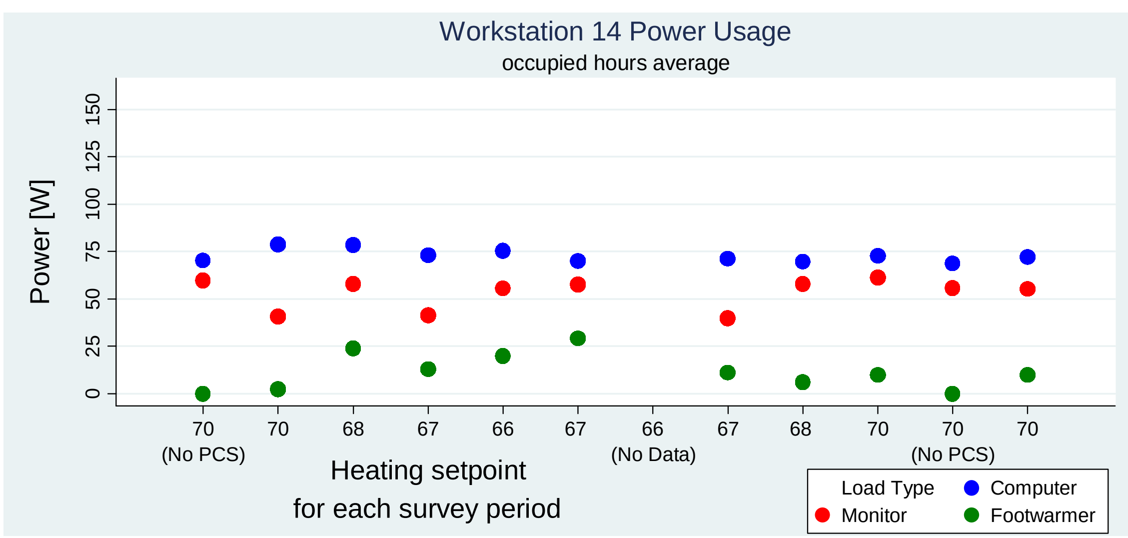


Figure 5.2-4 Workstation 14 Average Workstation Power

In Table 5.2-1, which summarizes the thermal acceptability and workstation power, 35.7% of occupants (6 people) had percent acceptable values that increased by at least 7% compared to the existing conditions (70F, no footwarmer) as shown by the dark green shading. Of the 31% (5 people) whose thermal acceptability dropped by at least 7% regularly compared to the existing conditions, only 12% (2 people) consistently had a percent acceptable figure of less than 70%. These workstations, Workstation 3 and Workstation 13, were people who did not use the footwarmer because they did not like the ergonomics. While both of those people explained this in their exit interviews, Table 5.2-1 shows that their average footwarmer power is often greater than 0W. It is important to keep in mind that the average footwarmer power reported in this table is overestimated as described in 0 rent setpoints.

Footwarmer Power, which explains that the footwarmer power is the total workstation power minus the computer and monitor power. If workstations had additional devices plugged in at their workstation in addition to the computer, monitor, and footwarmer, these loads are reflected in the average footwarmer power values.

Table 5.2-2 shows that the thermal acceptability of Workstation 12 dropped later in the study as did the average footwarmer power readings. In the exit interview, Workstation 12 mentioned that the footwarmer was used in the beginning of the study but then not used the later parts of the study because the ergonomics were bothersome. This table shows that the people least satisfied with thermal acceptability are those which did not use the footwarmer for ergonomic reasons, suggesting that thermal acceptability could be even higher if the ergonomics of the device were improved such that more people used the device to provided their desire for more heating. Table 5.2-2 shows that Workstation 12 and 13 consistently had a whole body thermal sensation slightly cooler than the rest of the office. Table 5.2-2 also shows just how different people's thermal sensations are when exposed to the same conditions. For example, the whole body thermal sensation was statistically significantly higher for Workstation 17 three times at the coldest setpoint temperatures than that of the rest of the office. In the exit interview, Workstation 17 said the footwarmer was not used because there was rarely a cold thermal sensation. This shows that people have much different thresholds for thermal sensation as some people using footwarmers still felt cool at the same setpoint. Such findings confirm that personal control is a valuable asset for helping account for such drastic differences in thermal preference.

Key to tables in this section:

- Table 5.2-1 Individual Workstation Summary: Percent Acceptability, Thermal Acceptability Statistical Significance, and Average Workstation Power (W)

- Top spacing in rows = Percentage acceptable for each survey period for the workstation specified in the first cell of each row.
    - Percent acceptable = (sum of “4,” “5,” “6,” and “7” votes for that category in that survey period) / (total number of votes for that category in that survey period)
- Middle spacing in rows = Statistically significant difference for each survey period for the workstation specified in the first cell of each row.
    - If there is a “✳”, then there is a statistically significant difference between the thermal acceptability votes for that workstation in that survey period compared to the votes of everyone else in the office for that same survey period.
- Bottom spacing in rows = Average footwarmer power (W) for the workstation specified in the first cell of each row.
- Cell shading:
    - Dark green = when the percent acceptable value is 7% or more higher than that of the first survey period in that row (representing the equivalent of one person changing his or her vote from unacceptable to acceptable)
    - Dark red = when the percent acceptable value is 7% or more lower than that of the first survey period in that row (representing the equivalent of one person changing his or her vote from unacceptable to acceptable)
    - Dark grey = when that category is not applicable for a particular survey period

- Table 5.2-2 Individual Workstation Whole Body Thermal Sensation Statistical Significance
    - Rows = Statistically significant difference for each survey period for the category specified in the first cell of each row.
        - If there is a “✳”, then there is a statistically significant difference between the whole body thermal sensation votes for that workstation in that survey period compared to the votes of everyone else in the office for that same survey period.
    - Cell Shading
        - Light green = when there is a “✳” and the mean of the results for that workstation is closer to neutral than the mean of the results of everyone else in the office for the same survey period
        - Light red = when there is a “✳” and the mean of the results for that workstation is further from neutral than the mean of the results of everyone else in the office for the same survey period

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Setpoint	70F (no PCS)	70F	68F	67F	66F	67F	66F	67F	68F	70F	70F (no PCS)	70F
WS 1 TA	82%	100% *	100% *	100% *	100% *	100% *	100% *	100% *	100% *	NA	NA	NA
Ftwmr (W)	0.0	4.4	6.5	12.6	20.3	16.7	NA	5.5	3.7	NA	NA	NA
WS 2 TA	71% *	100%	100% *	100% *	100% *	100% *	100% *	100% *	100% *	100%	93%	82% *
Ftwmr (W)	0.0	0.6	0.7	5.1	4.1	9.6	NA	0.0	1.6	0.0	0.0	0.0
WS 3 TA	NA	67% *	75% *	70% *	88% *	83% *	95% *	90% *	89% *	70% *	60% *	86% *
Ftwmr (W)	NA	0.7	NA	21.2	14.4	10.3	NA	3.7	0.1	0.0	0.0	0.4
WS 5 TA	100% *	100% *	100% *	100% *	100% *	100% *	100% *	100% *	100% *	93% *	100% *	100 *
Ftwmr (W)	0.0	1.1	3.7	3.5	14.8	0.0	NA	2.2	0.0	0.0	0.0	0.0
WS 6 TA	86% *	90% *	100% *	100% *	100% *	100% *	89% *	100% *	100% *	93% *	100% *	100 *
Ftwmr (W)	0.0	25.3	27.1	39.1	27.9	32.3	NA	27.8	9.7	9.0	0.0	0.3
WS 7 TA	62% *	85%	90%	100%	64% *	100%	100% *	96%	100%	100% *	100%	100
Ftwmr (W)	0.0	0.0	0.0	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0	0.0
WS 8 TA	100% *	100% *	100% *	100%	92%	100% *	100% *	100% *	92%	80% *	93% *	100 *
Ftwmr (W)	0.0	0.0	0.3	0.0	0.0	0.0	NA	0.3	0.0	0.0	0.0	0.0
WS 9 TA	100% *	93% *	94% *	88% *	100%	89% *	100% *	92% *	100% *	70% *	100% *	86% *
Ftwmr (W)	0.0	0.4	2.1	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0	0.0
WS 11 TA	100% %	100%	100%	100%	92%	100% *	100% *	100% *	100% *	100% *	100% *	100 % *
Ftwmr (W)	0.0	8.6	28.2	33.6	40.6	26.2	NA	17.8	11.6	0.0	0.0	0,0
WS 12 TA	100% *	100% *	100% *	95% *	100%	80% *	30% *	43% *	55% *	100%	100% *	100 *
Ftwmr (W)	0.0	1.6	2.1	0.6	0.0	0.3	NA	0.2	0.0	0.0	0.0	0,.0
WS 13 TA	NA	67% *	63% *	39% *	25% *	80% *	23% *	27% *	0% *	89%	100%	100
Ftwmr (W)	NA	0.0	2.2	3.1	0.1	9.0	NA	3.9	3.5	0.5	0.0	0.0
WS 14 TA	100% *	100% *	100% *	100% *	100%	100% *	100% *	100% *	100% *	100% *	100% *	100 % *
Ftwmr (W)	0.0	2.2	23.7	12.9	19.8	29.1	NA	10.8	6.0	9.8	0.0	9.7
WS 15 TA	100%	100%	96%	100%	92%	100% *	96%	100% *	100% *	NA	100% *	100 *
Ftwmr (W)	0.0	NA	NA	5.9	5.8	1.1	NA	NA	NA	NA	NA	NA
WS 17 TA	100% *	100% *	100% *	100% *	100% *	100% *	100% *	100% *	100% *	100% *	100% *	100 *
Ftwmr (W)	0.0	0.6	0.2	0.0	0.9	0.4	NA	2.4	3.8	9.4	0.0	0.1
WS 20 TA	33% *	60% *	50% *	40% *	62% *	17% *	41% *	35% *	50% *	22% *	42% *	62% *
Ftwmr (W)	0.0	1.2	7.2	2.2	21.2	21.1	NA	0.2	0.2	0.0	0.0	0.0
WS 24 TA	NA	100% *	100% *	100% *	100% *	100%	100% *	100% *	100% *	100% *	100% *	100 *
Ftwmr (W)	NA	15.5	36.0	0.0	68.0	58.7	NA	30.0	7.1	0.0	0.0	0.0

Table 5.2-1 Individual Workstation Summary: Percent Acceptability, Thermal Acceptability Statistical Significance, and Average Workstation Power (W)

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Setpoint	70F (no PCS)	70F	68F	67F	66F	67F	66F	67F	68F	70F	70F (no PCS)	70F
WS 1 WBTS						*	*	*	*			
WS 2 WBTS	*			*	*			*		*	*	*
WS 3 WBTS	NA						*			*		*
WS 5 WBTS			*			*						
WS 6 WBTS		*	*	*	*			*	*			
WS 7 WBTS			*			*	*			*	*	
WS 8 WBTS	*	*	*	*	*	*	*	*	*	*	*	*
WS 9 WBTS			*					*	*		*	*
WS 11 WBTS					*	*	*		*	*	*	*
WS 12 WBTS	*		*	*			*	*	*			
WS 13 WBTS	NA			*	*	*	*	*	*	*	*	*
WS 14 WBTS	*	*	*	*		*						
WS 15 WBTS		*	*	*			*	*	*			*
WS 17 WBTS					*	*	*					*
WS 20 WBTS						*						
WS 24 WBTS	NA			*			*					

Table 5.2-2 Individual Workstation Whole Body Thermal Sensation Statistical Significance

5.3 Insights from Exit Interviews

One to two weeks after the Right Now Survey, plug load monitoring, and heating energy monitoring data collection ended, each participant had a fifteen minute exit interview that was aimed to gain general feedback about their use and opinion of the PCS devices. The summary of the insights gained from the exit interview focus on the footwarmer though complete summaries of all of exit interviews are provided in Appendix E: Individual Workstation Results. The list of questions asked during the exit interviews are provided in Appendix B: Exit Survey Interview Script

Those people who said that they frequently or sometimes used the footwarmer reflected the values recorded for average footwarmer power at the corresponding workstations shown in Table 5.2-1. The only discrepancy is that Workstation 7 said she used the footwarmer in the exit interview but her footwarmer power readings are consistently 0 W in Table 5.2-1, which suggests that there was something wrong in that workstation's plug load monitoring data. The exit interviews otherwise confirm that frequent footwarmer users were workstations 1, 6, 11, 14, 15, and 24. Occasional footwarmer users were workstations 5, 7, and 20. Footwarmer non-users were workstations 2, 3, 8, 9, 12, 13, and 17. This totals six people (38%) who used the footwarmer frequently, three people (19%) who used it occasionally, and seven people (44%) who rarely or never used it. Of the people who used the footwarmer frequently or sometimes, about half said there were a few times when their feet were warm but other parts of their body were still cool and times when they occasionally wished the footwarmer could provide more, which reinforces the results shown in Figure 5.1-5. However, both the exit interviews and Figure 5.1-5 suggest that this was a rare occurrence and not a consistent problem.

All of the seven people (43%) who never used the footwarmer were asked the main reason why they never used the device. Three people (43%) said they found its ergonomics problematic, three people (43%) said that they were never cold, and one person (14%) said that she has extremely sensitive skin and was worried that the footwarmer would irritate her skin. The main reasons why people did not use the footwarmer were therefore because they were not cold or they didn't like the footwarmer ergonomics. While three of the footwarmer non-users (43% of non-users) did not like the ergonomics of the footwarmer, three of the footwarmer users (33% of users) also thought that the ergonomics of the footwarmer also needed improvement. This totals seven people (44%) in the office who thought that the footwarmer could have better ergonomic design. The main ergonomic complaints from these people were that using the footwarmer meant that they had to sit more upright, which may be better posture but not their preferred position, and that the upper lip of the footwarmer was bothersome because it hit their shins.

When asked how the functionality of the footwarmer could be improved, recommendations included that it would be useful for the footwarmer to be on wheels so it could be moved easily, for the reflector to be better secured as it sometimes slipped out, and for the device to be activated from a sensor when feet are placed inside the device as opposed to gently pressing feet downwards on the pressure plate in the current design.

There was nearly consensus in the interviews regarding the footwarmer aesthetics and clothing levels. People consistently said that they didn't have any recommendations for the aesthetics of the footwarmer, often saying that the equipment is hidden under the desk so its aesthetic design is not important. Also, people said that they did not change their clothing or shoes throughout the study. While clothing level is one of the variables that is measured for calculating thermal comfort, which was not part of the scope of this thesis, it is valuable to know that the participants generally say that their clothing level was a constant throughout the study and therefore is unlikely an unmeasured confounding variable.

5.4 Energy Results

The energy results begin with an analysis of average computer power, monitor power, and footwarmer power to examine how footwarmer usage changed throughout the study by looking both at the average workstation power results for each day as well for each survey period. There was an error in the workstation power data collection during Survey Period 7 so no computer, monitor, or footwarmer loads were recorded during that time.

The analysis continues by looking closely at the recorded indoor air temperature by sMAP to confirm whether or not the zone temperature matched the specified setpoint temperature during each Survey Period. This includes an assessment of whether or not there were differences in temperature between perimeter and core locations in the office as well as whether or not the outside weather impacted the ability of the system to meet the setpoint temperature.

The heating energy is then calculated to determine the amount of energy savings from lowering the heating setpoint in the winter. The energy results conclude with calculating the overall savings for each setpoint for two outdoor temperature ranges when considering both the reduced heating power from the setpoint adjustments and the increase in plug load power from footwarmer use. As energy use depends on weather, analyzing energy consumption during a specified range of outdoor temperatures allows for a comparison of energy consumption at different setpoints.

5.4.1 Footwarmer Power

Using the power readings recorded at each workstation, this section presents the results both for the calculated average footwarmer power of each survey period as well as for each day. There was one ACme power plug at each workstation continuously recording its total power draw. From this data stream, it was possible to identify the typical computer and monitor plug load for each workstation. An example of this is shown below in Figure 5.4-1, which is typical of the power profiles of workstations in which the occupant used the footwarmer.

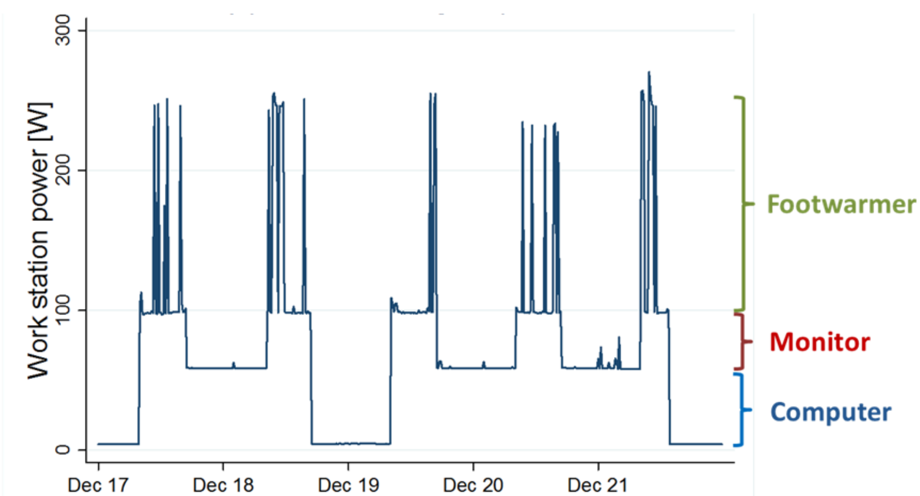


Figure 5.4-1 Example of Recorded Data for Workstation Power

Figure 5.4-1 reveals two important typical characteristics of footwarmer use that are consistent with Figure 5.2-3 and Figure 5.2-4. Firstly, it was typical to use the footwarmer at full power or not at all, as opposed to adjusting the power setting to any level from 0-100%. Secondly, the footwarmer was used for short periods of time sporadically throughout the day. Unlike space heaters that are on continuously when they are plugged in, the footwarmer is only activated when feet press down on the pressure plate so it is always turned off when people are not at their desk. This pattern also suggests that people did not feel the need to use it continually if they did not move from their workstation during the day. Table 4.3-2 shows that the occupants were at their workstations during almost their full workday.

The footwarmer power was calculated by subtracting the monitor power and the computer power from the total power. The footwarmer power is likely over estimated as any other device that was plugged in at the workstation was therefore counted as footwarmer power. This is why Table 5.4-1 has 0.5W as the average footwarmer for Survey Period 11 when the footwarmers were deactivated. For example, if someone was using the PCS fan, its power is included in the calculated footwarmer power. However, the PCS fan is only 4W so is nearly negligible. A future study could solve this data collection issue by recording the footwarmer power directly at each workstation, but this calculation nonetheless proves useful insight regarding footwarmer power patterns even if it could be slightly overestimated.

The next step was to then calculate the average computer, monitor, and footwarmer power representative for occupied hours for each survey period, which is shown in Figure 5.4-2 and Table 5.4-1. The average computer power is fairly consistent from survey period to survey period and hovers around 62W. The average monitor power is also fairly consistent throughout the study and is typically around 32W. The average footwarmer power, however, followed a different pattern. Rather than stay consistent throughout the study, the footwarmer power increased as the setpoint temperature decreased and vice versa. The highest average footwarmer power for a survey period was 11.0W and occurred at the coldest setpoint (66F). This shows that people adjusted their use of the footwarmer as the setpoint changed, specifically that they used the footwarmer more during cooler setpoints.

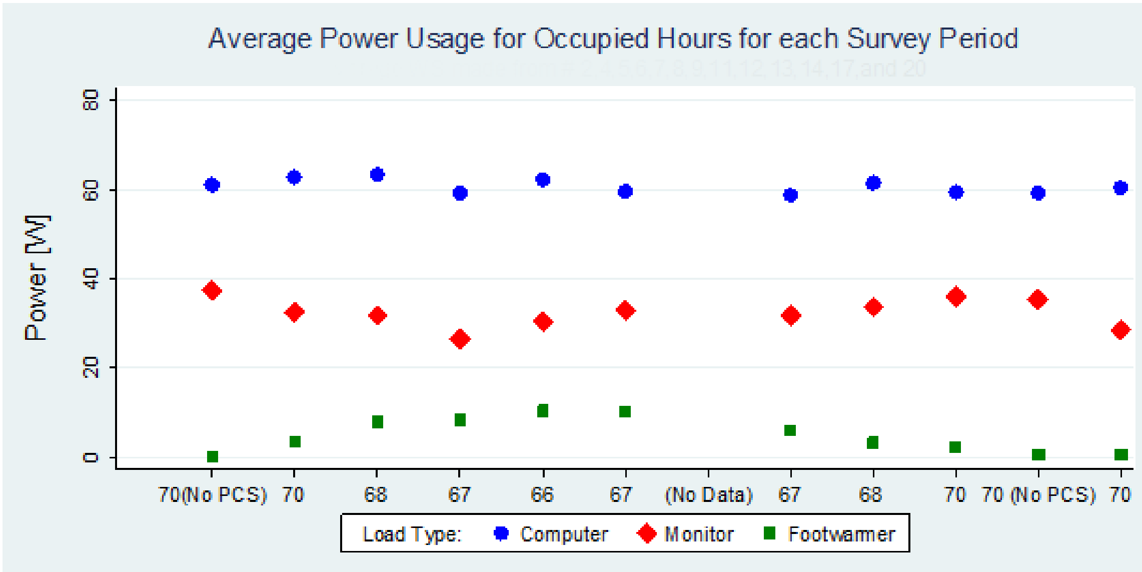


Figure 5.4-2 Average Workstation Power Usage for Occupied Hours for Each Survey Period

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
	70F (no PCS)	70F	68F	67F	66F	67F	66F	67F	68F	70F	70F (no PCS)	70F
Computer (W)	60.4	65.2	64.2	61.6	63.1	60.7	NA	61.4	62.5	63.7	60.0	63.8
Monitor (W)	36.7	33.1	33.0	26.4	30.9	32.2	NA	31.8	33.7	38.9	33.0	31.2
Ftwmr (W)	0.0	3.5	8.3	8.6	11.0	10.8	NA	5.7	3.1	2.6	0.5	0.4

Table 5.4-1 Average Workstation Power Usage for Occupied Hours for Each Survey Period

Figure 5.4-3 and Figure 5.4-4 below show no consistent day to day increase or decrease in the average footwarmer power for a particular survey period. This suggests that people did not adapt to the cool environment throughout a singular survey period but rather had a similar level of usage for each particular setpoint. However, footwarmer usage was slightly higher first half of the study suggesting that people perhaps adapted to the cooler zone temperatures later in the study and felt they needed less heat from the footwarmer to keep warm.

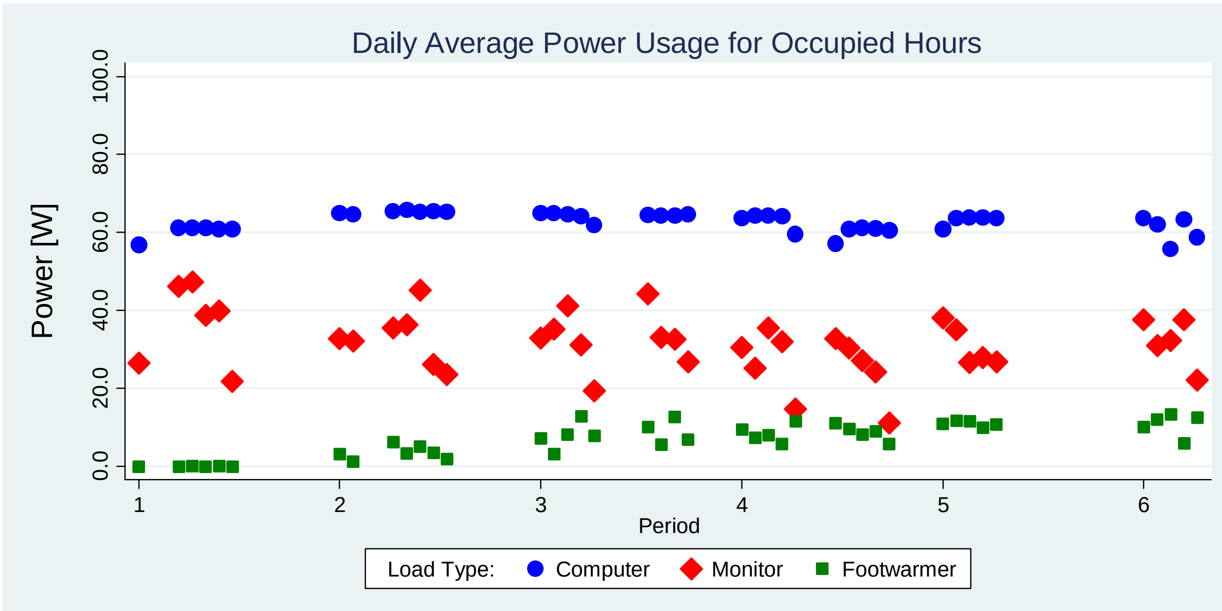


Figure 5.4-3 Daily Average Workstation Power Usage for Occupied Hours Periods 1 – 6

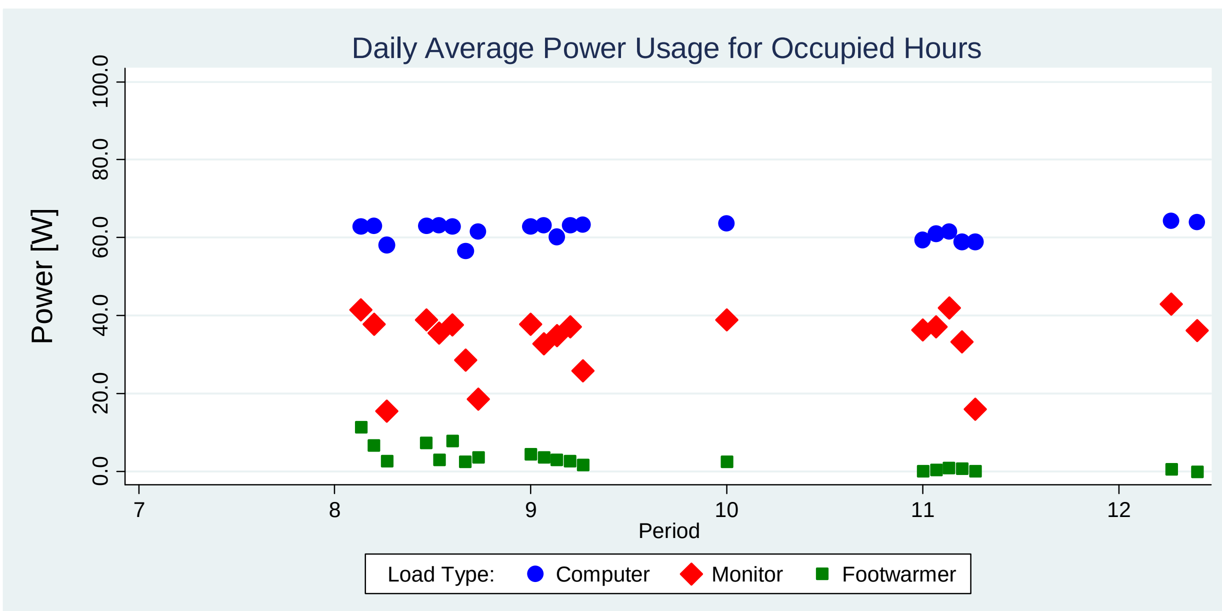


Figure 5.4-4 Daily Average Workstation Power Usage for Occupied Hours Periods 7 – 12

5.4.2 Indoor Air Temperature Monitoring

With so much scrutiny given in this study as to occupant perception and energy consumption at specific setpoints, it is important to know whether or not the zone temperature actually matched the setpoint specified by the BMS system. While the main windows of the office face north so there is a reduced impact of solar gain on sunny days, operative temperature and solar radiation were not measured to verify this potential impact. Similar to how the survey responses were analyzed by workstations located in the perimeter vs the core of office, this analysis of perimeter temperatures help to evaluate if occupants may have experienced different thermal conditions as a result of the location of their workstation.

Figure 5.4-5 shows the perimeter temperature, core temperature, setpoint, and outside temperature every fifteen minutes during occupied hours throughout the study. This graph shows that the decrease and then increase in setpiont temperature followed the same seasonal decrease and the increase in temperatures as the seasons transitioned from late fall, to winter, and to early spring. While there are so many data points in Figure 5.4-5 that it is difficult to discern the difference between the perimeter and the core temperatures, the graph shows that both temperatures fairly frequently swung a degree above and below the setpoint but were more often higher than the setpoint, especially at the lower setpoints. This later phenomenon is shown in Figure 5.4-6, which graphs the daily average perimeter temperature, core temperature, setpoint, and outside temperature. When the temperatures are averaged by occupied hours each day, both the perimeter and core temperatures are often about half a degree warmer than the setpoint when it is 70F and 68F, and closer to 1 degree warmer than the setpoint when it is 67F and 66F. The perimeter temperature is slightly warmer than the core temperature at the higher setpoints and vice versa at the lower setpoints, though the difference between the perimeter and the core temperature is so small that it is arguably negligible. These general trends are also reflected when the perimeter temperature, core temperature, and average zone temperature are averaged by survey period, as shown in Table 5.4-2. The greatest difference between the average zone temperature and the setpoint temperature is Survey Period 7 when the setpoint is 66F, in which the average zone temperature is 0.8F higher than the setpoint on average. Table 5.4-2 also shows that the system had roughly the same average zone temperature regardless of the outside weather. The 55-60F outdoor temperature range was chosen because there was a fairly high frequency of these outdoor temperatures in all of the survey periods. The results during the 52-57F outdoor temperature are shown as a point of comparison.

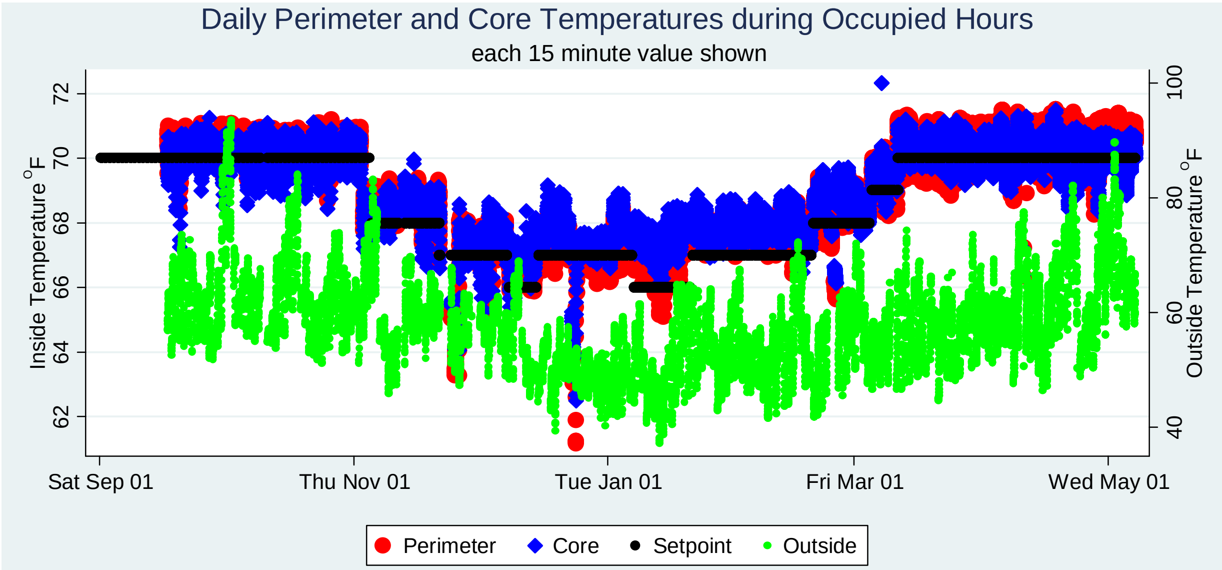


Figure 5.4-5 Daily Perimeter and Core Temperatures during Occupied Hours (every 15 min)

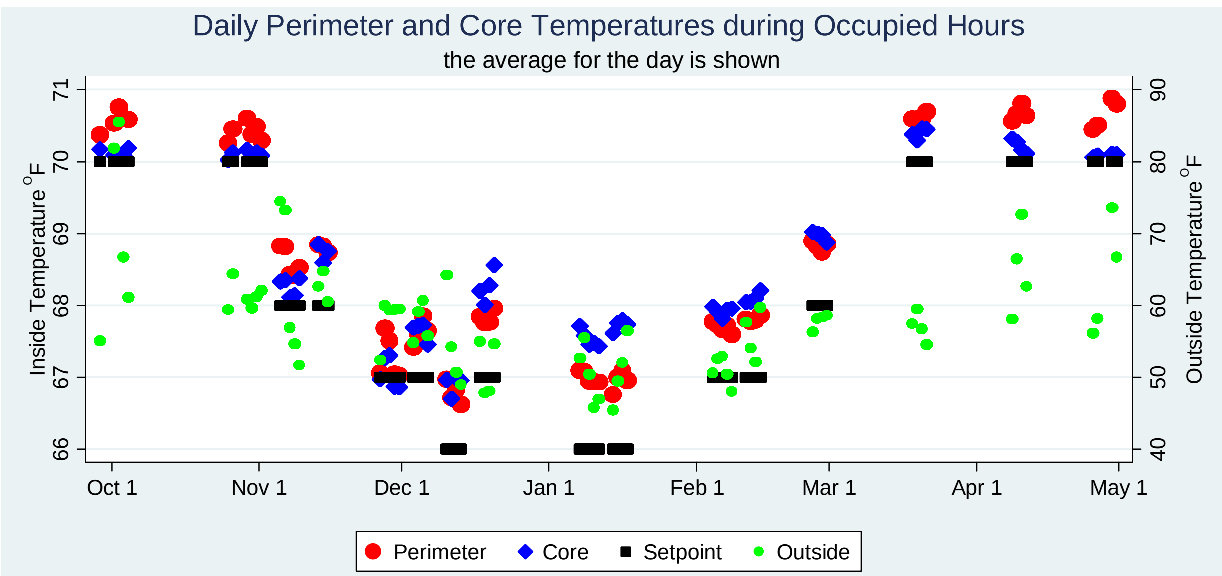


Figure 5.4-6 Daily Perimeter and Core Temperatures during Occupied Hours (daily average)

Survey Period	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Setpoint	**(no PCS) 70.0**	**70.0**	**68.0**	**67.0**	**66.0**	**67.0**	**66.0**	**67.0**	**68.0**	**70.0**	**(no PCS) 70.0**	**70.0**
Perimeter Temp (all OAT)	70.6	70.4	68.7	67.5	66.7	67.8	67.0	67.8	68.8	70.6	70.7	70.7
Core Temp (all OAT)	70.1	70.1	68.5	67.4	66.9	68.2	67.6	68.0	68.9	70.4	70.2	70.1
Avg. Zone Temp (all OAT)	70.3	70.2	68.4	67.3	66.5	67.6	66.8	67.5	68.5	70.4	70.3	70.3
Avg. Zone Temp (OAT 55 – 60F)	70.2	70.3	68.4	67.4	66.5	67.8	66.9	67.5	68.5	70.3	70.4	70.2
Avg. Zone Temp (OAT 52 – 57F)	70.2	70.5	68.3	67.3	66.6	67.7	66.8	67.5	68.7	70.4	70.5	70.2
Avg. Outdoor Temp (F)	69.8	61.4	62.3	57.8	54.0	51.8	52.3	56.3	58.7	58.4	64.8	71.9

Table 5.4-2 Perimeter, Core, and Average Interior Temperatures by Survey Period

5.4.3 Heating Energy Savings from Setpoint Changes

The power required to heat the space was calculated based on data measured and provided by the BMS system. This included airflow (Q) and discharge air temperature (DAT) that were measured at each VAV box and the supply air temperature (SAT) provided by the BMS trend data. The calculation method below slightly overestimates the heating power. This is because the DAT will be slightly higher than the SAT even when the VAV heating valve is fully closed as the air in the ducts heats up some as it flows through the building to the VAV box. A schematic diagram of the HVAC system can be found in Figure 5.4-7.

Heat Power (kW) = Q * T * k
Q = Airflow (cfm)
 T = [Discharge Air Temperature (F)] – [Supply Air Temperature (F)]
k = (0.0283 m^3/s)/(60 cfm) * ($_{air}$) * (C_p) / (1000 kW/W) * (5C/9F)
$_{air}$ = density of air = 1.204 kg/m^3
C_p = specific heat capacity of air = 1006 Joules / kg K

Looking at the heating power during a limited range of average outdoor temperatures allows for a more direct comparison of heating energy between periods of time at different setpoints. Two ranges of daily average daily outdoor temperature, 55 – 60F and 52F – 57F, both capture data from all survey periods yet normalize the effect of outdoor weather on the evaluation of heating energy consumption. Both the 55 – 60F and 52 – 57F ranges are well within the city's typical winter weather range, which supports the goal of the experiment to consider the applicability of localized heating during the heating season. Looking at the heating energy consumption during two ranges of average daily outdoor temperatures provides an opportunity to better substantiate results and conclusions.

Figure 5.4-7 shows that the heating power depends both on the setpoint and the outside temperature and plots the average heating power for 15 minute intervals throughout the study. For every setpoint, Figure 5.4-7 shows a line in which 50% of the datapoints are above the line and 50% of the datapoints are below the line. As expected, this graph shows that heating power deceases when the outdoor temperature increases as well as when the setpoint is lowered. This graph shows that the heating power is similar at the 67F and 68F setpoints, but that both power levels are noticeably lower than the 70F power levels. While the 67F and 68F lines are similar, the 66F line shows lower heating power levels especially at cooler outside air temperatures. The average heating power for each setpoint for specific outdoor temperature ranges is in Table 5.4-3, where the data is presented in the context of analyzing overall energy savings in the office.

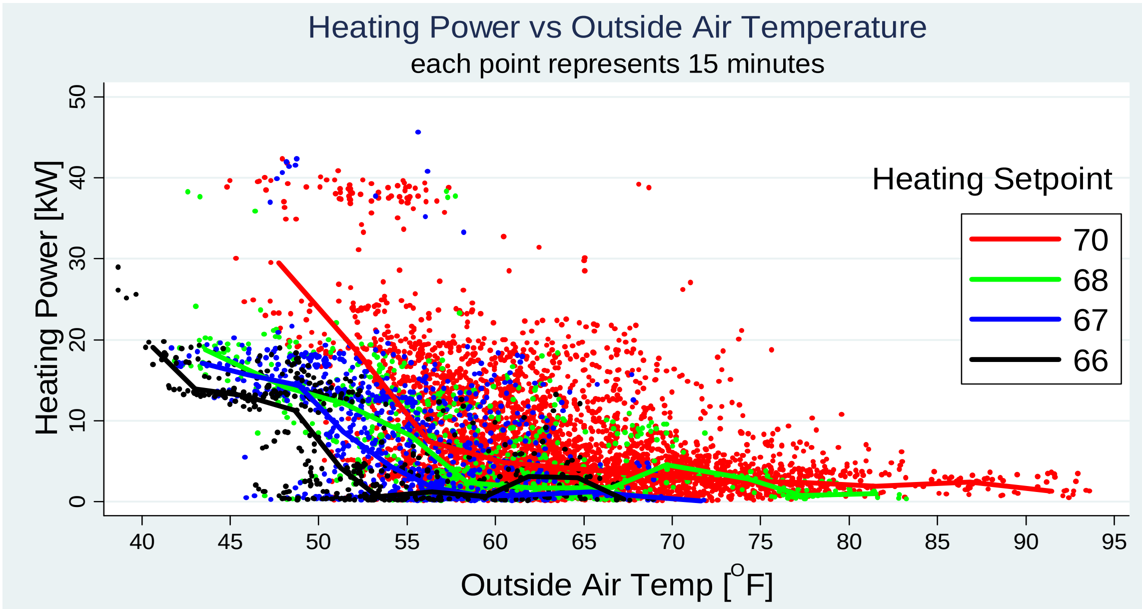


Figure 5.4-7 Heating Power vs Outside Air Temperature

5.4.4 Overall Energy Savings

From measuring the footwarmer power and the heating power, it is possible to calculate the overall change in power from the basecase condition at the existing 70F with no footwarmers. Table 5.4-3 shows the average footwarmer power at each setpoint for two different outdoor temperatures ranges, both which reinforce the results of Figure 5.4-2 that footwarmer power increases as the setpoint decreases. The footwarmer power is that of an average workstation during occupied hours (8 hours/day).

Table 5.4-3 also shows the average heating power at each setpoint during occupied hours for two different outdoor temperature ranges, showing both that heating power is reduced at lower setpoints and that there is greater heating power required when outdoor temperatures are cooler. The percent savings for each outdoor temperature range is calculated as overall savings compared to the basecase condition of the average heating power at 70F without the footwarmer. An example of the percent savings calculation is shown below for when the setpoint was 66F. All values are specific to the same outdoor temperature range.

Percent Savings = 100*(1-((Heating Power 66F) +(Footwarmer Power 66F))/(Heating Power 70F no PCS))

The overall power was reduced by 38 – 75% depending on the setpoint and the outdoor temperature range. Across all the reduced setpoints and both temperature ranges, the heating power was roughly half of that of the existing condition. These results are shown in Figure 5.4-8 and Figure 5.4-9, which differ only in the y axis scale(s). These results show that the increase in power due to footwarmer use is extremely small, especially in comparison to the decrease in power due to lowering the setpoint.

Table 5.4-4 takes the heating power values during the 8 occupied hours shown in Table 5.4-3, multiplies them by three to get an estimated 24 hour value, then divides by the area of the office building to calculate the heating power density. The ehating power density for the existing conditions (70F, no PCS) provide a point of comparison for future studies as it shows results normalized by area.

	Setpoint 66F	Setpoint 67F	Setpoint 68F	Setpoint 70F	Setpoint 70F (no PCS)
Footwarmer Power (W) (OAT 55 – 60)	12	8	7	2	0
Heating Power (W) (OAT 55 – 60)	133	195	145	332	328
Percent Savings (from 70F no PCS) (OAT 55 – 60)	56%	38%	54%	-2%	NA
Footwarmer Power (W) (OAT 52 – 57)	12	8	8	2	0
Heating Power (W) (OAT 52 – 57)	119	265	281	567	532
Percent Savings (from 70F no PCS) (OAT 52 – 57)	75%	49%	46%	-7%	NA

Table 5.4-3 Overall Energy Savings

	Setpoint 66F	Setpoint 67F	Setpoint 68F	Setpoint 70F	Setpoint 70F (no PCS)
Heating Power Density (W/sf) (OAT 55 – 60)	0.12	0.17	0.13	0.29	0.29
Heating Power Density (W/sf) (OAT 52 – 57)	0.11	0.24	0.25	0.50	0.47

Table 5.4-4 Heating Power Densities

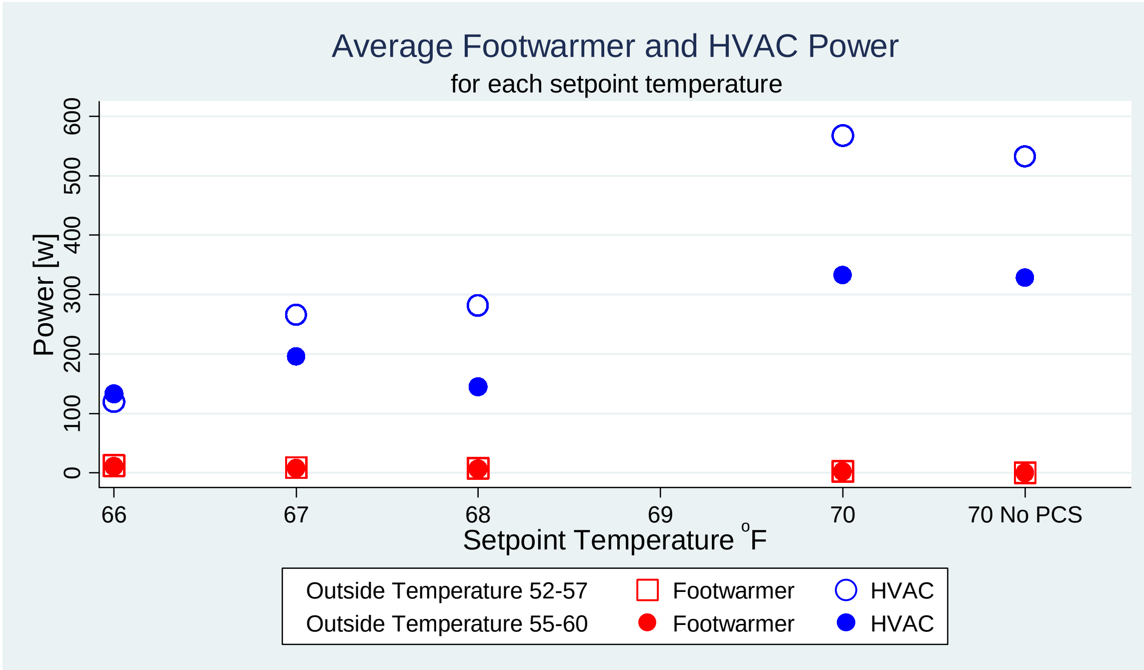


Figure 5.4-8 Average Footwarmer and HVAC Power (Version 1)

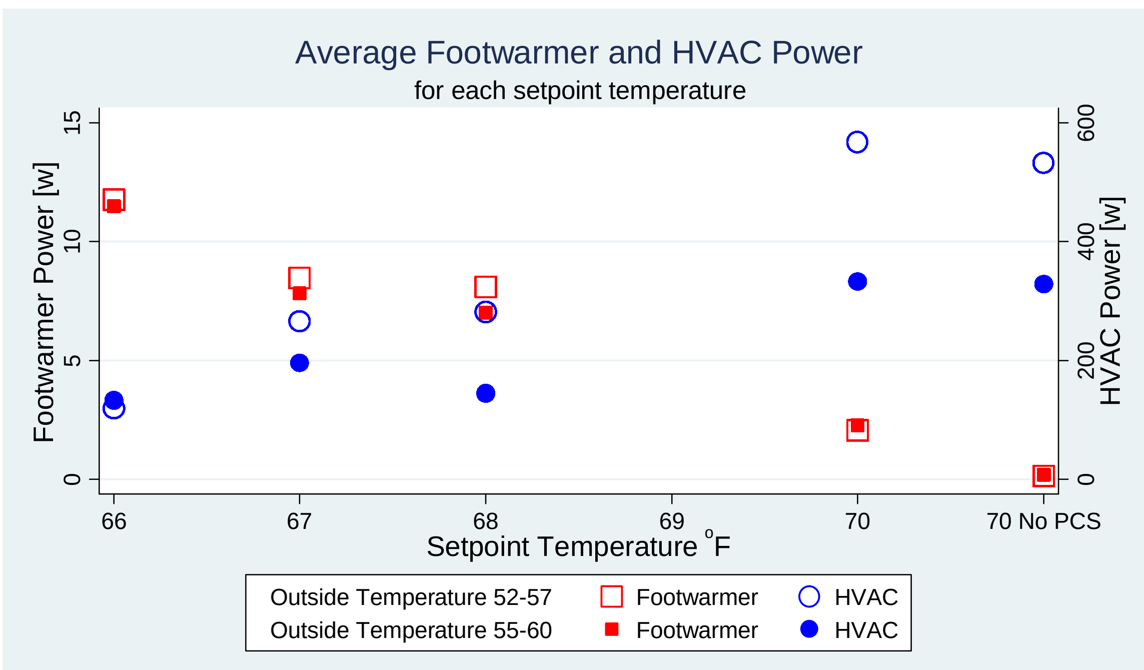


Figure 5.4-9 Average Footwarmer and HVAC Power (Version 2)

6. Discussion

These results provide excellent insights as a demonstration of the personal comfort system concept. They provide a first stepping stone for field studies that combine personal comfort systems and setpoint changes to investigate whether or not it is an effective energy efficiency measure that maintains thermal comfort. While the results indicate that thermal comfort was generally maintained at lowered setpoints and that the footwarmer load was substantially offset by the heating power savings, the detailed results analysis provides a more in depth examination of thermal comfort, the footwarmer, and performance of the HVAC system.

When considering the Right Now Survey responses and the energy savings in such detail, it is important to keep in mind that the zone temperatures were not always an exact match to the setpoint. This is likely why there is not a clear regression of energy savings for each setpoint even during specific outdoor temperature ranges. Even in the case of the field study building, which was recently renovated and has an advanced control system, the mechanical system did not operate absolutely perfectly so the survey results focused on statistically different responses and the footwarmer and energy savings focused on average power. Nonetheless, the two largest trends in the results are that footwarmer use increases as setpoints decrease and that there are substantial overall energy savings from reducing the setpoint.

Of all the variables used to calculate thermal comfort (metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity), this field study focused only on occupant perception of thermal acceptability and thermal sensation as a result of changing only one of the variables: air temperature. As most people said that their metabolic rate and dressing habits did not change during the field study, these other variables are assumed to be constant and the footwarmer remains as the one aspect that was adjusted to impact thermal comfort.

Looking in detail at the Right Now Survey results, there was general consistency in thermal acceptability and whole body thermal sensation votes even in most of the analyzed subgroups of people. The consistency of votes between people on the perimeter and core reinforces the quantitative results that there was minimal difference on average between perimeter and core temperatures. Combined with the conclusion that there was also minimal difference in thermal comfort for votes in the morning and those in the afternoon, solar gain was not likely a factor that impacted people's comfort in office with only northern exposure.

Similar to how the survey responses showed minimal statistically significant difference in thermal acceptability and thermal sensation when analyzed on a day by day level, the measured footwarmer use tended not to vary substantially during each survey period. The quantitative footwarmer power results reinforced the occupants survey results and interview responses that they used the footwarmer more at colder temperatures.

While the survey results and power calculations provide data key to the analysis, some of the most important insights came from the exit interviews. At first, it was surprising that there was little difference in the thermal acceptability and whole body thermal sensation between people using the footwarmer and people not using the footwarmer. However, in the exit interviews, quite a few of the footwarmer non-users said that they didn't use the device because they were not cold. While the other non-users cited the footwarmer as their main barrier to use, several of the footwarmer users also found the footwarmer ergonomics problematic. While the energy results and thermal comfort responses are promising, the ergonomic design of the footwarmer could be improved.

While some people in the exit interview said that there were times when they were a bit cold as also shown in frequent slightly cool whole body thermal sensation results, the thermal acceptability remained fairly constant throughout the study and well above the minimum 80% acceptable threshold set forth in ASHRAE Standard 55. This suggests that people do not necessarily require a strictly neutral thermal sensation to be satisfied with the thermal environment of their workspace. This finding supports the theory of alliesthesia, which is based on the idea that people actually prefer some amount of non-uniformity in their thermal environment. This acceptance of spatial alliesthesia could change the conceptualization of thermal comfort from the current static and isothermal neutral environment set by ASHRAE Standard 55 to a more dynamic and non-uniform condition that can still be acceptable. Given that the heating power was reduced by roughly 50% during the winter in the Berkeley climate, the energy implications of accepting thermal comfort based on principles of alliesthesia are tremendous.

7. Conclusions

This six-month field study aimed to determine if it possible in the winter to maintain thermal comfort and save energy by lowering the setpoint while providing occupants with a personally controlled low-power foot-level heating device to compensate. The study was done on 16 knowledge workers in their normal workplace, a typical sealed office in which people are primarily stationary at their workstation. The methodology used in the study is a substantial contribution of this research as surveys, plug load monitoring, energy monitoring, and interviews all contributed to gaining as complete a picture as possible to the performance of the system and the thermal comfort of the occupants.

The results show that there was no statistically significant difference in the thermal acceptability when the setpoint was gradually reduced from 70F to 66F and then raised gradually back to 70F. Occupants had low-power footwarmers during this time and their use increased as the setpoint decreased. The added plug load from the device was so small in comparison to the heating power savings from the reduced setpoints that the overall energy savings ranged from 38-75% during typical outdoor temperatures. While this is a large savings range and the number of participants in the study were small, the results do indicate that personal control of thermal conditions at workstations can be an effective way to reduce energy. Whether it is a more ergonomically designed footwarmer or another low-power device, the key is for the localized conditioning to be driven by low-power technology to achieve the great overall energy savings and maintained comfort possible from relaxed setpoints in mechanically ventilated offices. As 54%of occupants used the footwarmer and 19% of occupants did not use the footwarmer since they were not cold, this shows that the footwarmer was able to help account for people's individual thermal preferences.

Personal comfort systems could be widely effective as part of larger efforts to improve energy efficiency in new buildings as well as existing buildings. When retrofitting existing buildings for energy efficiency, adding a personal comfort system would incur minimal associated costs as it is noninvasive and does not require any adjustment to the envelope or mechanical system. An in-depth financial analysis would likely confirm that a personal comfort system is a low-cost way to achieve big savings, though this is an area that warrants further research.

There are several additional opportunities for further research. One area would be to apply the methodology to field studies with more occupants, different climates, and/or different mechanical systems. These studies could continue to test the footwarmer or other low-power devices to expand research in personal comfort systems. Once there is eventually a large body of research showing that personal control of localized conditioning can maintain thermal comfort under relaxed setpoints in mechanically ventilated buildings, then it would be possible to adopt such measures into thermal comfort standards and effectively begin to mandate the savings.

While personal comfort systems are currently developed primarily in research labs, commercializing the technology is an important next step in broadening the impact of the concept of low-power localized conditioning. Commercializing the technology could lower the cost of production, improve industrial design, and make the devices widely available on the market. There is a business opportunity for companies to develop a market of personalized comfort devices for buildings and to integrate them with the overall building HVAC system to save energy as well as provide effective thermal comfort. This thesis contributes to ongoing research in this field, especially at the Center for the Built Environment at the University of California Berkeley that is developing low-power legwarmers, heating and cooling chairs. While these devices are under development in the context of building science research, the scientifically proven concepts at the heart of these devices could be incorporated with industrial design expertise to commercialize this technology for greater impact. While a business case for PCS devices is beyond the scope of this thesis, this work aims to support future endeavors to provide field test result to improve PCS technology for improved energy savings and occupant comfort.

In the context of a large push to improve the energy efficiency of buildings, there must be a balance between energy efficiency and comfort. After all, the minimum energy consuming office building would have no windows, no lights, and no temperature control. The ultimate goal of office design should be to create a comfortable and delightful working environment for its occupants as buildings are ultimately for people. As people have different preferences, providing personal control is one way in which people can best adjust their workspace to their needs. After showing that personal control can lead to substantial energy savings, low-power localized conditioning is a valuable asset for improving both energy efficiency and thermal comfort.

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9. Appendix A: Right Now Survey

1. TEMPERATURE

Right now, how acceptable is the temperature at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

You feel (*Please mark on the scale*)?

Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold

You would prefer to be:

Cooler	No change	Warmer
○	○	○

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2. AIR MOVEMENT

Right now, how acceptable is the air movement at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

Right now, how do you feel the air movement?

No air movement (don't notice any)	A little (slightly perceptible)	A moderate amount (clearly noticeable)	Strong air movement	Very strong air movement

You would prefer:

More air movement	No change	Less air movement
○	○	○

3. AIR QUALITY

Right now, how acceptable is the air quality at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

4. THE PERSONAL COMFORT SYSTEM

Right now, does the footwarmer provide enough heat?

Yes	No
○	○

Right now, does the desk fan provide enough cooling?

Yes	No
○	○

5. COMMENTS TO THE ENVIRONMENT PROVIDED BY THE PERSONAL COMFORT SYSTEM

If you have additional comments to your Personal Comfort System, click here

10. Appendix B: Exit Survey Interview Script

Footwarmer:

Please check the following statements with which you agree regarding your experience with the footwarmer:

- I like having the footwarmer
- I do not like having the footwarmer [Why?]
- the footwarmer provides relief from feeling cold
- the maximum setting on the footwarmer is not strong enough
- the footwarmer gives more individual control
- the footwarmer changes the way I sit at my workstation (posture). Please explain__
- Other ______

In what ways, if any, did you adapt to using the footwarmer during the 6 month study? Did you wear different clothes or shoes? Did you change the way you sat? Did you like the footwarmer more or less as the study progressed?

Were there specific or regular times in which the footwarmer did not keep you warm enough at your workstation?

- Yes/No. If yes, please explain________

What suggestions do you have to change how the footwarmer operates (how it works)? Are there ways in which you would prefer to adjust the footwarmer such as changing the height and tilt? Did you have trouble getting your feet into the device or was the footwarmer hitting your shins?

What suggestions do you have to change the aesthetics of the footwarmer (how it looks)?

Desk fan:

Did you use the desk fan? If yes, when and how often? Why did you use the fan? Did your use vary during the last 6 months? Did you use your own fan during the study and if so, why?

[skip if no fan use] Please check the following statements with which you agree regarding your experience with the desk fan:

- I like having the desk fan
- I do not like having the desk fan
- I like the feeling of air movement

- I think the air movement is disruptive (papers blow, etc.)
- the fan provides relief from feeling warm
- the fan does not provide enough temperature relief
- the fan improves air quality (reduces stuffiness)
- the maximum setting on the fan is not strong enough
- the fan provides a sense of outdoors
- the fan is too noisy
- the fan gives more individual control
- Other ______

[skip if no fan use] In what ways, if any, did you adapt to using the fan during the 6 month study? Did you like the fan more or less as the study progressed? Where was the fan at your workstation and did you move it during the study?

[skip if no fan use] Were there specific or regular times in which the desk fan did not keep you cool enough at your workstation?

- Yes/No. Please explain________

What suggestions do you have to change how the desk fan operates (how it works)?
What suggestions do you have regarding the aesthetics of the desk fan (how it looks)?

<u>General questions</u>:
Did you notice a difference in your thermal comfort when you were not at your workstation but in your office? Is the conference room noticeably comfortable or uncomfortable?

During the work day, do you often work outside of your office?

Do you have any additional comments about the desk fan and footwarmer not yet covered in this interview?

Do you have any feedback about how we are conducting the field study?

11. Appendix C: Right Now Survey Day by Day Results for Each Survey Period

Notes on the following graphs:

- The "*" marks represent a statistically significant difference at a 95% confidence level between the votes for each day (starting Day 2 and onwards) compared against the votes of the first day of the survey period.
- The numbers without a percentage sign are the n values of each boxplots.
- In each thermal acceptability graph, the percentages are votes that are acceptable (responses of "4," "5," "6," and "7") relative to the total number of votes for each boxplot ("1," "2," "3," "4," "5," "6," and "7").
- The red dots represent the mean of each boxplot.

11.1 Period 1 Day by Day Votes (Setpoint = 70F, no PCS)

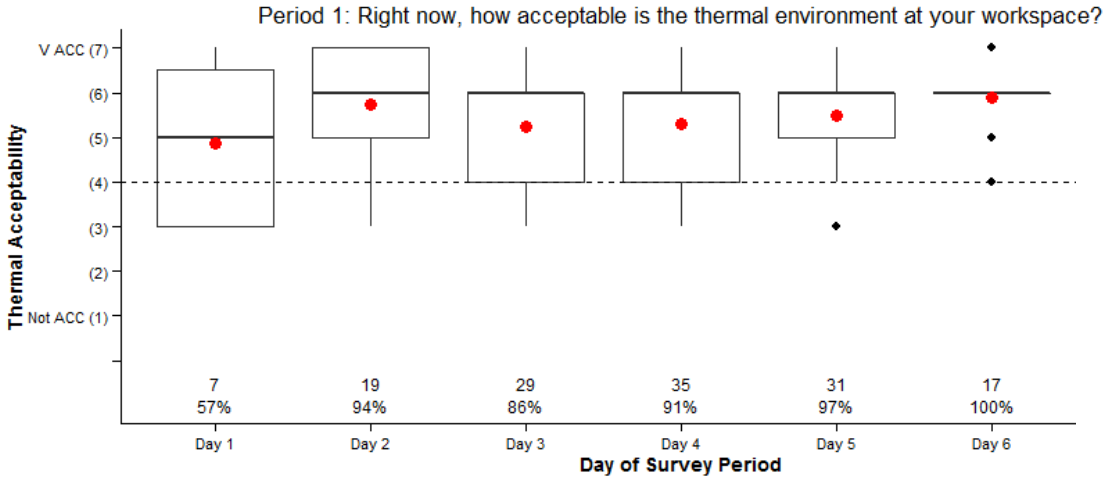

Figure 11.1-1 Period 1 Day by Day Votes: Thermal Acceptability

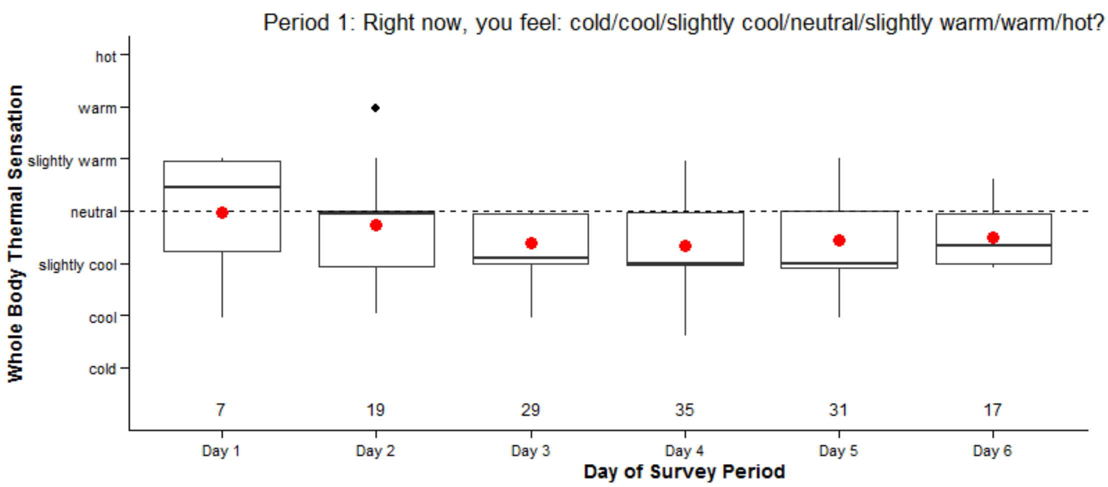

Figure 11.1-2 Period 1 Day by Day Votes: Whole Body Thermal Sensation

11.2 Period 2 Day by Day Votes (Setpoint = 70F)

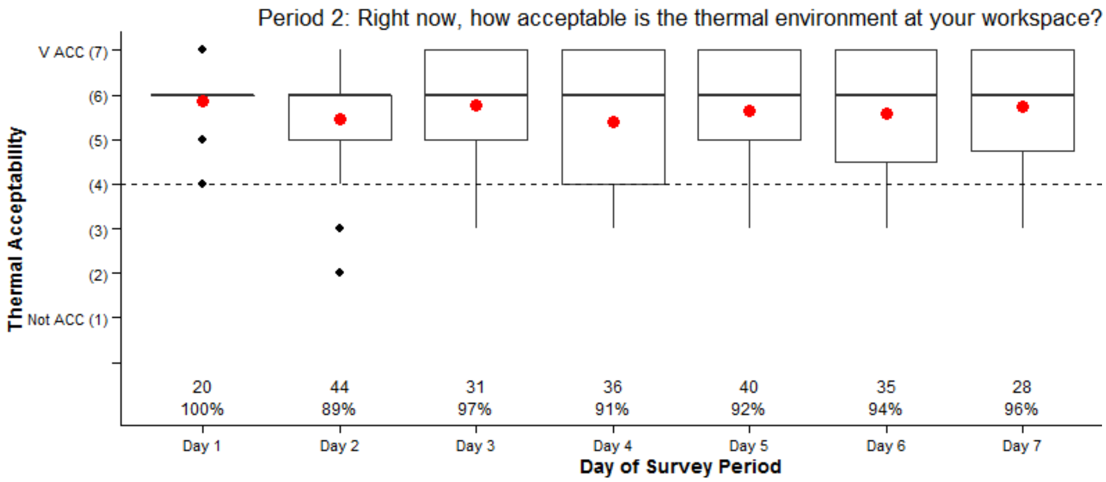

Figure 11.2-1 Period 2 Day by Day Votes: Thermal Acceptability

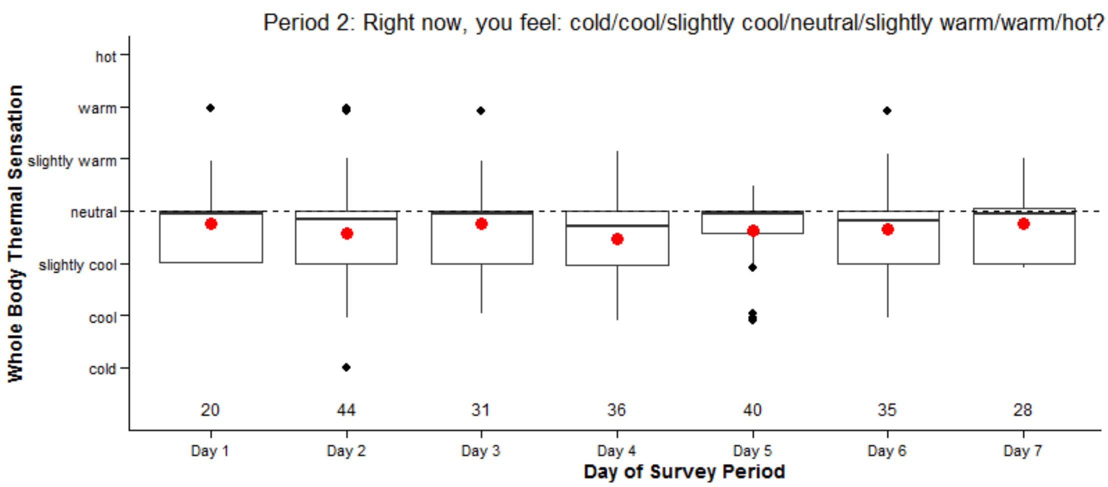

Figure 11.2-2 Period 2 Day by Day Votes: Whole Body Thermal Sensation

11.3 Period 3: Day by Day Votes (Setpoint = 68F)

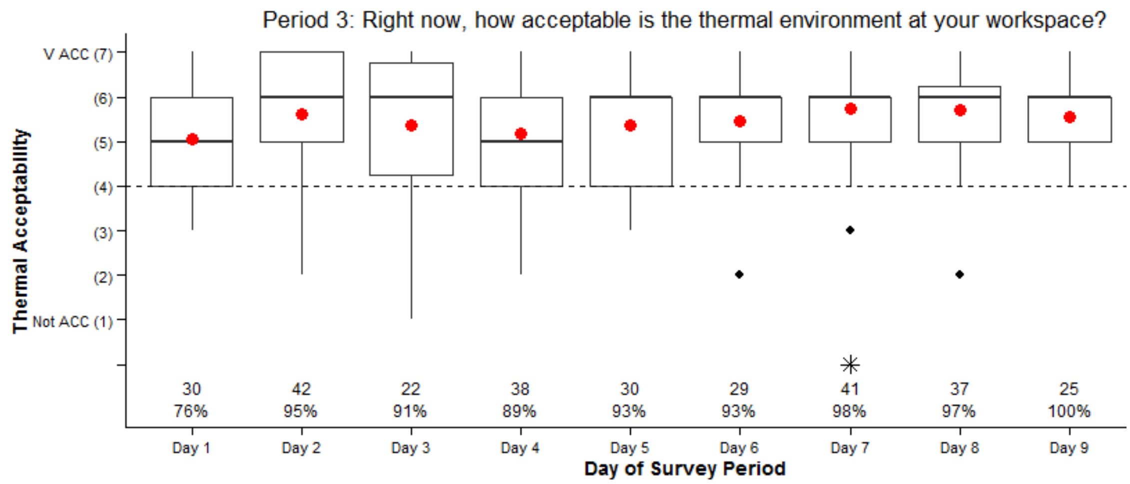

Figure 11.3-1 Period 3 Day by Day Votes: Thermal Acceptability

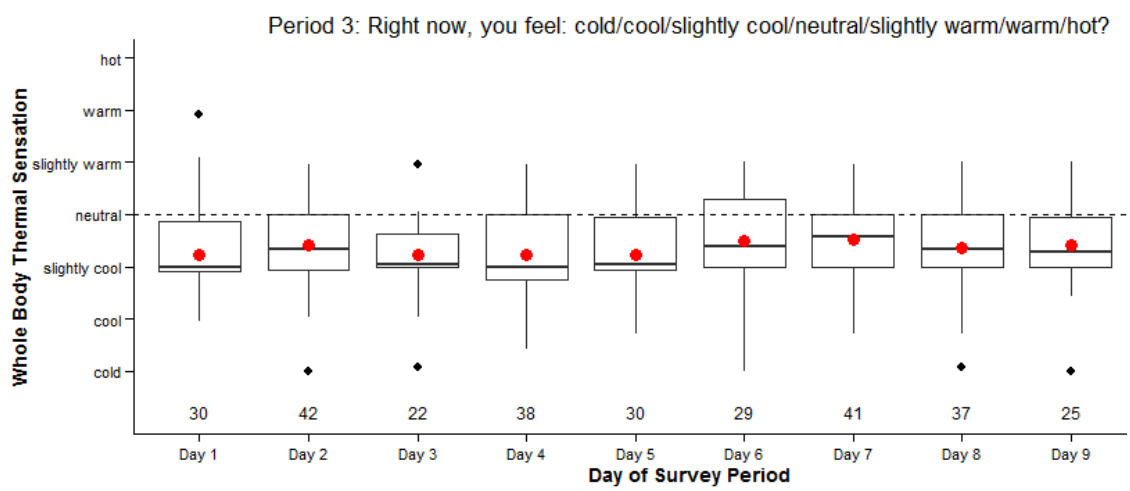

Figure 11.3-2 Period 3 Day by Day Votes: Whole Body Thermal Sensation

11.4 Period 4 Day by Day Votes (Setpoint = 67F)

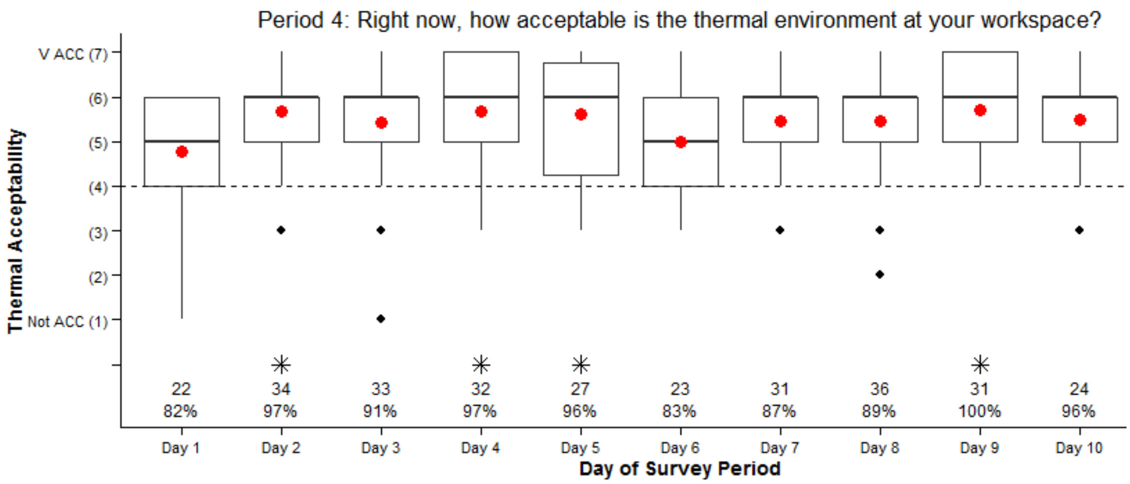

Figure 11.4-1 Period 4 Day by Day Votes: Thermal Acceptability

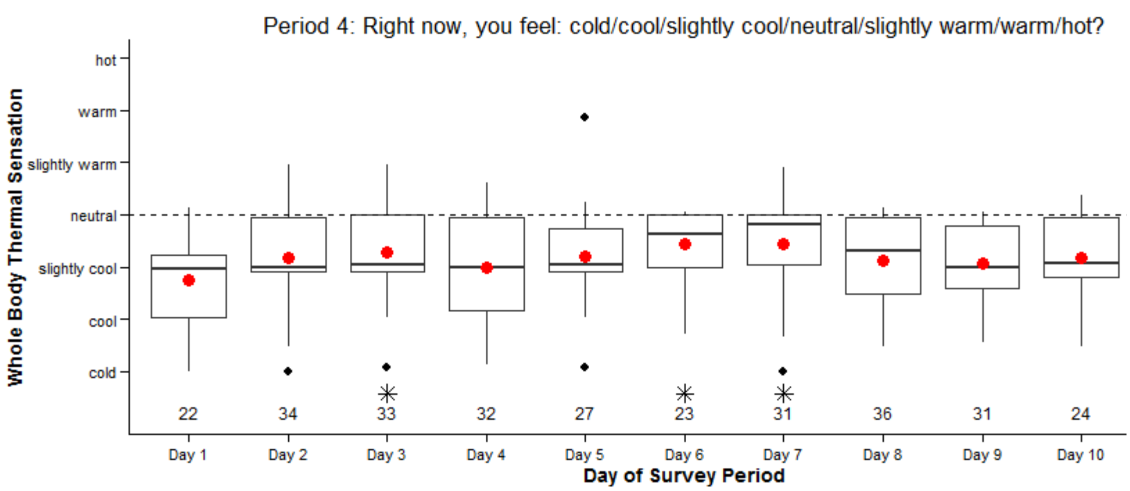

Figure 11.4-2 Period 4 Day by Day Votes: Whole Body Thermal Sensation

11.5 Period 5 Day by Day Votes (Setpoint = 66F)

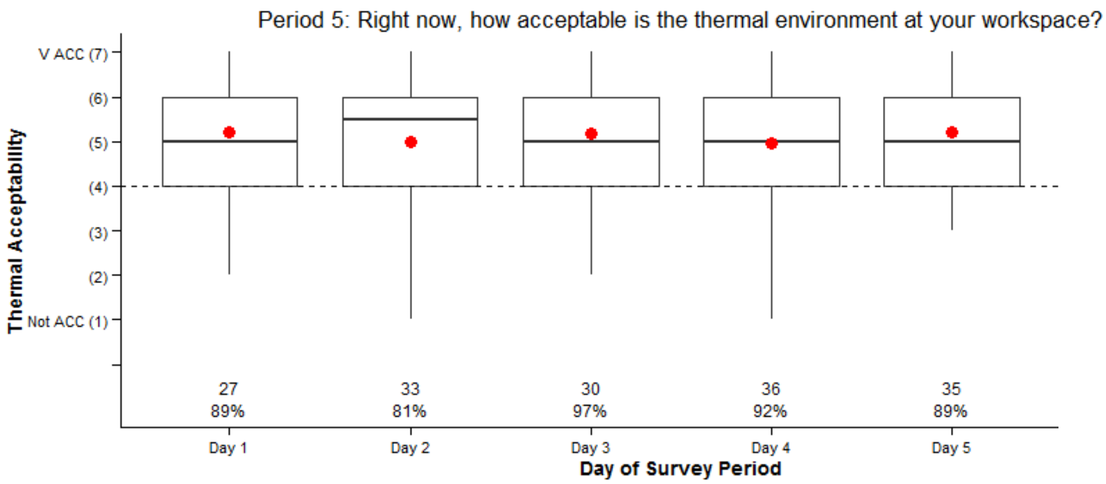

Figure 11.5-1 Period 5 Day by Day Votes: Thermal Acceptability

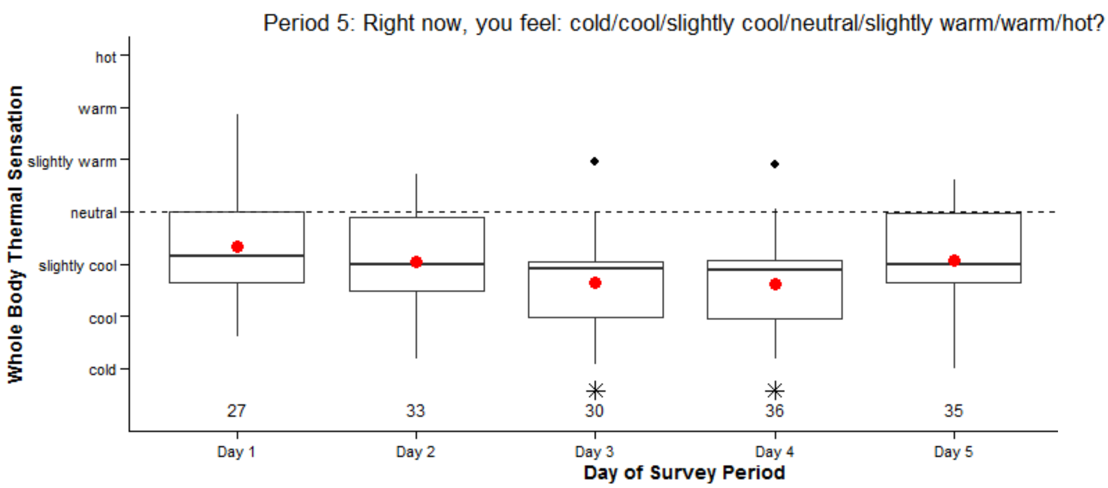

Figure 11.5-2 Period 5 Day by Day Votes: Whole Body Thermal Sensation

11.6 Period 6 Day by Day Votes (Setpoint = 67F)

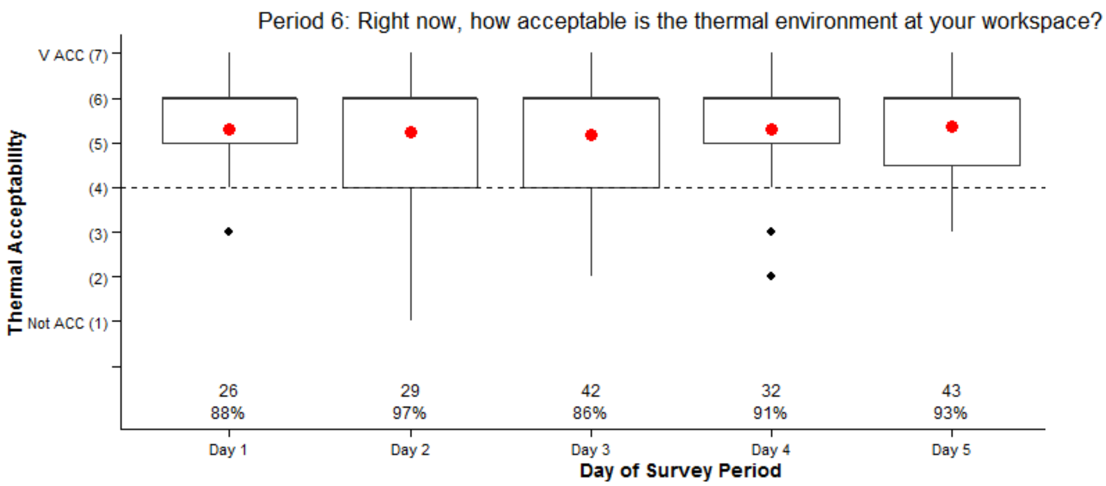

Figure 11.6-1 Period 6 Day by Day Votes: Thermal Acceptability

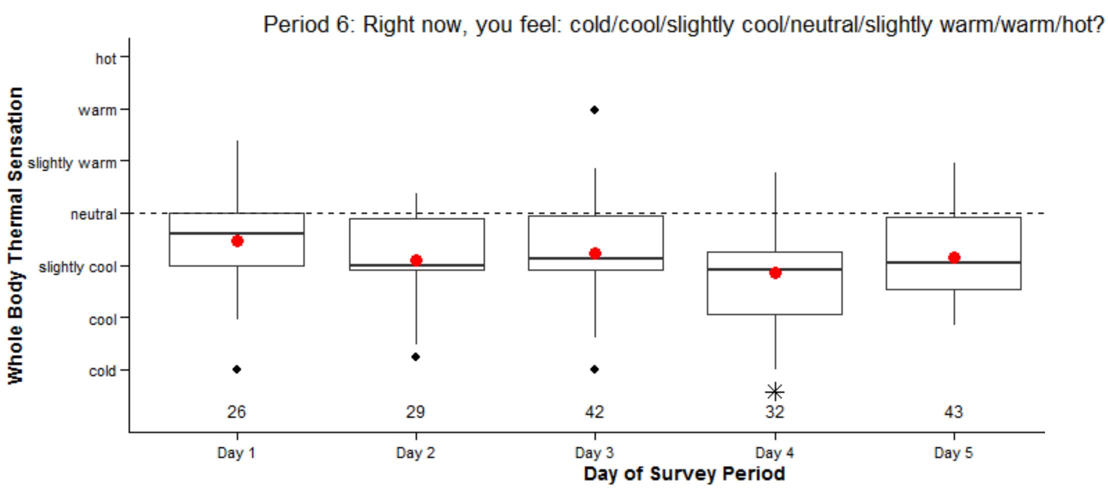

Figure 11.6-2 Period 6 Day by Day Votes: Whole Body Thermal Sensation

11.7 Period 7 Day by Day Votes (Setpoint = 66F)

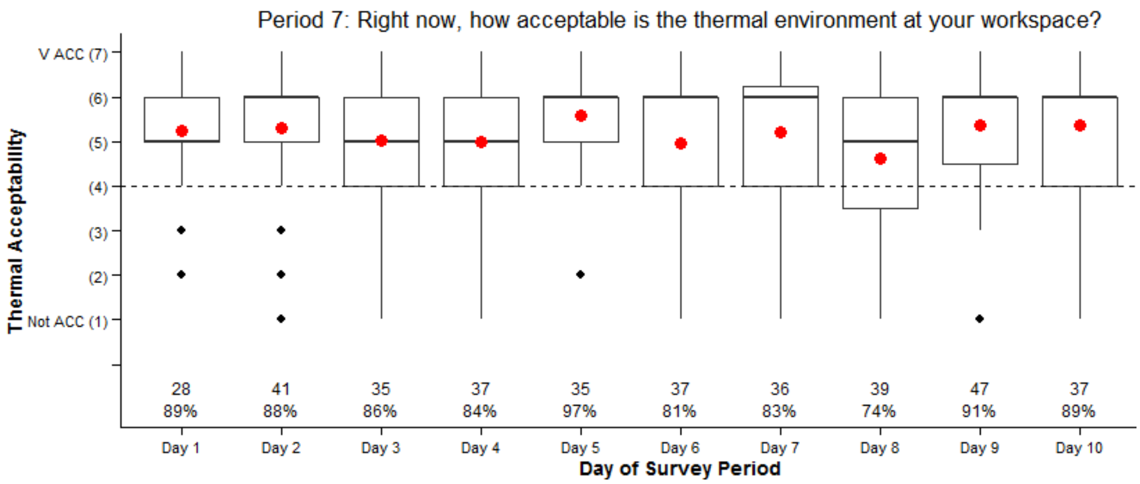

Figure 11.7-1 Period 7 Day by Day Votes: Thermal Acceptability

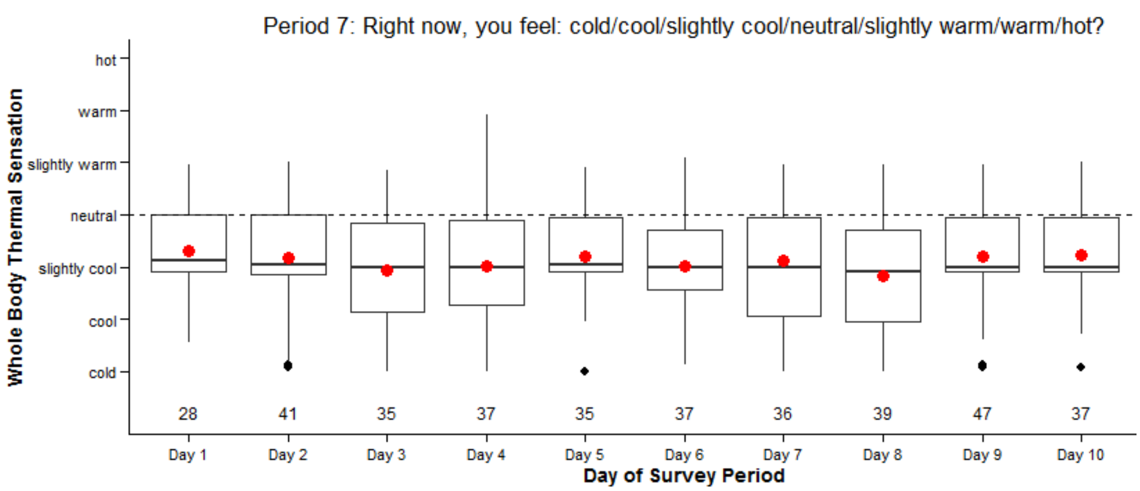

Figure 11.7-2 Period 7 Day by Day Votes: Whole Body Thermal Sensation

11.8 Period 8 Day by Day Votes (Setpoint = 67F)

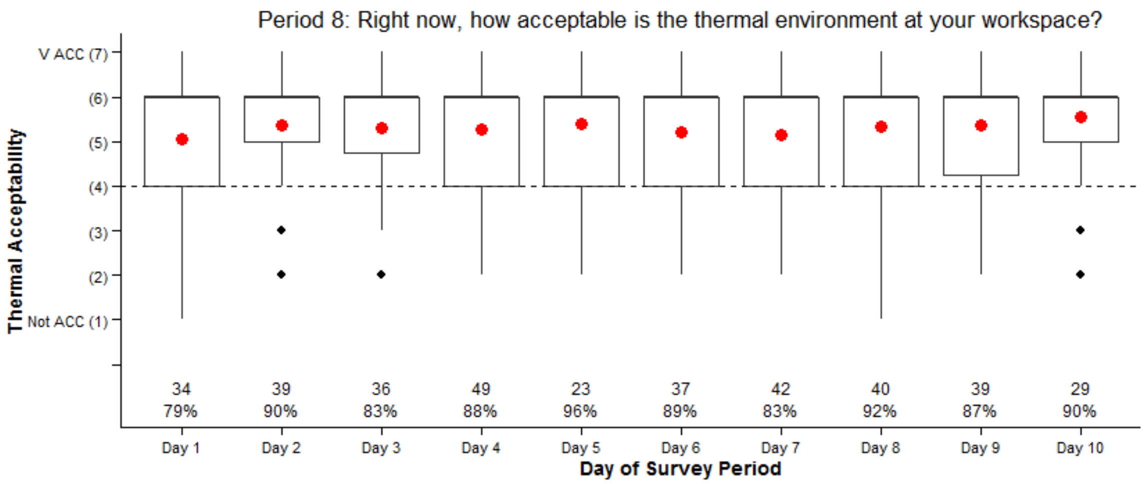

Figure 11.8-1 Period 8 Day by Day Votes: Thermal Acceptability

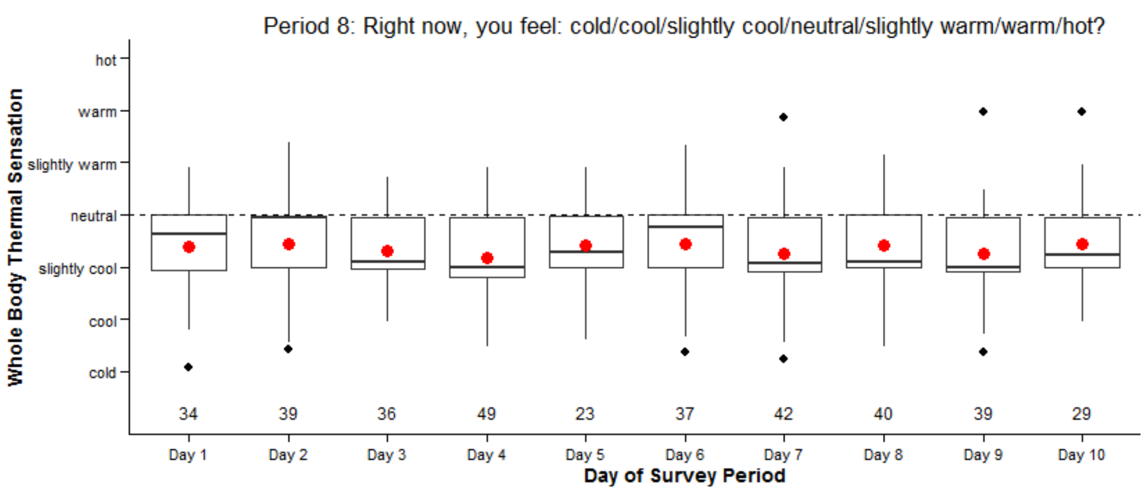

Figure 11.8-2 Period 8 Day by Day Votes: Whole Body Thermal Sensation

11.9 Period 9 Day by Day Votes (Setpoint = 68F)

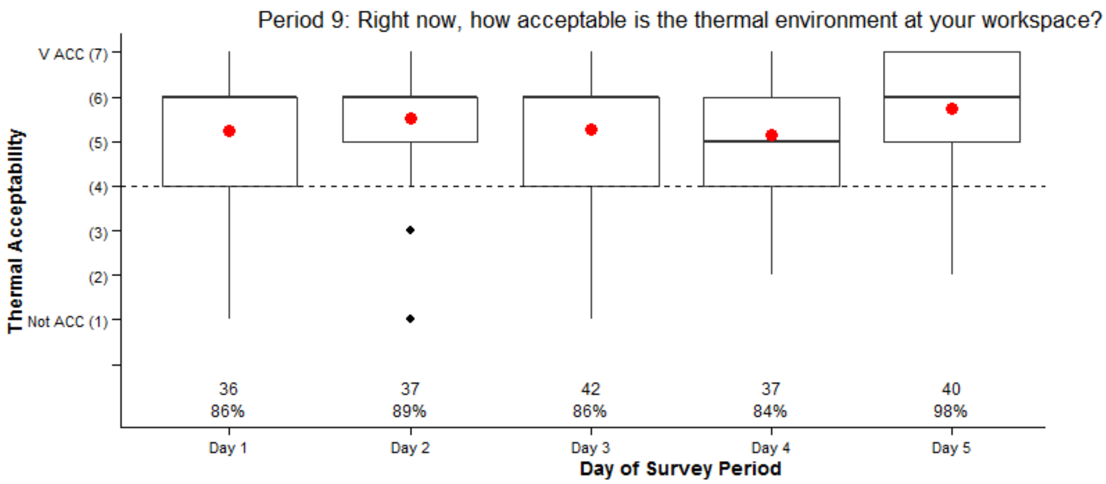

Figure 11.9-1 Period 9 Day by Day Votes: Thermal Acceptability

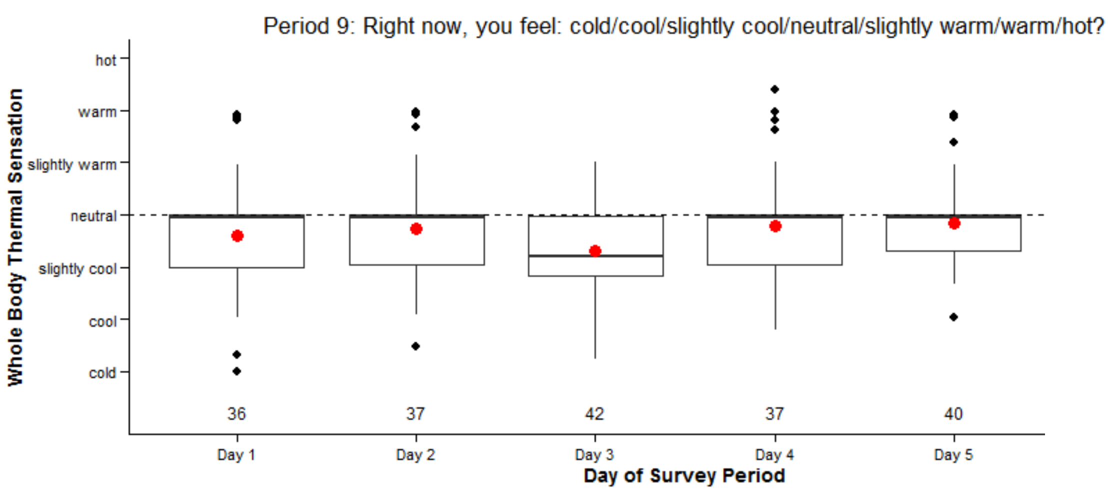

Figure 11.9-2 Period 9 Day by Day Votes: Whole Body Thermal Sensation

11.10 Period 10 Day by Day Votes (Setpoint = 70F)

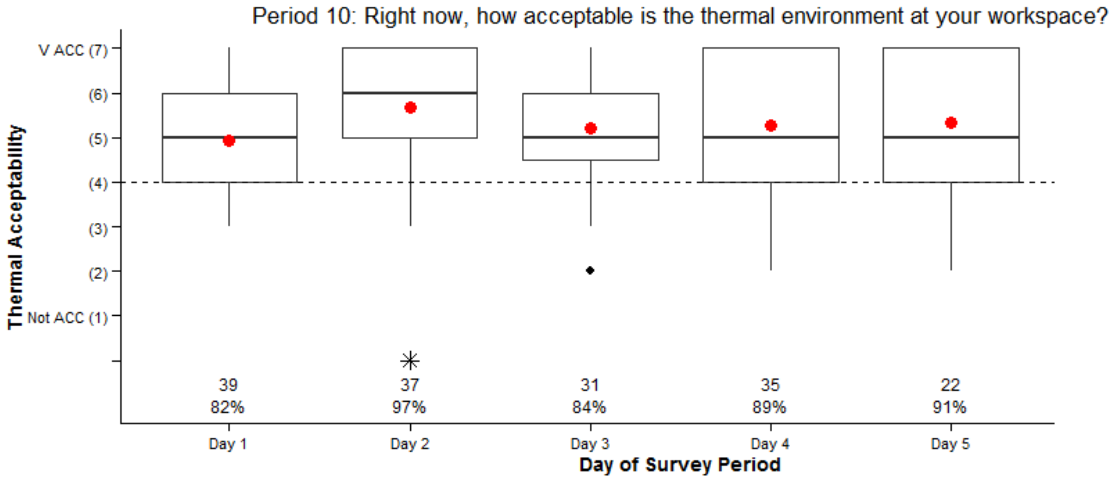

Figure 11.10-1 Period 10 Day by Day Votes: Thermal Acceptability

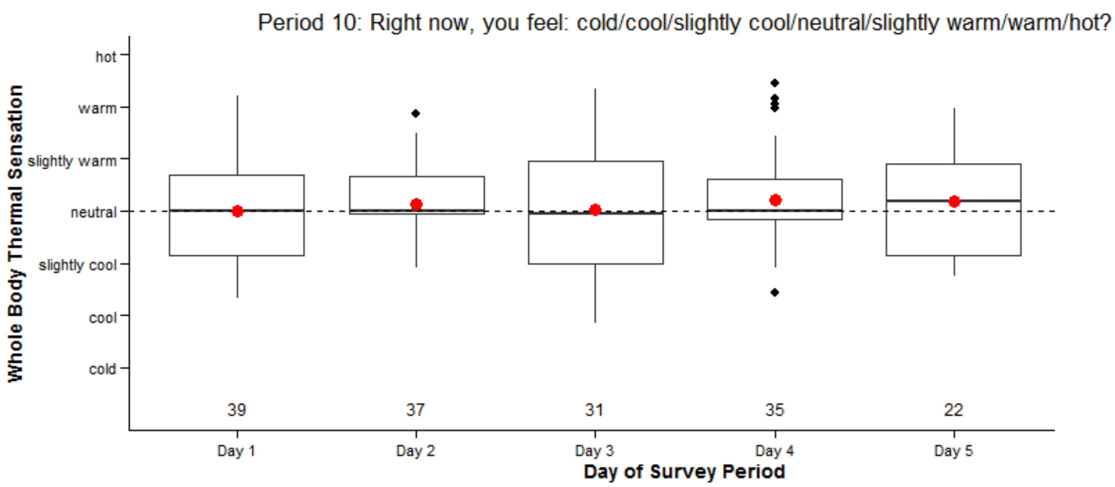

Figure 11.10-2 Period 10 Day by Day Votes: Whole Body Thermal Sensation

11.11 Period 11 Day by Day Votes (Setpoint = 70F, no PCS)

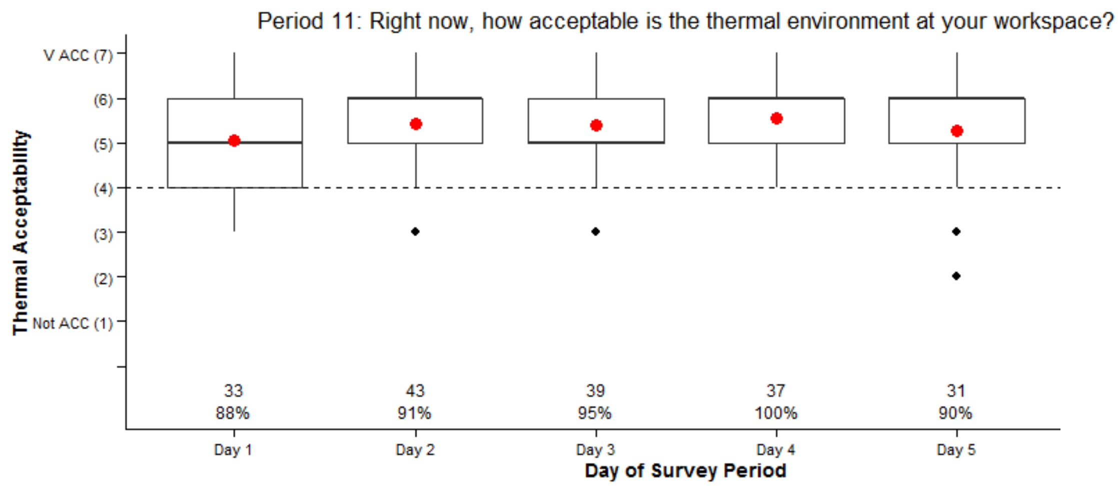

Figure 11.11-1 Period 11 Day by Day Votes: Thermal Acceptability

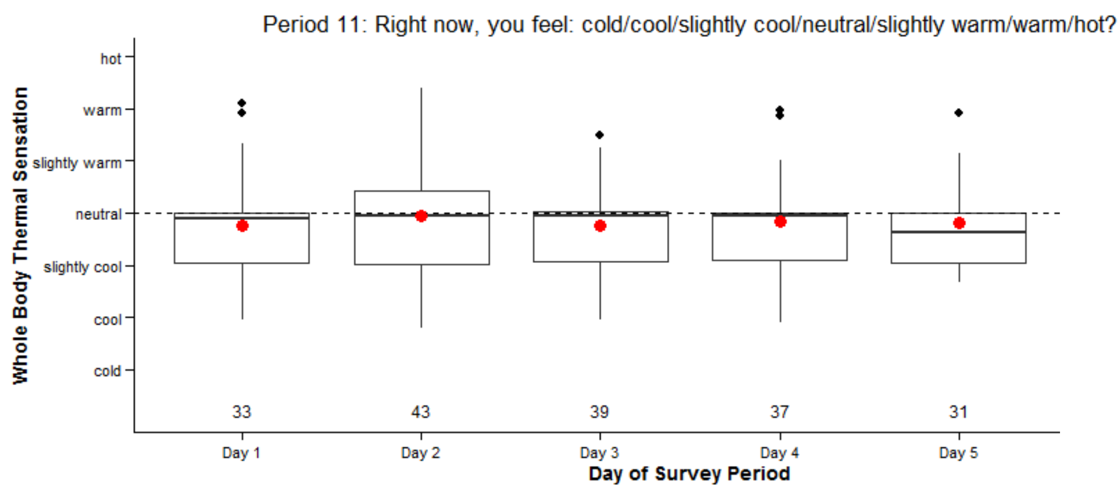

Figure 11.11-2 Period 11 Day by Day Votes: Whole Body Thermal Sensation

11.12 Period 12 Day by Day Votes (Setpoint = 70F)

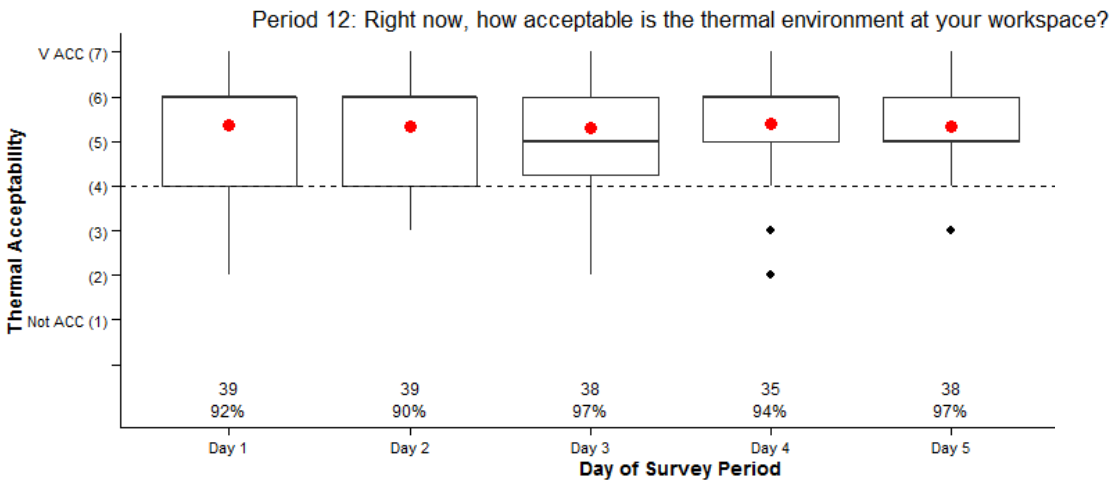

Figure 11.12-1 Period 12 Day by Day Votes: Thermal Acceptability

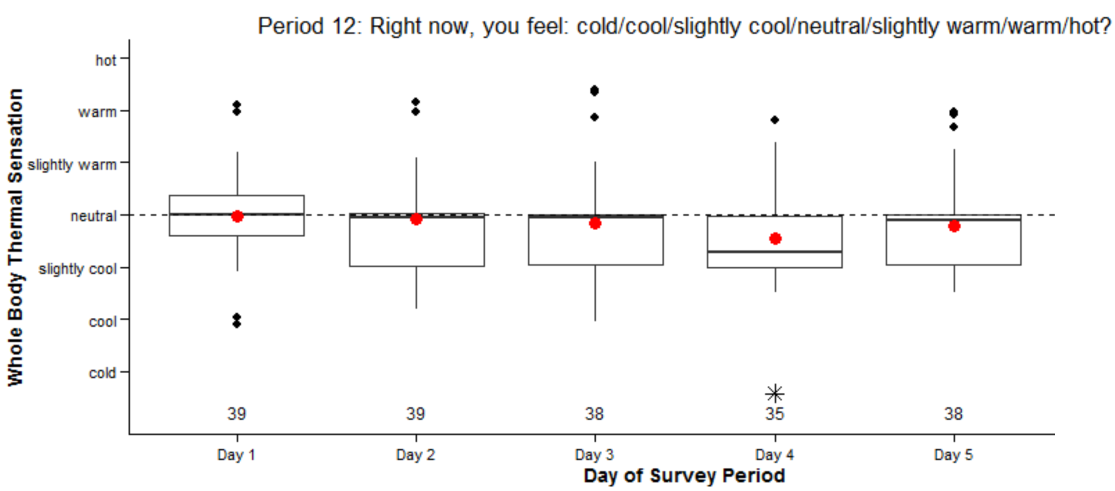

Figure 11.12-2 Period 12 Day by Day Votes: Whole Body Thermal Sensation

12. Appendix D: For each Setpoint: Right Now Survey Results by Outdoor Temperature

Notes on the following graphs:

- The "*" marks represent a statistically significant difference at a 95% confidence level between the boxplots of votes from specified outdoor temperature ranges and the boxplot of the votes during outdoor temperatures from 55 – 60F. Using the votes during outdoor temperatures 55 – 60F is the most appropriate base case as there were votes during all survey periods during these outdoor temperatures , which is also the reason why this temperature range was used to normalize the heating energy results in the energy analysis.
- The numbers without a percentage sign are the n values of each boxplots.
- In each thermal acceptability graph, the percentages are votes that are acceptable (responses of "4," "5," "6," and "7") relative to the total number of votes for each boxplot ("1," "2," "3," "4," "5," "6," and "7").
- The red dots represent the mean of each boxplot.

12.1 Setpoint 70F (no PCS)

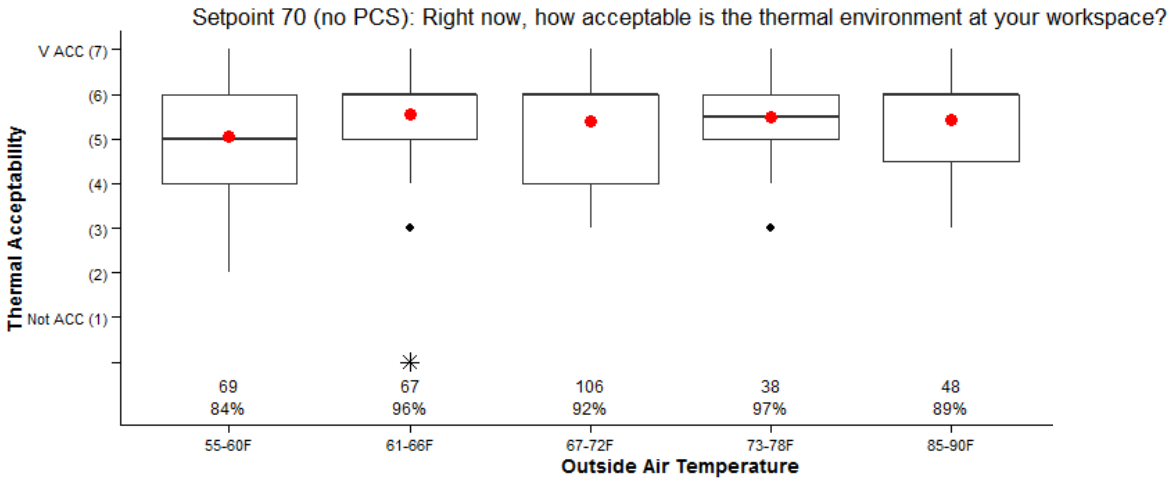

Figure 12.1-1 Votes by Outdoor Temperature (Setpoint 70F, no PCS): Thermal Acceptability

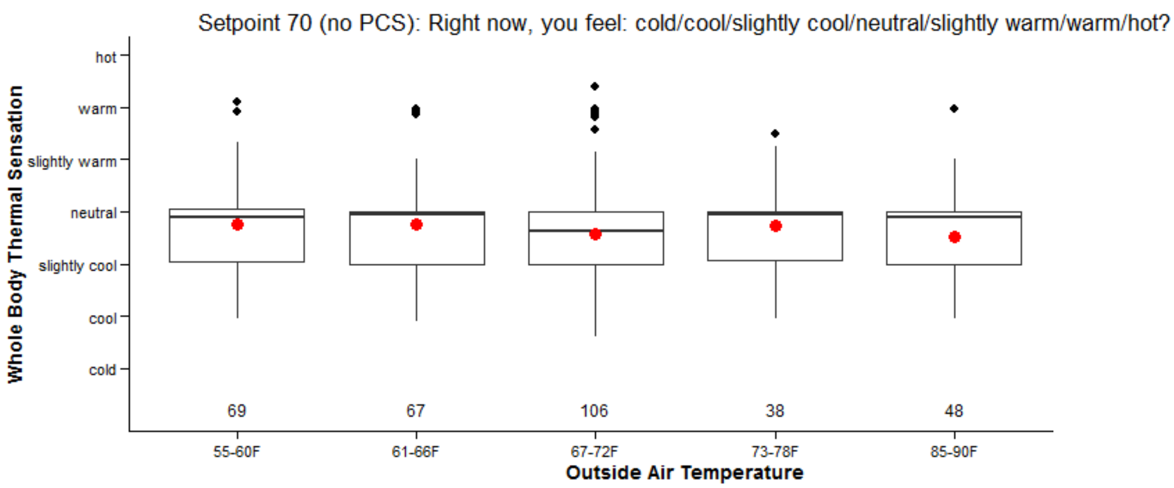

Figure 12.1-2 Votes by Outdoor Temperature (Setpoint 70F, no PCS): Whole Body Thermal Sensation

12.2 Setpoint 70F

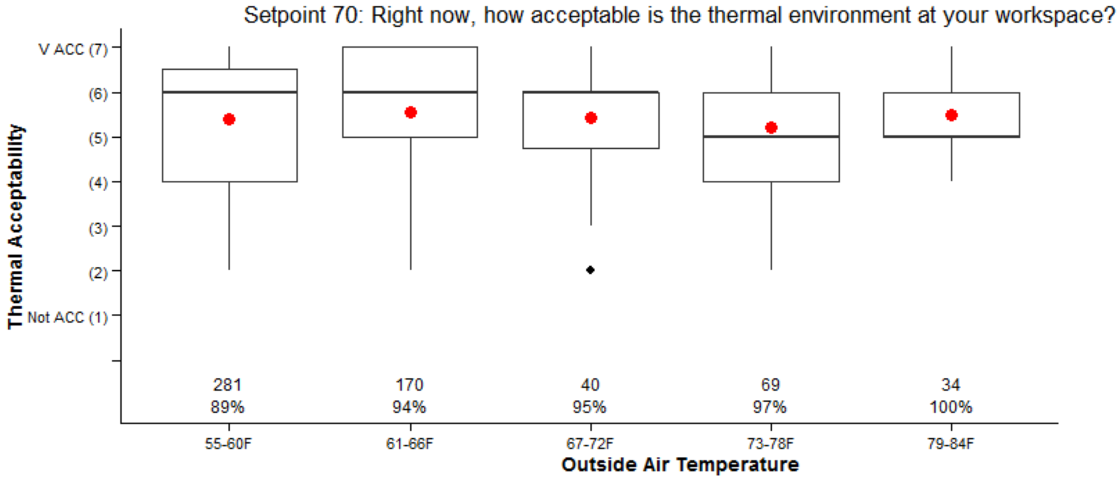

Figure 12.2-1 Votes by Outdoor Temperature (Setpoint 70F): Thermal Acceptability

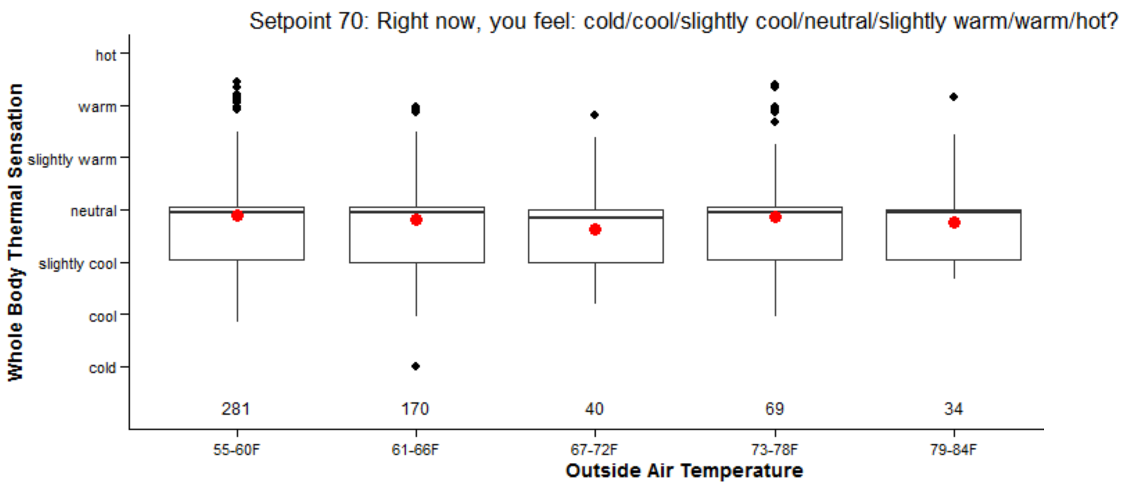

Figure 12.2-2 Votes by Outdoor Temperature (Setpoint 70F): Whole Body Thermal Sensation

12.3 Setpoint 68F

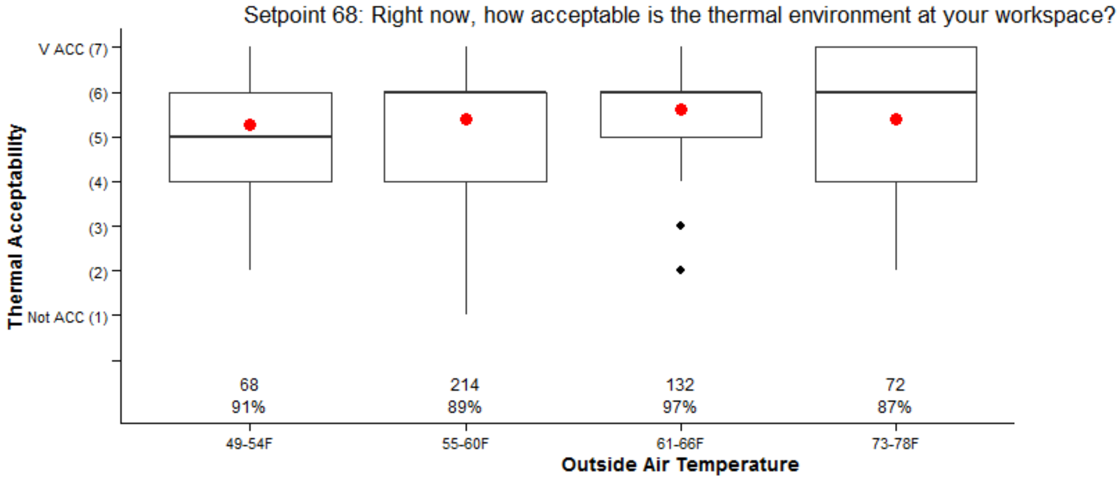

Figure 12.3-1 Votes by Outdoor Temperature (Setpoint 68F): Thermal Acceptability

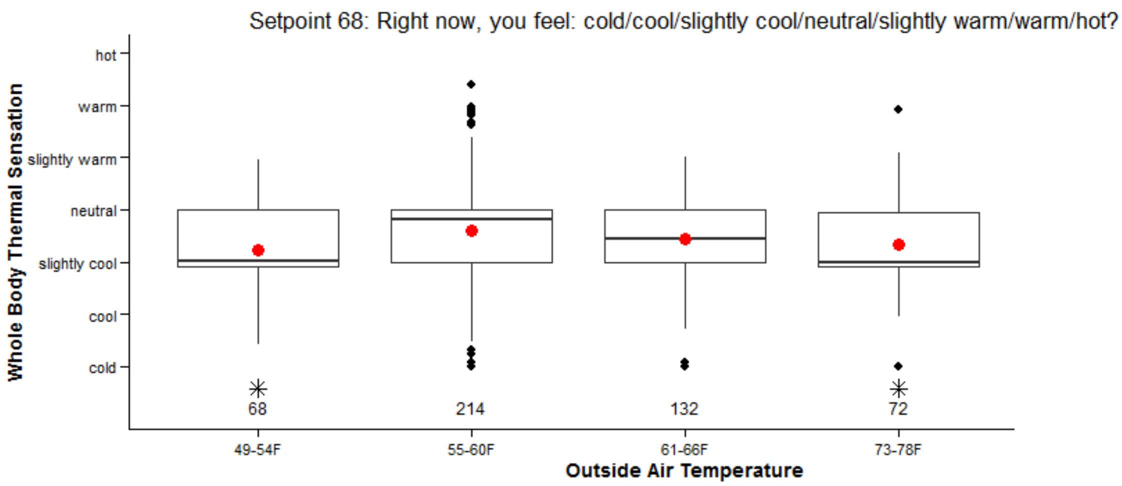

Figure 12.3-2 Votes by Outdoor Temperature (Setpoint 68F): Whole Body Thermal Sensation

12.4 Setpoint 67F

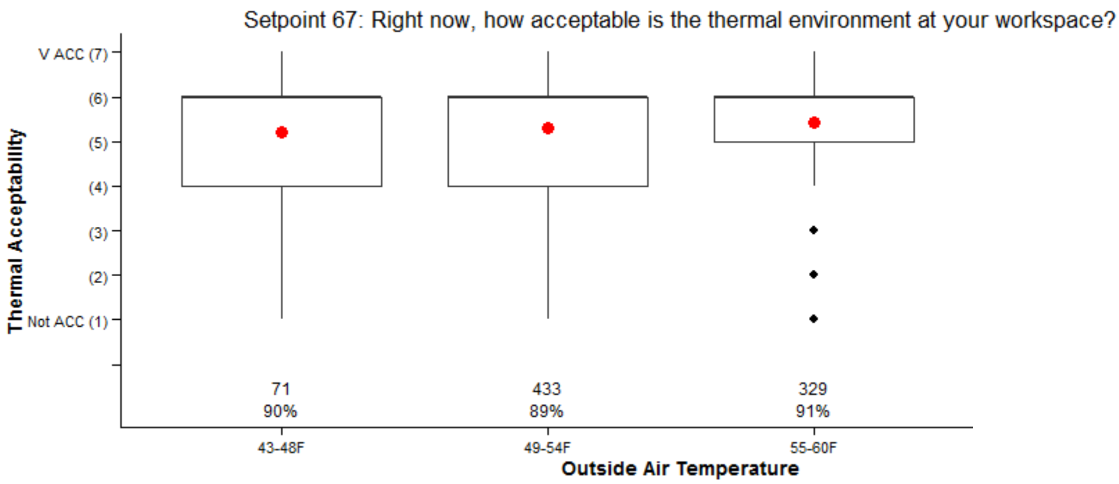

Figure 12.4-1 Votes by Outdoor Temperature (Setpoint 67F): Thermal Acceptability

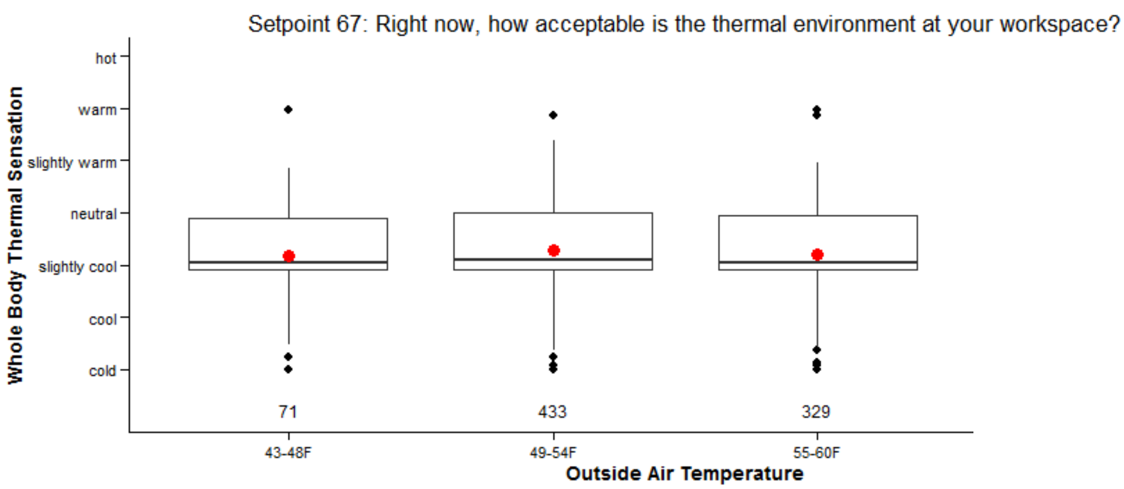

Figure 12.4-2 Votes by Outdoor Temperature (Setpoint 67F): Whole Body Thermal Sensation

12.5 Setpoint 66F

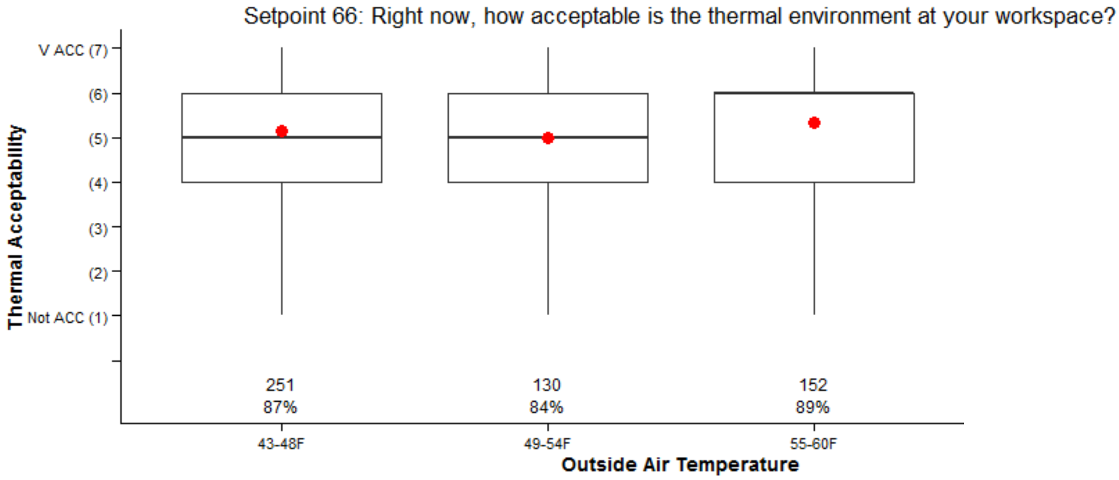

Figure 12.5-1 Votes by Outdoor Temperature (Setpoint 66F): Thermal Acceptability

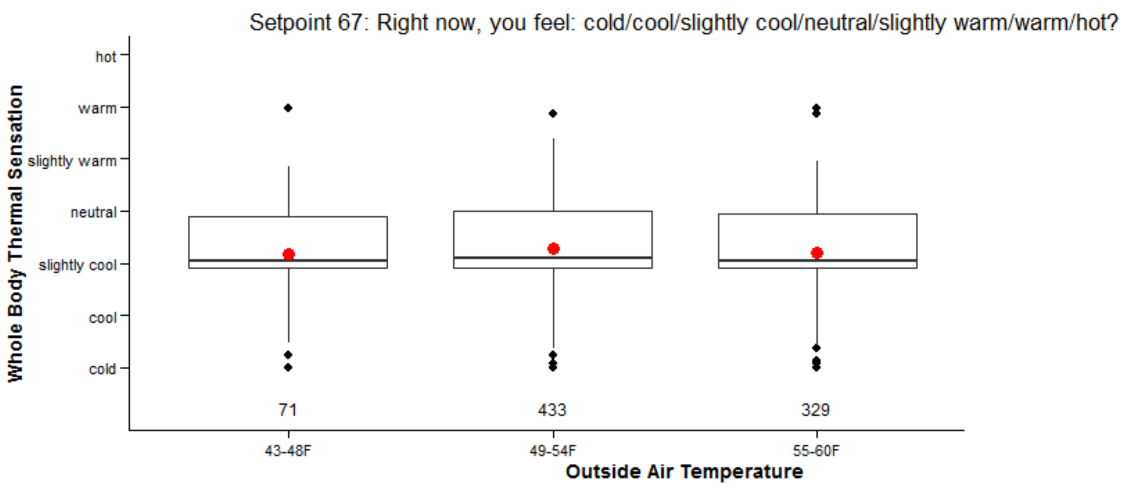

Figure 12.5-2 Votes by Outdoor Temperature (Setpoint 66F): Whole Body Thermal Sensation

13. Appendix E: Individual Workstation Results

Notes on the following graphs:

- The "*" marks represent a statistically significant difference at a 95% confidence level between the particular workstation (red boxplots) and all other workstations in the office (blue boxplots) for each survey period.
- The red numbers are the n values of the boxplots for the particular workstation and the blue numbers are the n values of the boxplots for all other workstations.
- In each thermal acceptability graph, the percentages are votes that are acceptable (responses of "4," "5," "6," and "7") relative to the total number of votes for each boxplot ("1," "2," "3," "4," "5," "6," and "7").

13.1 Workstation 1

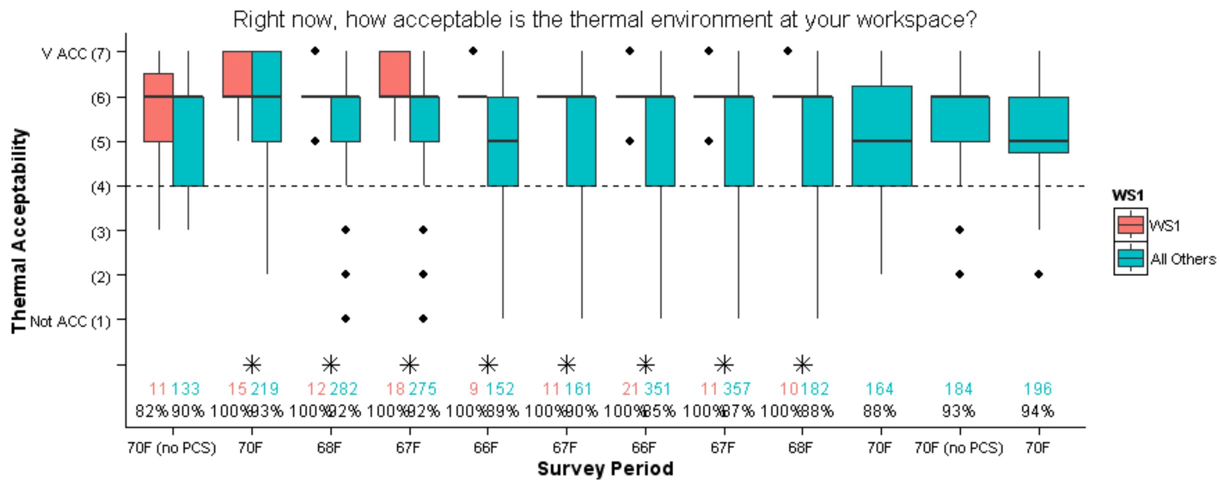

Figure 13.1-1 Workstation 1 Thermal Acceptability

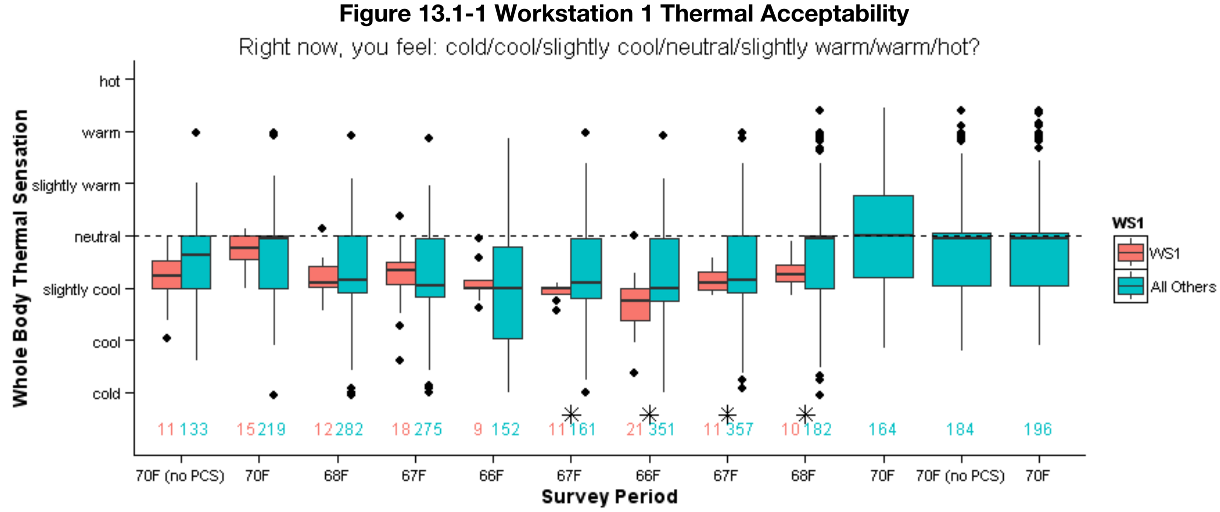

Figure 13.1-2 Workstation 1 Whole Body Thermal Sensation

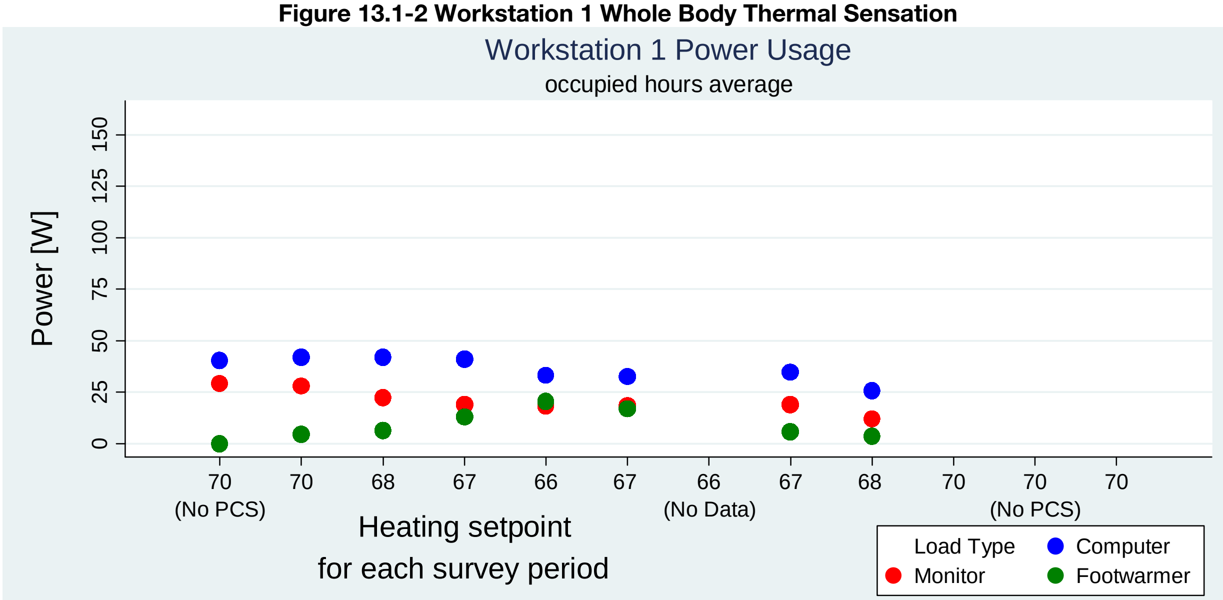

Figure 13.1-3 Workstation 1 Average Power

Workstation 1 Exit Interview Summary

3:00 pm, May 3rd, 2012

- She liked having the footwarmer, found it to provide relief from feeling cold, thought it gave more individual control, and changed the way she sat at her desk. She found the footwarmer to be most effective when sitting upright. When using the footwarmer, she had to put her feet further under the desk than she would have otherwise. She didn't use the footwarmer every day. It was a slightly negative change to have to sit with her feet deeper under the desk since she was slightly less comfortable in that position.
- During the study, she never changed her clothes or shoes. She used the footwarmer more and more as time went on, especially since she felt colder and colder as the study progressed.
- There were not specific or regular times at which the footwarmer did not keep her warm enough at her desk.
- Since she felt cold air blowing on her hands, she often wore gloves. The footwarmer was good for heating her feet but her hands were often cold.
- The footwarmer did hit her shins so she would prefer if the top was recessed a bit. She didn't like having to push her feet so far forward.
- She didn't have any thoughts about the aesthetics of the footwarmer.
- She almost never used the fan since the office was really cold. She felt that there was a lot of air circulation, which she described as blowing cold air.
- She was at her desk at least 5/6th of the day though she has occasional meetings out of the office. Before and during the study, she always felt warmer in other parts of the office.
- The thinks it is a good idea to give people fans and footwarmers. She would like to have a device to heat her hands.
- She thought the research team was friendly and responsive. She thought the candy was nice.

13.2 Workstation 2

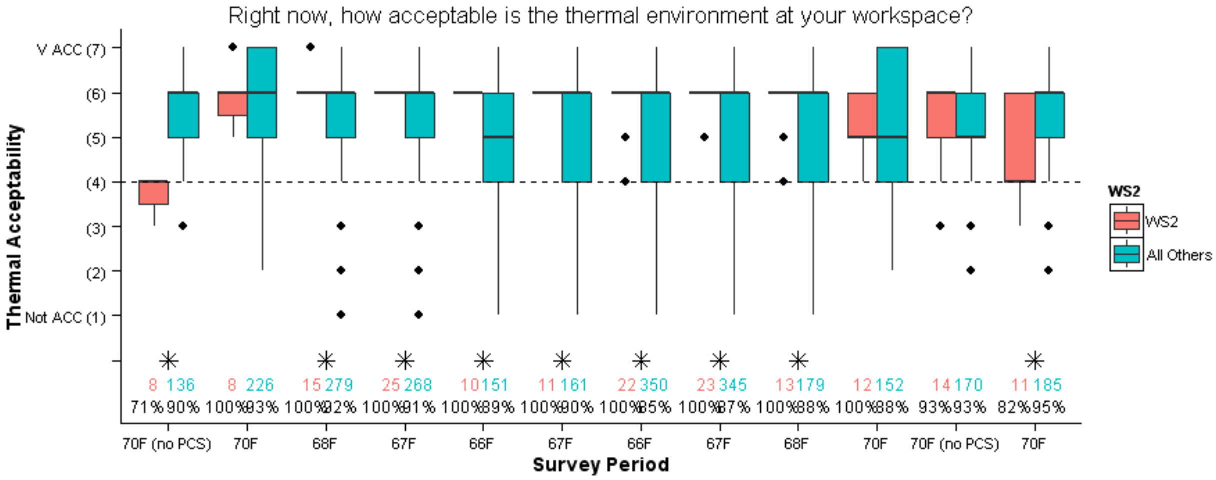

Figure 13.2-1 Workstation 2 Thermal Acceptability

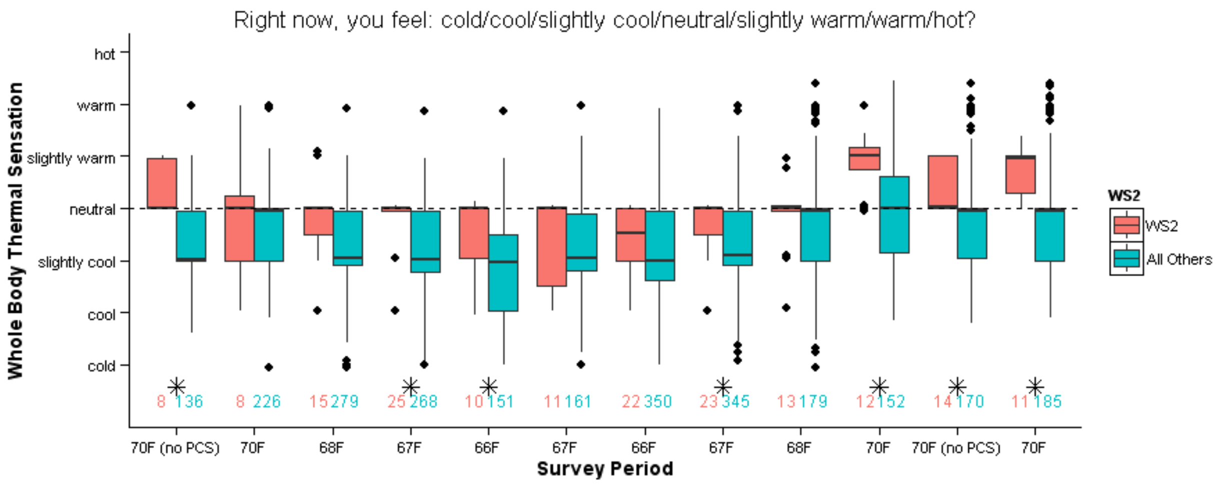

Figure 13.2-2 Workstation 2 Whole Body Thermal Sensation

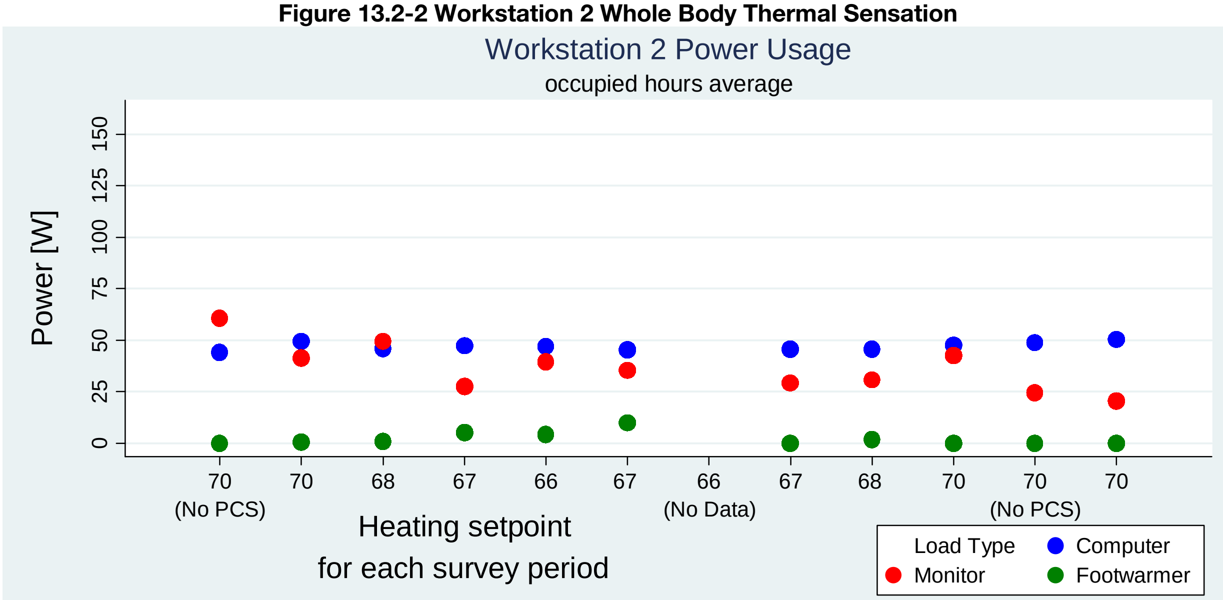

Figure 13.2-3 Workstation 2 Average Power

Workstation 2 Exit Interview Summary
10:00 am, May 9th, 2012

- Her feet are rarely cold and sometimes she is barefoot in her office. She only used the footwarmer the one or two times that her feet were cold. She has many meetings and is rarely stationary. She liked having the footwarmer because it worked well for her as a footrest. She doesn't sit upright, but this didn't seem to matter since she didn't need to use the footwarmer for warmth.
- She uses the fan every day and all day. It is almost always at the highest setting since she loves air movement. Even when she drives in the winter, she keeps the windows down (and tends to turn on the heat by the feet).
- During the winter, she used her personal fan less. Her personal fan covers more area than the PCS fan. Having a larger area is useful since she moves around her desk so much. She is rarely stationary in front of her monitor.
- The aesthetics of the fan were not an issue though she thinks it would be fun to have the fan available in different colors (she likes brightly colored things).
- The fan operates fine. It would be cool to be able to control the fan from the computer, but the nob is very easy and not a problem. The highest desk fan setting isn't strong enough for her, but she is a self-proclaimed extremist when it comes to her high desired level of air movement.
- Some days, she is in her office all day. About 1 day per week, she is at meetings in the conference room. About 2 days per week, she spends about 80% of the day outside of the office in other parts of the library.
- The conference room is stuffy with the door closed. There is no noticeable temperature difference for her in the conference room. She prefers her office to the conference room. She is generally more sensitive to air circulation than temperature.
- The rest of the library is very cold in the winters, but it the worse problem is that it is very hot in the summer. The older parts of the library are not as comfortable or nice as her office.
- The field study was great and she has a good impression of the team. She appreciated that the team was conscious not to interrupt the workday.

13.3 Workstation 3

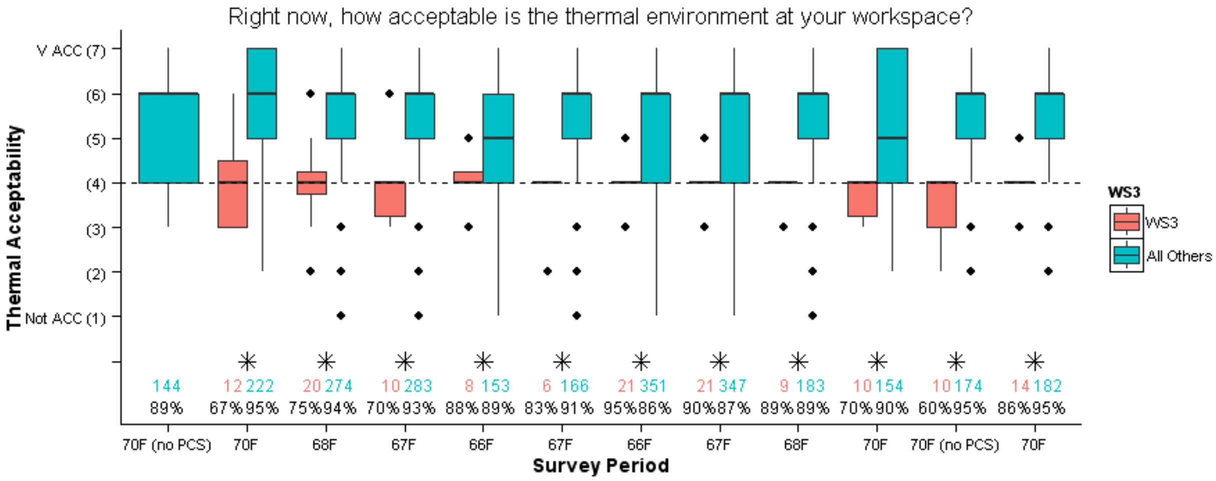

Figure 13.3-1 Workstation 3 Thermal Acceptability

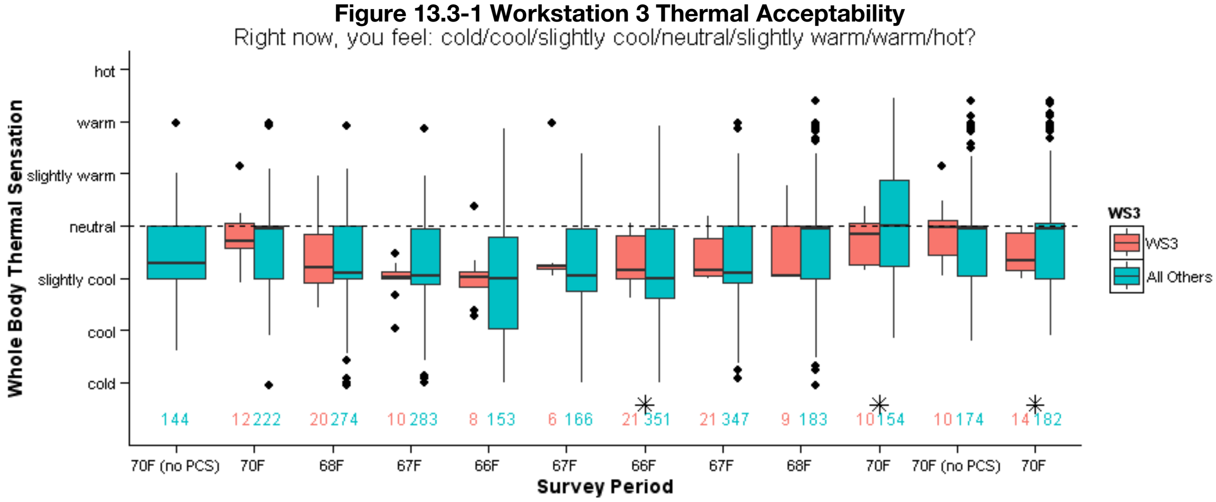

Figure 13.3-2 Workstation 3 Whole Body Thermal Sensation

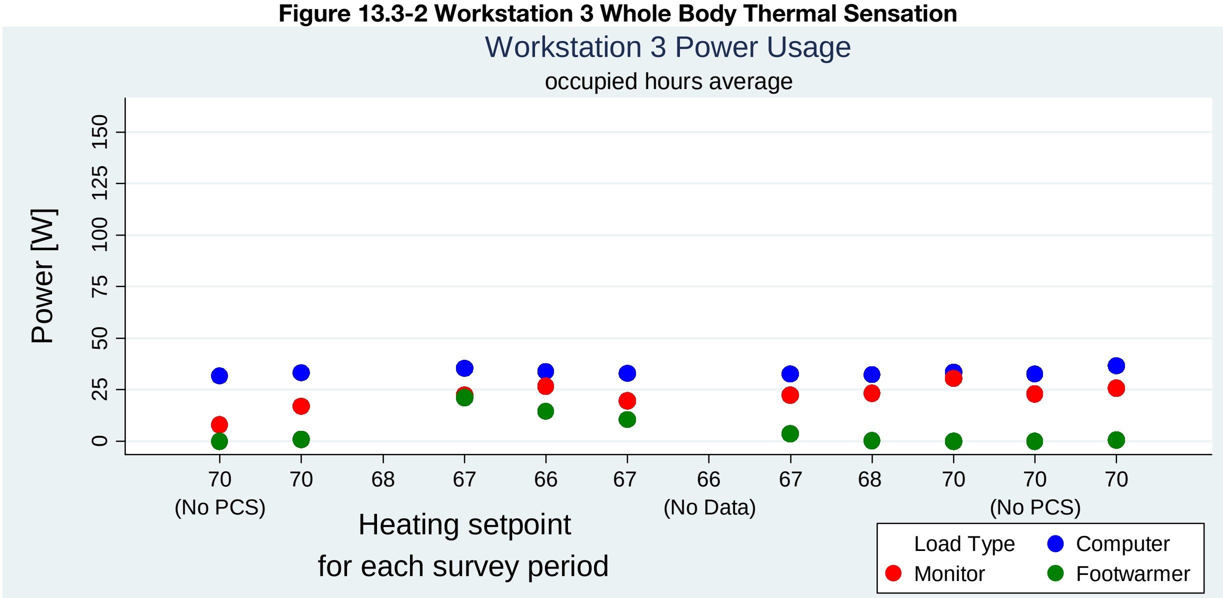

Figure 13.3-3 Workstation 3 Average Power

Workstation 3 Exit Interview Summary

2:00 pm, May 7th, 2013

- He infrequently used the footwarmer since the lip on the top made it hard to use. Also, the footwarmer would have changed his posture. He also found the heat a little uncomfortable. The main reasons why he didn't use the footwarmer was that it was uncomfortable and he found the office to be plenty warm.
- He would recommend changing the design to make it more comfortable by designing it so it doesn't hit your shins.
- He thinks that the footwarmer looks fine though it is a little big. It is under the desk so it can't be seen, so the aesthetics don't really matter.
- He used the fan for a little bit but found it annoying because it turns off if you move away. He found it distracting that the fan would start and stop. He would like to be able to override the fan so it constantly stays on. However, he doesn't particularly like fans in general.
- If the design keeps an occupancy sensor, he would prefer it to have a more forgiving delay, meaning it shouldn't turn off so quickly if it doesn't sense someone is there.
- He is almost always at his desk.
- He didn't notice a difference in his thermal comfort between when he was at his desk, elsewhere in the office, or out of the office.
- He thinks the fan and the footwarmer are good ideas but need some refining.
- The thought the study was conducted well. He didn't mind that the room was a little cold.

13.4 Workstation 5

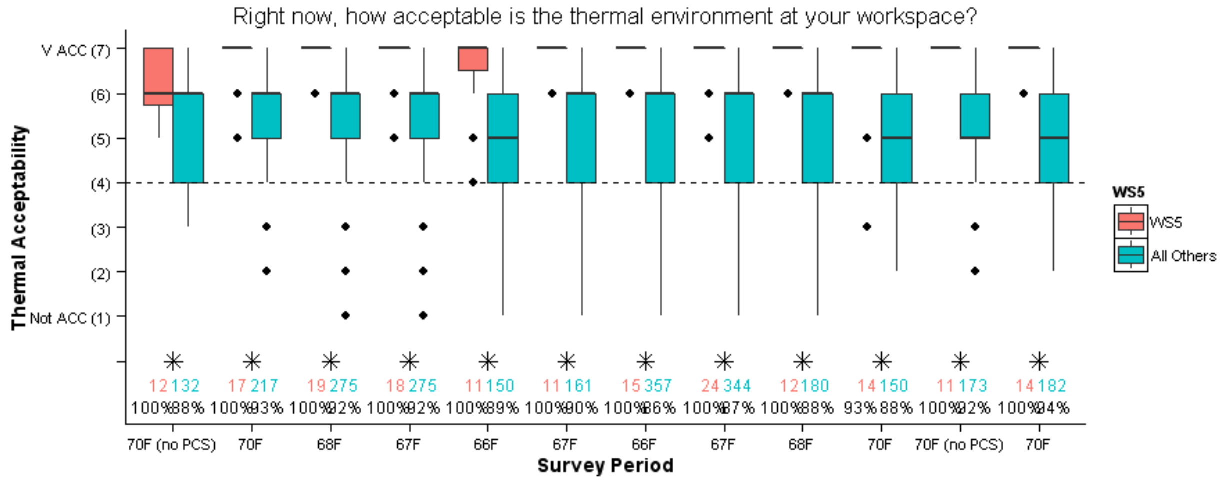

Figure 13.4-1 Workstation 5 Thermal Acceptability

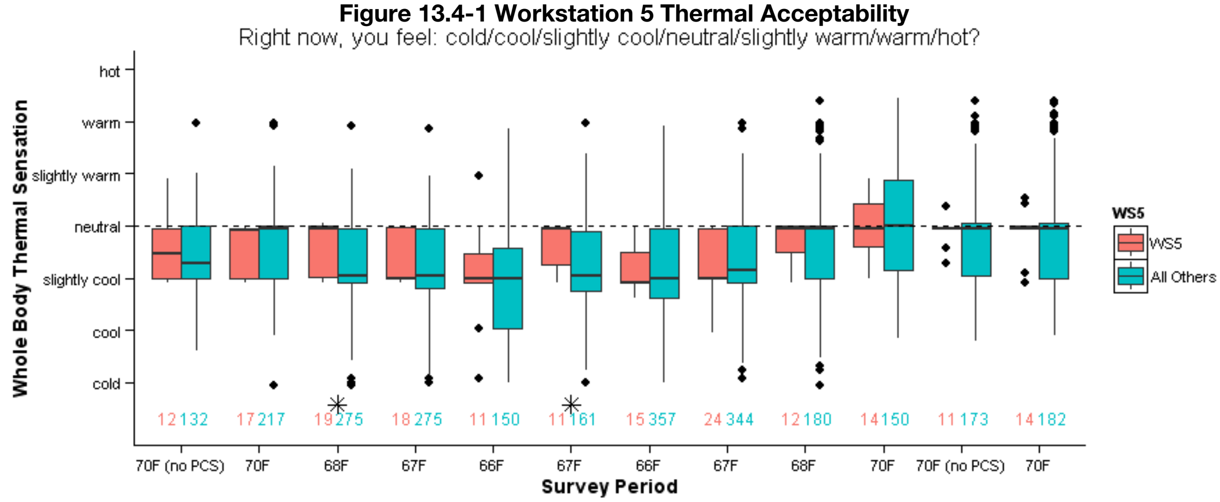

Figure 13.4-2 Workstation 5 Whole Body Thermal Sensation

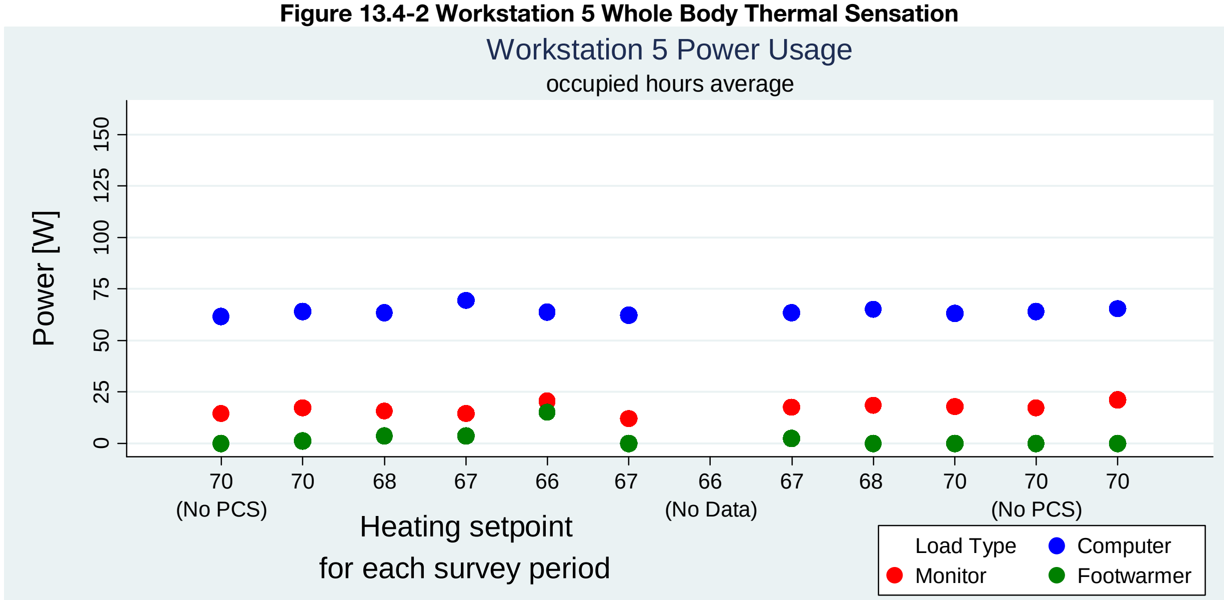

Figure 13.4-3 Workstation 5 Average Power

Workstation 5 Exit Interview Summary

10:30 am, May 16th, 2013

- She did not use the footwarmer every day. She only used the footwarmer when her feet were cold. Sometimes her feet felt ok using the footwarmer but here hands were still cold. She found that warming her feet did not heat her hands or the rest of her body. She only used the footwarmer during the winter. In January and February, it was just too cold even when wearing fingerless gloves. She said it was 67F in the office during those months.
- The upper part of the footwarmer made it difficult for her to get her feet into the footwarmer. She liked that the footwarmer doubles as a footrest.
- Aesthetically, she thought that the footwarmer looked better before the insulation was added. The insulation was not well secured and it moved around.
- She has used the fan, but she does not use it often. She used the fan when there was not very much air circulation or when it was stuffy, which was often in the mornings.
- She liked having the desk fan and the feeling of air movement. The fan provided relief from feeling warm, improves air quality (reduces stuffiness), and gives more individual control. She likes that the fan is quiet. She thinks that the maximum setting is fine as she typically uses the fan at 25% power.
- She used the fan less in the winter and has used it the most in the last month. She is not often hot so she does not frequently use the fan.
- She is at her desk 80 – 85% of the time. The rest of the time, she usually has meetings in the office.
- She thinks her desk is cold so she appreciates having individual control over a heating element.
- The conference room is generally cold.
- She thought that the study was well executed and very accommodating. She liked the gift certificates.

13.5 Workstation 6

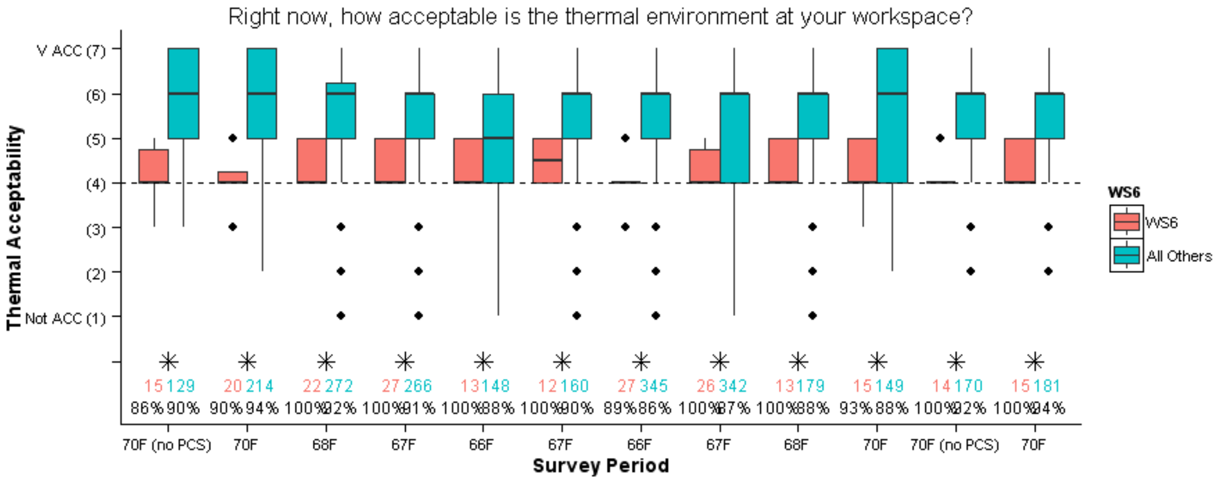

Figure 13.5-1 Workstation 6 Thermal Acceptability

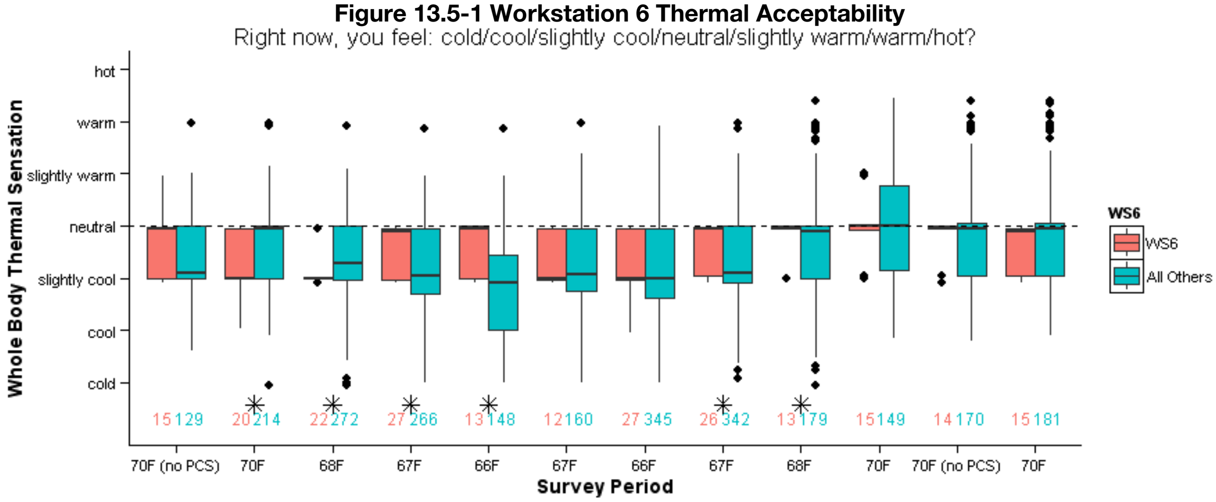

Figure 13.5-2 Workstation 6 Whole Body Thermal Sensation

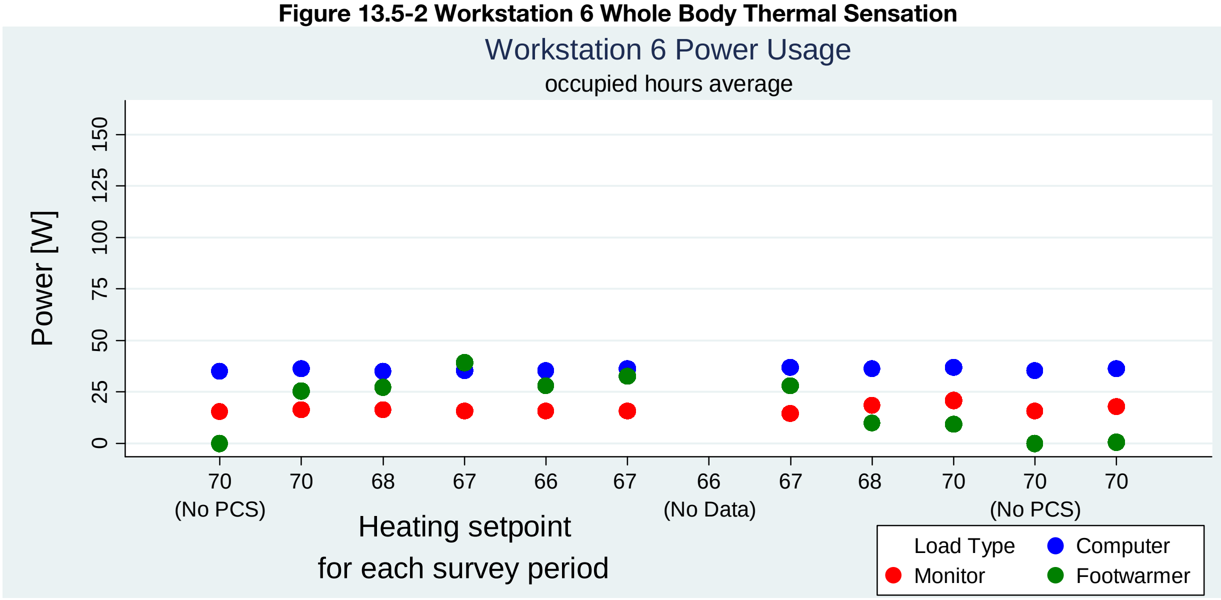

Figure 13.5-3 Workstation 6 Average Power

Workstation 6 Exit Interview Summary
9:15 am, May 9th, 2013

- He loved the footwarmer and it provided relief from feeling cold. He never needed to have the footwarmer on the maximum setting. He typically kept it at half power and removed his shoes.
- Besides taking his shoes off to use the footwarmer, he didn't change anything any other before during the study.
- When he left his desk, his feet would cool down and then he was more aware of the cold.
- There were not specific or regular times in which the footwarmer did not keep him warm enough at his workstation.
- As far as suggestions for how the footwarmer operates, he said that the reflector frequently slipped out and it needs to be better attached. There were a few times when the footwarmer did not turn off. When that happened, he simply unplugged and the replugged the device to solve the problem.
- He doesn't have any suggestions to change the aesthetics of the footwarmer as the aesthetics were not an issue for him.
- He did not use the fan except for once or twice at the very beginning of the study. He never felt warm in the office, but more importantly he generally dislikes having air movement around his face. He prefers still air unless it is really hot, which is never the case in the office. He sometimes used the fan to cool down his tea.
- Before and during the study, the private offices and the conference room were cooler than everywhere else in the office.
- He is at his desk about 95% of the time, with the other 5% primarily being meetings within the office.
- He felt that participating in the study was easy and that everyone in the office was treated well. He liked getting the gift certificates.
- In the survey, he thought the question "how do your feet feel" was awkward if he was not using the footwarmer. If he was not using the footwarmer, he always answered neutral.

13.6 Workstation 7

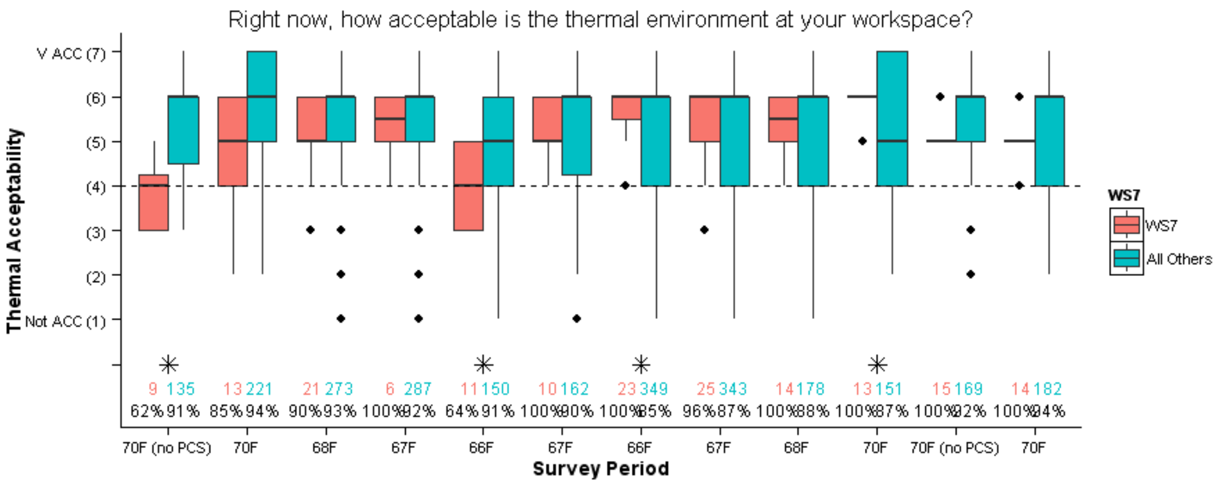

Figure 13.6-1 Workstation 7 Thermal Acceptability

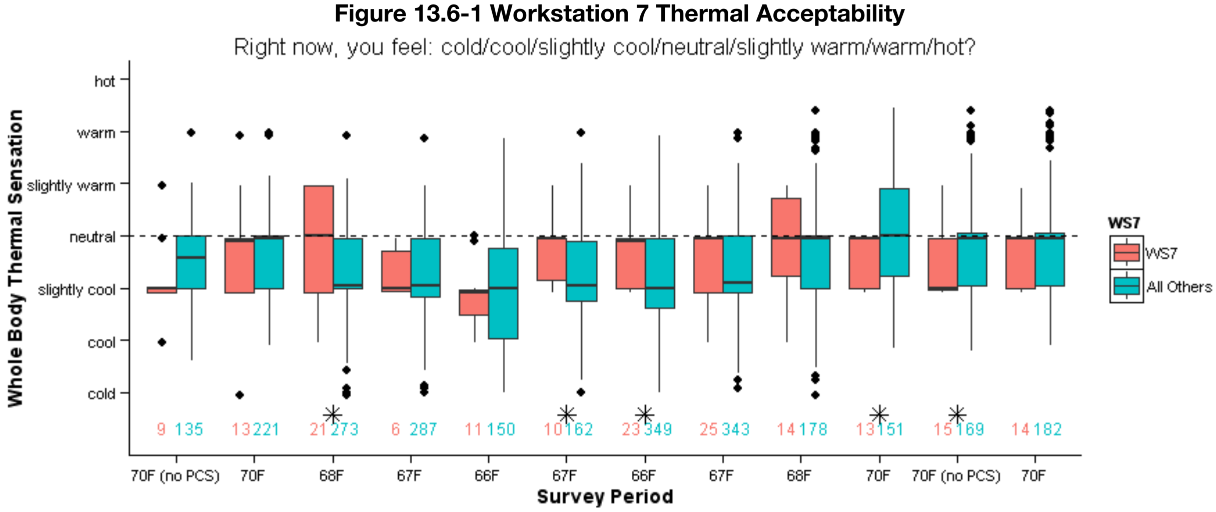

Figure 13.6-2 Workstation 7 Whole Body Thermal Sensation

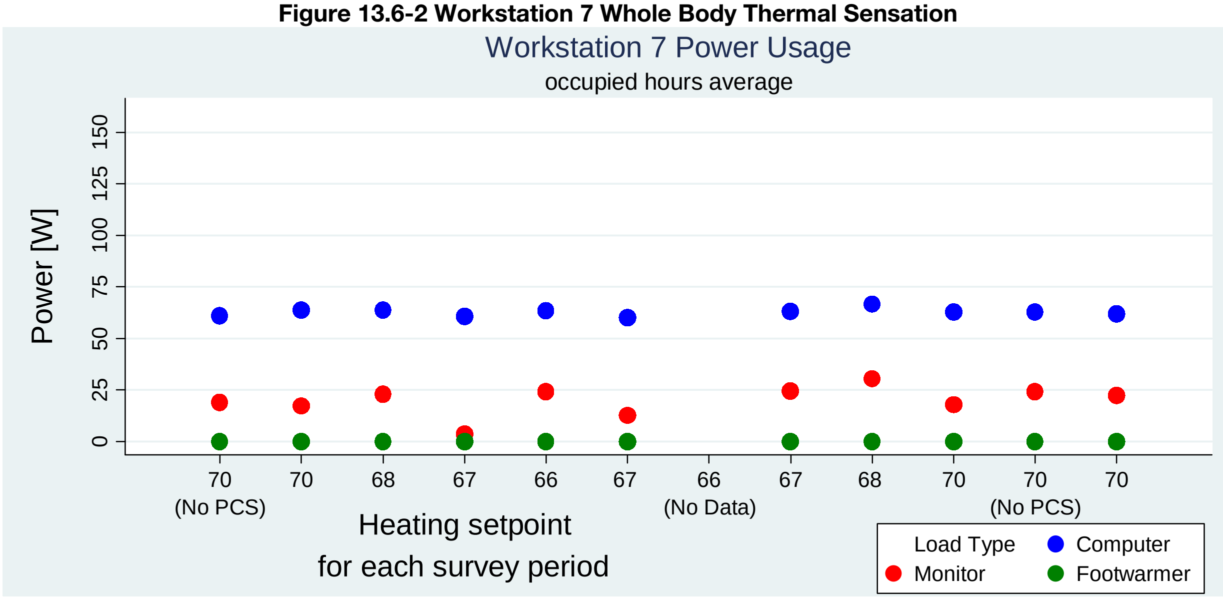

Figure 13.6-3 Workstation 7 Average Power

Workstation 7 Exit Interview Summary
3:15 pm, May 7th, 2013

- She used the footwarmer. If the room was too cold, it did not provide enough relief. It changed her posture though she generally liked having the footwarmer. She is short and previously used a footrest. It is ok to have the footwarmer on a stand, though it isn't ideal (neither was the previous set up). The footwarmer is a bit far under the desk but she hasn't tried moving it in.
- She liked the footwarmer more throughout the study, though she doesn't use it every day.
- When the room was cold, she needed a jacket though it was nice to have warm feet. The temperature seems to drop on Friday afternoons. There were some specific times when the room was too cold and the fotowarmer was not enough. The wall thermostat sometimes dropped below normal. She felt that the thermostat wasn't always accurate and that it sometimes was colder than it said. She thinks it is significantly warmer out of the office.
- The footwarmer never hit her shins. It might help if it were on an adjustable stand to change the height. She thinks that people don't want to give up the footwarmer and her sense is that people like them. She thought that the reflective insert needed to be better secured. She doesn't care about the aesthetics of the footwarmer. It's a bit humorous and looks like a 50s sci-fi piece, but it's not a problem. never turned on the footwarmer or the fan to their max setting. This might have changed if the software was working that allowed users to see their setting on their monitor. There were a few times when the footwarmer didn't turn on.
- She used the fan in the beginning of the study, but then the room got colder and she stopped using it. She likes having the fan as an option. The office gets stuffy so a little air movement is nice and can provide a little relief if she is feeling sleepy. It provides relief from feeling hot, though it is rarely hot in the office. She likes that the fan and the footwarmer provide more individual control, which she finds counterbalances differences in people's comfort. She used the fan less and less as the study progressed as outdoor temperatures dropped.
- She thinks the maximum setting of the fan is fine. She grew up in the desert with air conditioning, which is less desirable because it dries. She would prefer to be able to open windows though having a sealed façade does prevent pollen from getting inside. They used to be able to open windows but now it's not allowed (not possible). The fan does provide some relief from the feeling of being indoors. She doesn't have any thoughts to change the fan design.

- When going into the conference room, she brings a jacket and a warm drink. Spaces outside of the office are warmer and sometimes too warm (especially when it is really hot outside). However, she is rarely out of the office.
- If having the footwarmer and the fan save energy, then she thinks the study is good. If they increase energy, then the devices are not so great. She is curious if there was an environmental impact / benefit to being able to have individual control. She thinks that it is generally good to be able to control the temperature at your desk.
- She thought the study was well executed.

13.7 Workstation 8

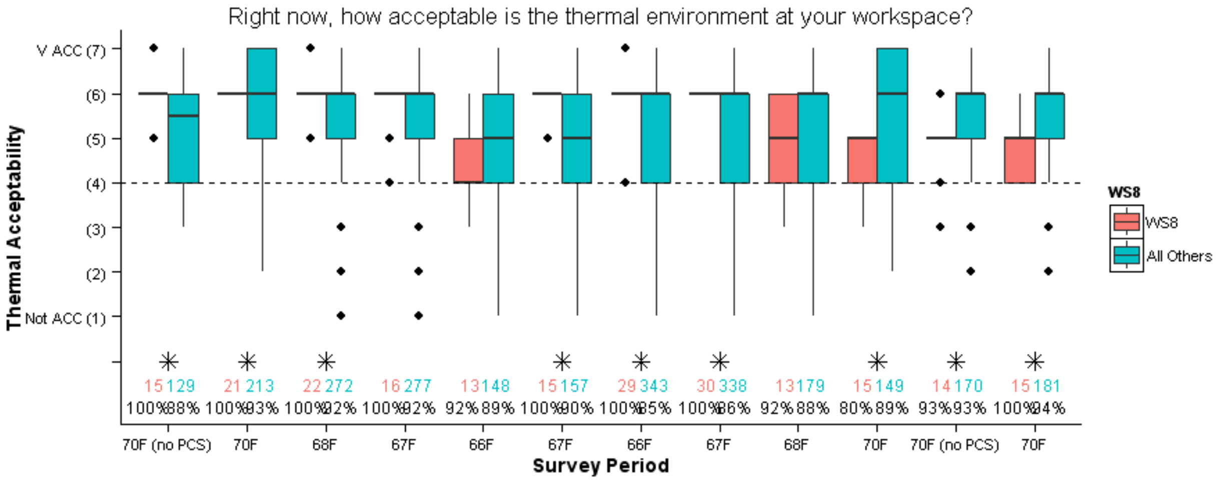

Figure 13.7-1 Workstation 8 Thermal Acceptability

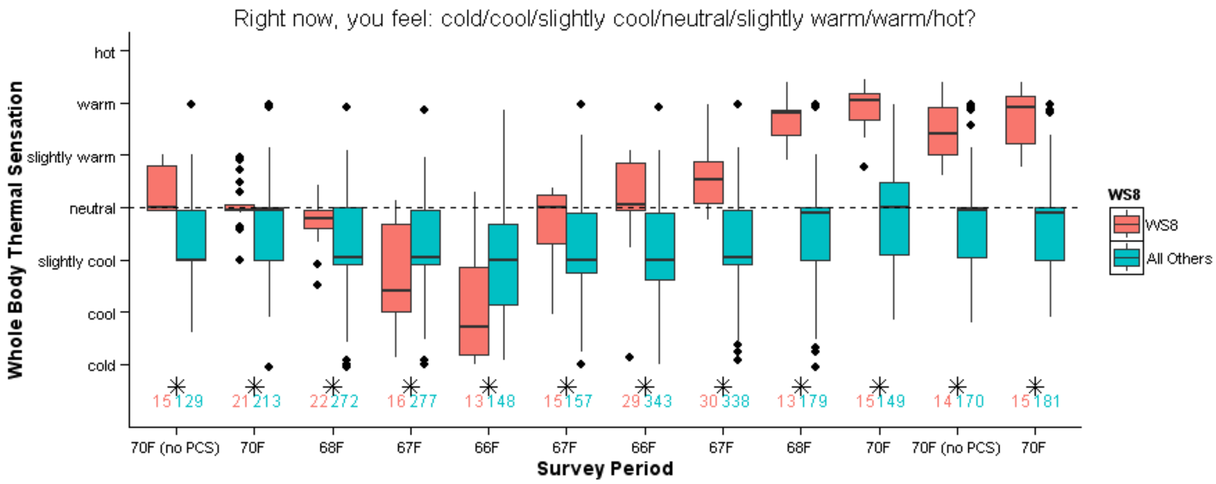

Figure 13.7-2 Workstation 8 Whole Body Thermal Sensation

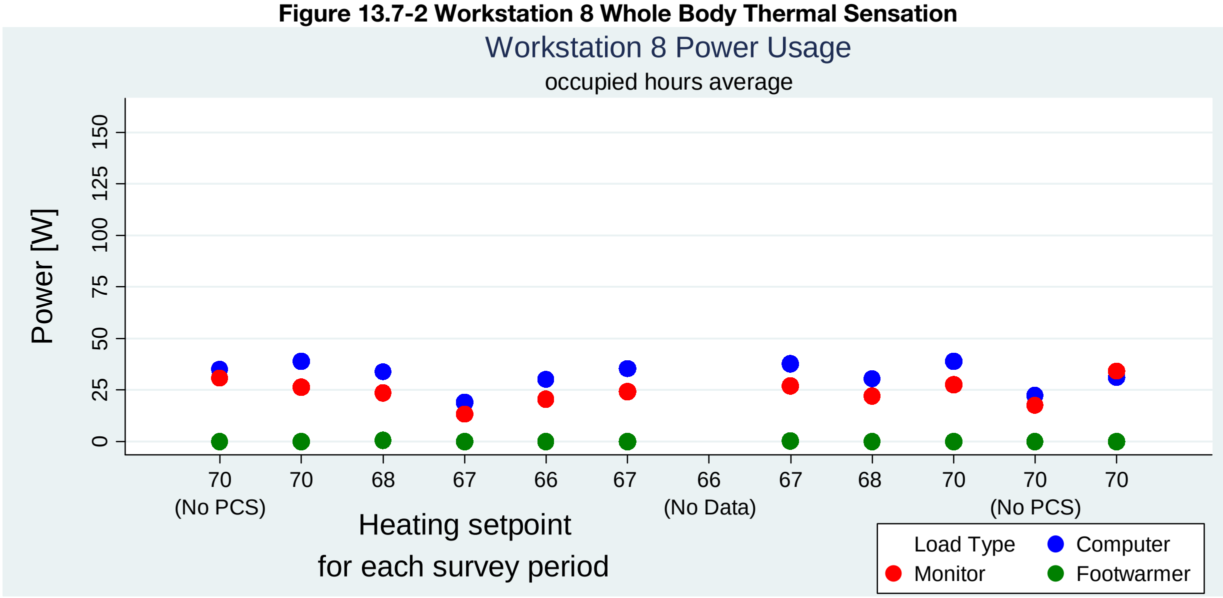

Figure 13.7-3 Workstation 8 Average Power

Workstation 8 Exit Interview Summary

3:00 pm, May 7th, 2013

- She didn't use the footwarmer. She had a heater in the past that caused her to have dry skin. She also didn't like that you had to press down to use the footwarmer since she is prone to muscle problems.
- She didn't use the fan because it dries her sinuses. The one time she tried using it, she got a headache within half an hour of using it.
- She is always t her desk except for breaks and occasional meetings.
- She arrives around 7:15 and it was often very cold at that time in the winter. It can also be very stuffy when it is warm outside (the warmer it is outside, the stuffier the office feels).
- She is concerned for people who don't use the devices if everyone else likes the devices since she can't use them for health reasons.
- She thought the study was easy to participate in.
- If the fan isn't pointed right at you, it doesn't turn on (she would change that). She doesn't want the air movement right at her face since she has sensitive skin. She might use the fan if you could override the sensor to keep it on if it isn't pointed right at you.

13.8 Workstation 9

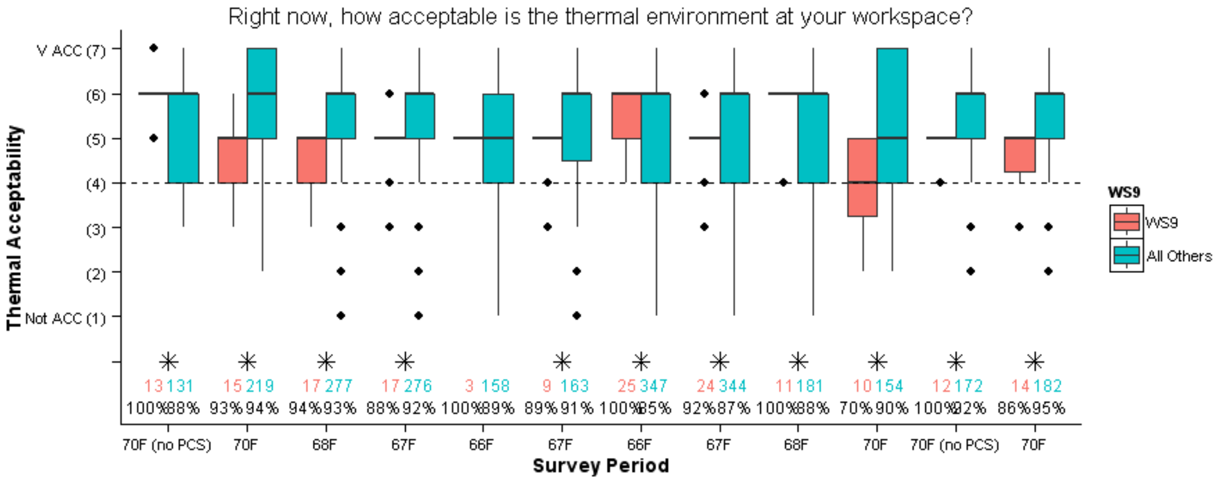

Figure 13.8-1 Workstation 9 Thermal Acceptability

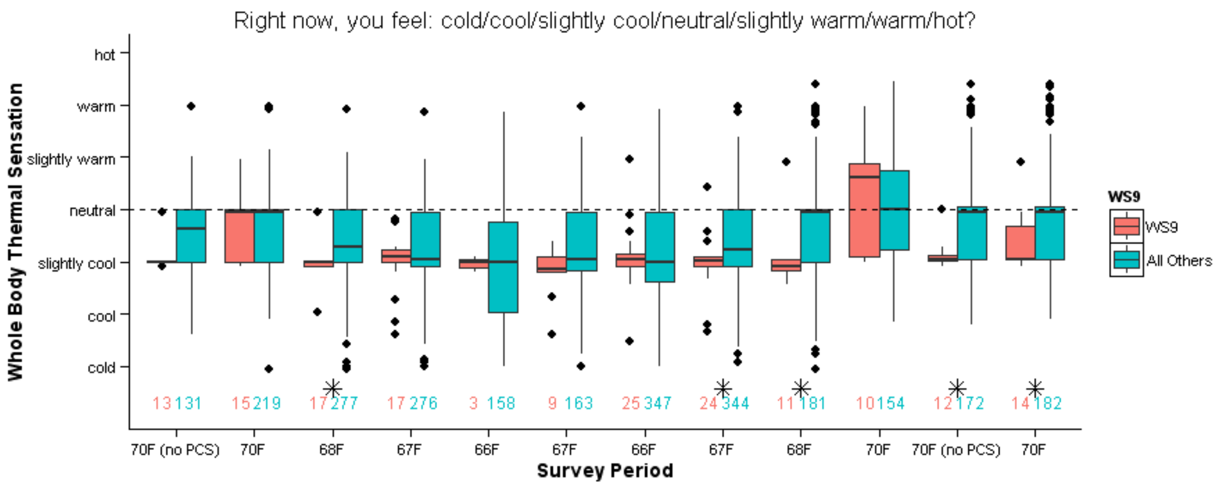

Figure 13.8-2 Workstation 9 Whole Body Thermal Sensation

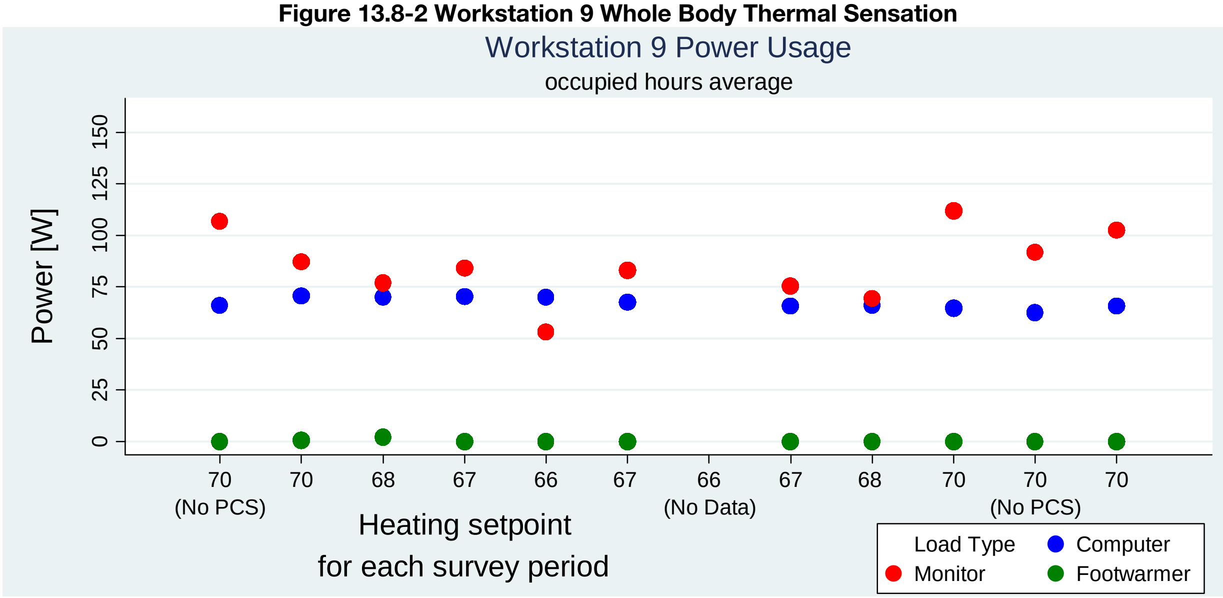

Figure 13.8-3 Workstation 9 Average Power

Workstation 9 Exit Interview Summary

10:15 am, May 16th, 2013

- She only used the footwarmer once and she used it on a cold day. Other than that, she is not cold in the office but she also didn't like the way it made her feet feel. She thought that the footwarmer broiled her feet and didn't warm the rest of her body.
- As far as suggestions for how the footwarmer operates, she thought the added foam guard for her shins did help but she still didn't end up using the footwarmer. Since she doesn't use the footwarmer, it is in her way and is a little high for a footrest. She might be more apt to use a footwarmer if the heat was provided by hot air. In general, she found the footwarmer to be a very large piece of equipment that might be limiting elsewhere.
- She didn't find the desk fan powerful enough so she used a personal fan. She now only uses her personal fan.
- The aesthetics of the fan are ok. The main problem of the fan is that it is not powerful enough.
- She is at her desk 90% of the time. The rest of the time, she is in the conference room or at meetings outside of the office.
- She feels that it is cooler in the hallway and is hotter closer to where she sits. At meetings during the conference room, the temperature starts out o but then it sometimes gets too hot or too cold. It usually gets too cold by the end of meetings in the conference room so she brings a jacket to most meetings.
- She thinks the air quality is horrifying in the office. The smell is a big issue and most of the smell is coming from people. Regarding smell, she complained about the smell coming from food at people's desks and overall hygiene. She has the sense that air is not ventilated out of the office. Even though there is an air filter next to her desk, there is still an odor issue.
- She thought that the gift cards were generous and great. The survey software was a little clunky. She thought that the surveys were not excessive or intrusive.

13.9 Workstation 11

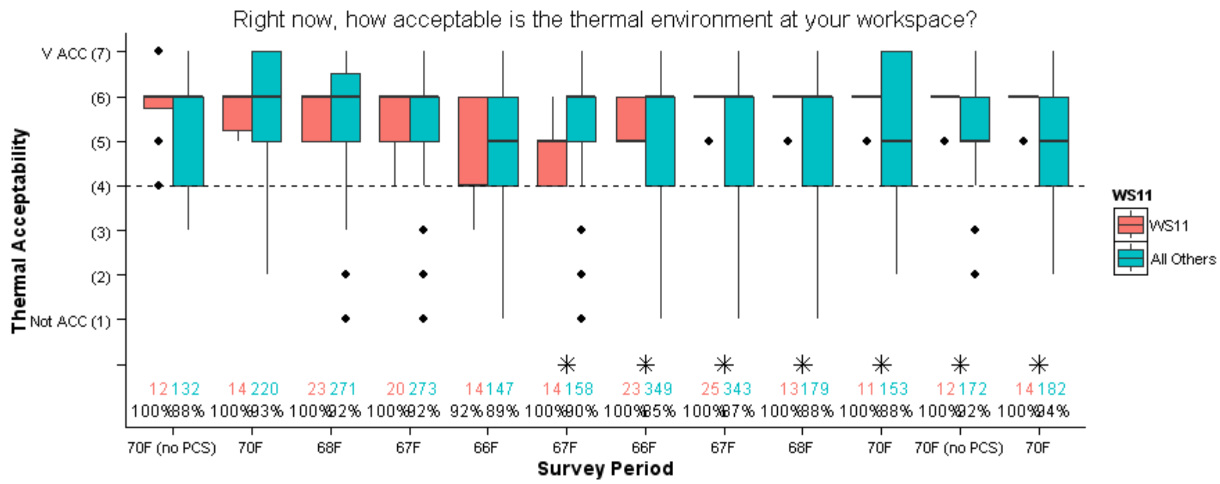

Figure 13.9-1 Workstation 11 Thermal Acceptability

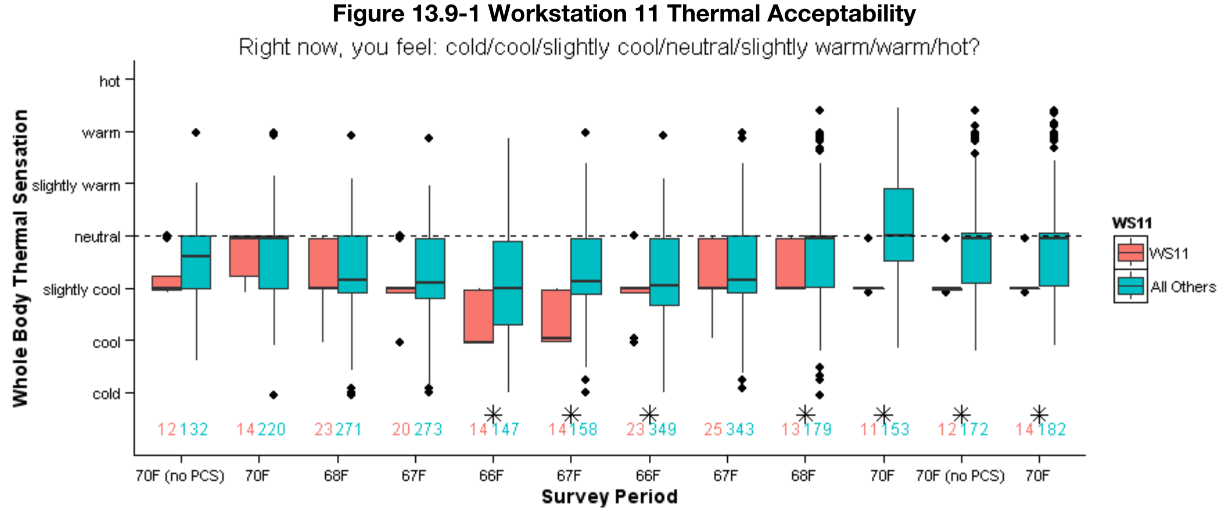

Figure 13.9-2 Workstation 11 Whole Body Thermal Sensation

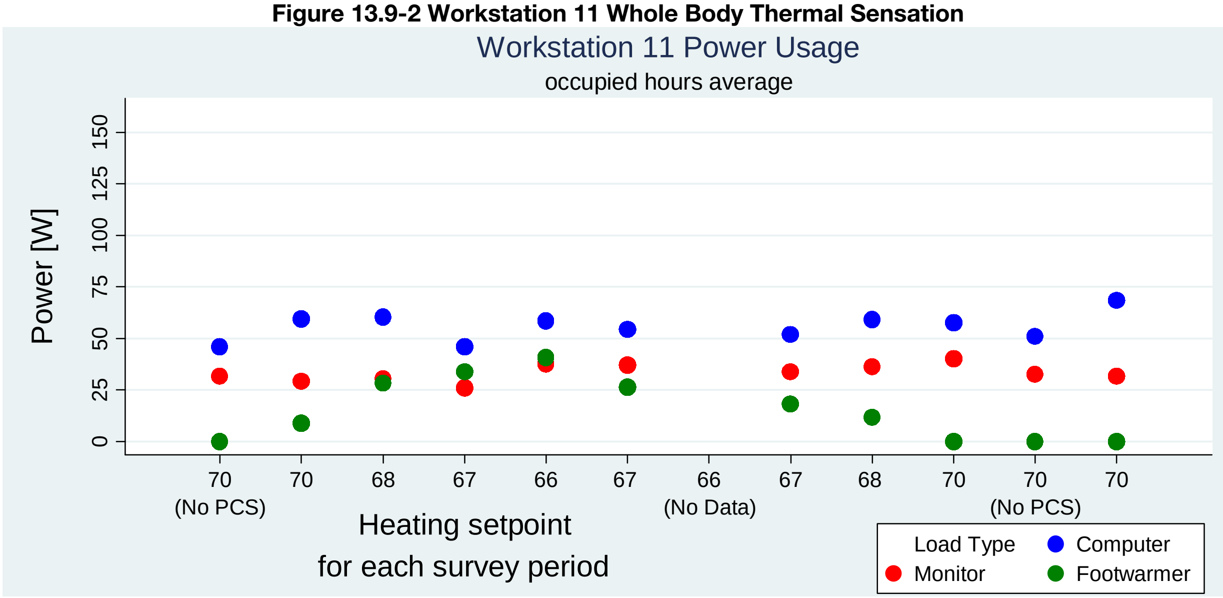

Figure 13.9-3 Workstation 11 Average Power

Workstation 11 Exit Interview Summary

3:00 pm, May 3rd, 2013

- The footwarmer changed the way he sat. He likes to stretch out his legs. While he also liked having the footwarmer, it was a difficult posture change. When the office was cold, using the footwarmer helped a lot. He never changed his shoes. He thought that using the footwarmer helped him stay away (he's a bit older and has started to have a tendency of dozing off).
- He liked the footwarmer and found it to be a welcomed addition to his desk set up. There were not specific or regular times in which the footwarmer did not keep him warm enough.
- Since the footwarmer was under his desk, he didn't care about the aesthetics of the device.
- He didn't think that the max setting of the footwarmer was very high but it was enough. If it were on wheels, it might make it possible to use the footwarmer while stretching out your legs though that might be a tough design challenge.
- He used the fan, but not frequently. He never used an additional fan. He feels cold more often than he feels warm. He found the fan gentle and effective and he liked the air movement. Sometimes, however, he found the air movement distracting. The fan was never noisy. The main reason why he didn't use the fan was because he is rarely too warm and never really noticed that the air was stuffy. Cubicle life can get boring so the fan sometimes helped with that. He likes that the fan sometimes turns off randomly. He liked the on/off cycling of the fan. He found that keeping the fan on a higher setting meant that the fan would stay on longer. The highest setting was fine.
- He used the fan more at first but it didn't become a habit. He often forgot it was there. He kept it on the right side of the desk and didn't think it was supposed to move.
- There were not specific or regular times in which the desk fan did not keep him cool enough.
- He wouldn't change the feature of the fan cycling on/off. He thinks the fan looks good.
- He thinks the rest of the office is cool.
- He is at his desk about 7 out of 9 hours a day. He is exercises during lunch. He tries to book appointments out of the office whenever possible (cubicle is not so great). He has more out of the office time than his colleagues though he is usually at his desk.
- He likes having the fan and the footwarmer but they make him slightly nervous. He would prefer to try to get the whole space comfortable. He thinks that they

should only be part of an attempt to get a good working environment. His fear is that providing these devices means that there will be no general effort to have good office-wide conditions. He doesn't think that the air is stagnant in the office but he thinks that a lot of other people do, particularly Lisa. He thinks the lack of air circulation contributes to early afternoon drowsiness (which might just be age related in his case). He thinks the air filters were added because one person in the office got a chest infection, which he attributed to the air quality in the office.

- He thinks that the study was well designed and non-obtrusive. He thinks the survey could be about 30 – 45 seconds longer if necessary. He thinks it might help to change the order of the online survey questions to avoid getting into habits of regularity.

13.10 Workstation 12

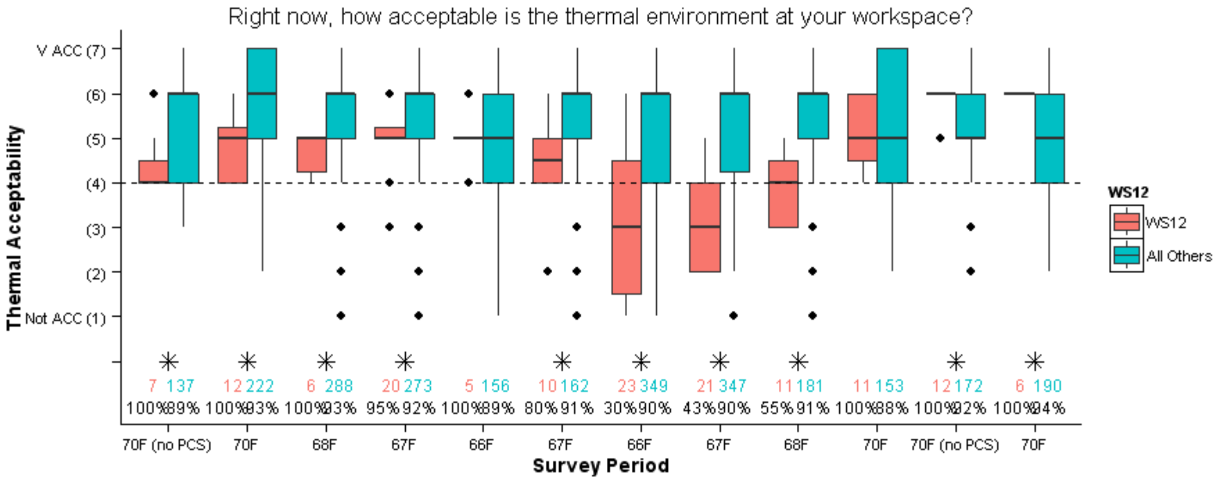

Figure 13.10-1 Workstation 12 Thermal Acceptability

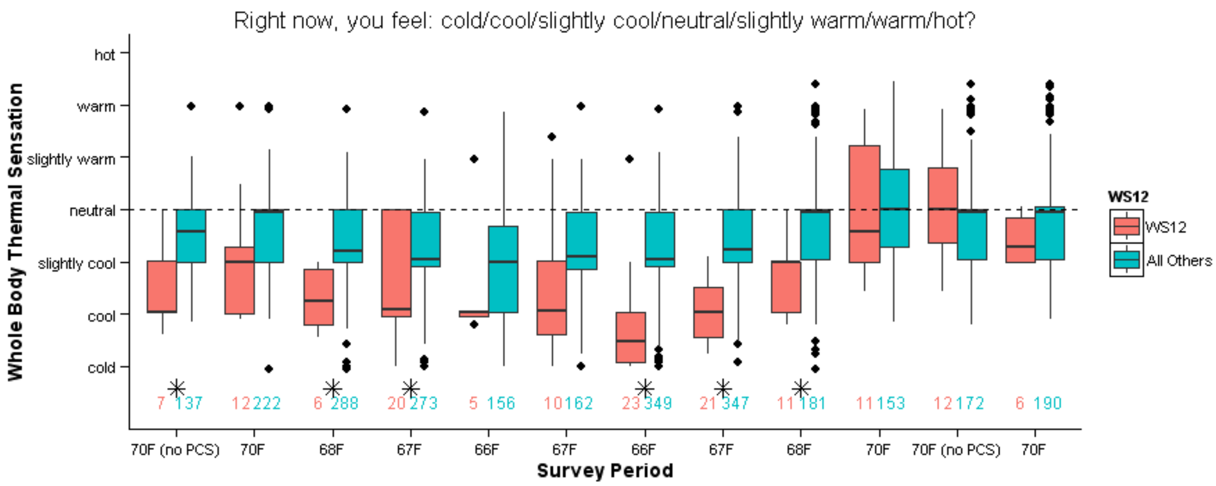

Figure 13.10-2 Workstation 12 Whole Body Thermal Sensation

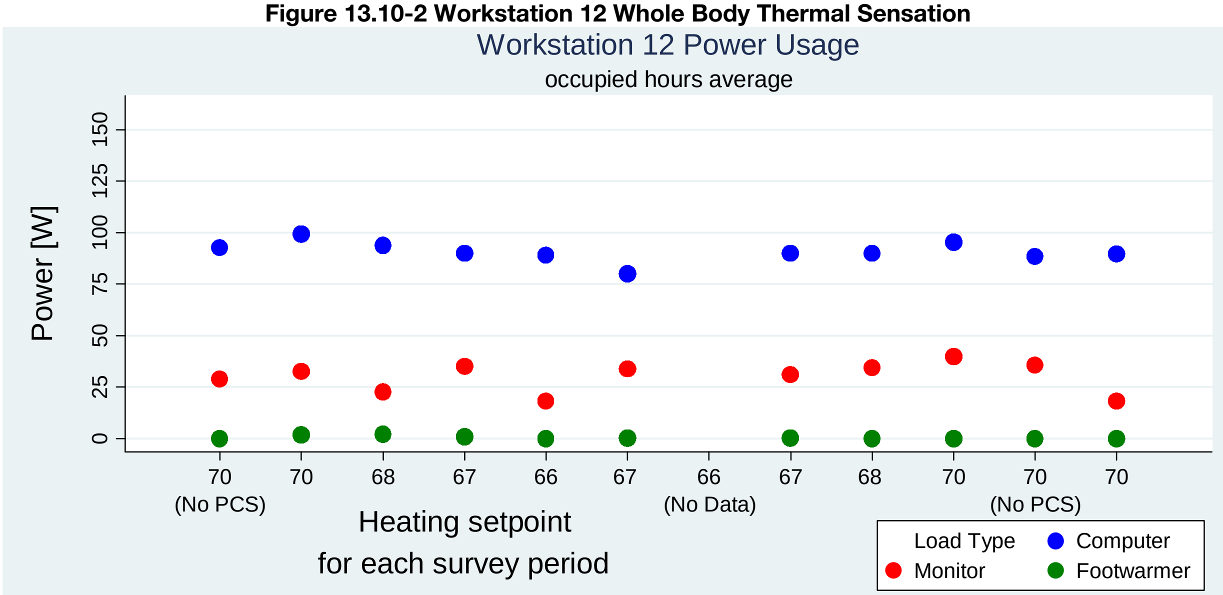

Figure 13.10-3 Workstation 12 Average Power

Workstation 12 Exit Interview Summary
9:30 am, May 9th, 2013

- She used the footwarmer a few times but stopped using it because she disliked the ergonomics. She didn't like pressing her feet downwards all day. She likes having her keyboard low, which was a challenge if she was using the footwarmer since it causes her to sit with her knees raised and to raise the keyboard higher than her preferred position. She likes the idea of having the footwarmer and her feet are always cold, but the ergonomics of the footwarmer prevented her from using it.
- During the study, she brought warm slippers to the office to wear when she was in the office. She wore them consistently throughout the winter.
- She would like the footwarmer to be activated by a sensor when feet are placed inside the device. She would have preferred there to be this occupancy sensor type activation, rather than the current activation through pressing down on the foot plate.
- She thought the aesthetics of the footwarmer were fine. "Can a footwarmer look good?" It is under the desk so it is more important for it to be functional. Perhaps it could be another color? If it were red, would this have a positive psychological effect to make people think that it was warm?
- She didn't use the fan since she was usually cold. She generally doesn't like to feel air movement on her face.
- She is at her desk about 98% of the time and has occasional meetings out of the office.
- The air circulation in the office is a little better than other rooms. The conference room and the kitchen are much colder. After thinking about it a little bit, she suggested that the office might feel a little colder than other places in the building.
- The study worked well and was not intrusive to her workday. She thought it was a good idea that the surveys were flexible.

13.11 Workstation 13

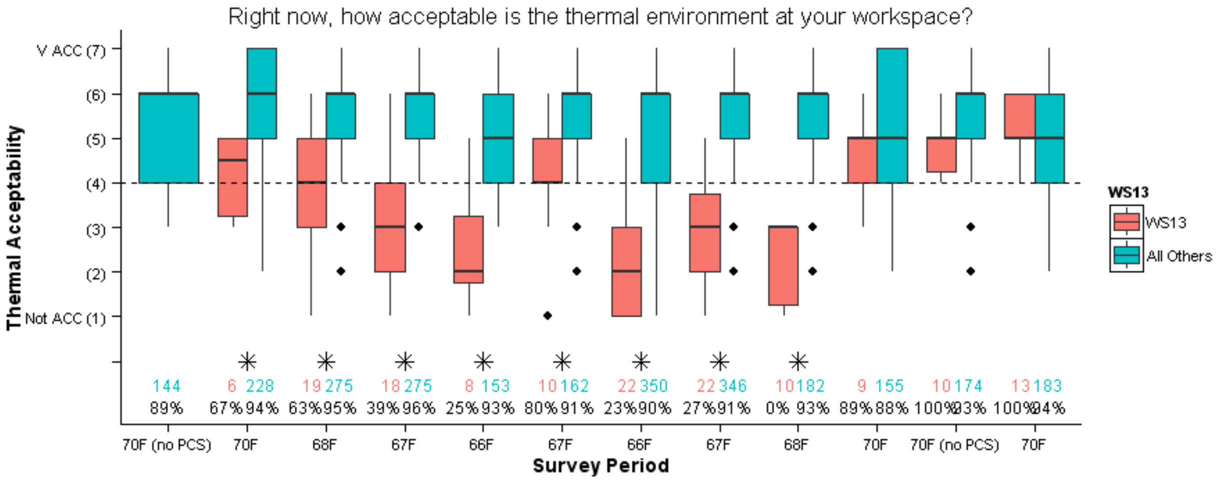

Figure 13.11-1 Workstation 13 Thermal Acceptability

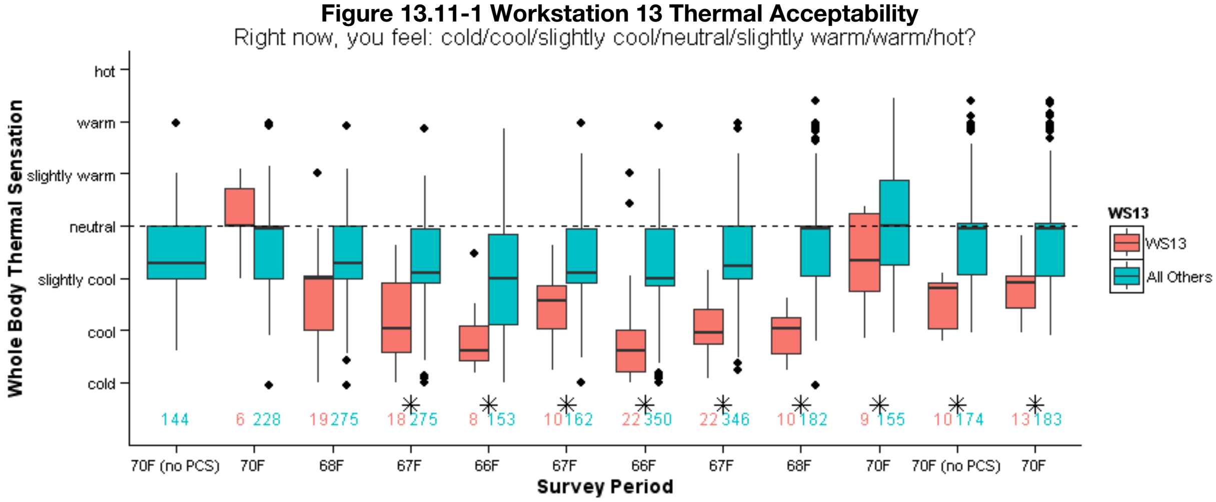

Figure 13.11-2 Workstation 13 Whole Body Thermal Sensation

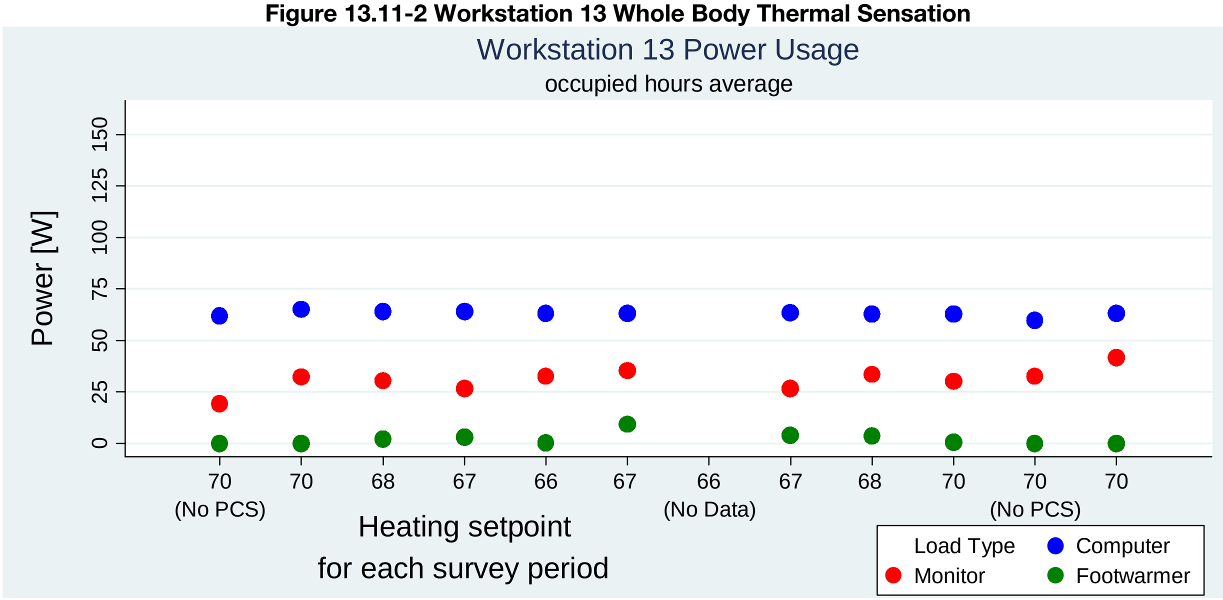

Figure 13.11-3 Workstation 13 Average Power

Workstation 13 Exit Interview Summary
9:45 am, May 9th, 2013

- He only used the footwarmer in the beginning to try it out. He had to take off his shoes to feel the heat and this was not ideal for him. He also didn't like that he felt cold when he turned the footwarmer off. Since he shifts around lot in his chair and at his desk, the ergonomics were also problematic. The ergonomics were the main reason why he didn't use the footwarmer.
- The footwarmer would have been more convenient if it were easier to move out of the way if he didn't want to use it.
- He used the desk fan at the beginning of the study when it was warmer, but once it got colder in the office there was no need to use the fan. He liked the fan when he used it.
- He doesn't have any suggestions for the aesthetics of the fan or how it operates.
- He felt that it got much colder in the late morning, especially during the winter.
- He is at his desk 80 – 90% of the time and occasionally has meetings out of the office.
- As far as feedback about how the field study was conducted, he was curious what we were after. He didn't think that air quality was clearly defined. He usually answered the air quality survey question based on temperature satisfaction.
- Even before the study, his desk feels like a "dead zone" with less air circulating near his desk compared to elsewhere in the office.
- The private offices have been significantly colder than the rest of the office, which was the case before and during the study.
- Ideally, he wouldn't be sitting at his desk as much. When it was colder, he would have to find a way to be more active. He thought it got very cold in the winter, but it was better now.

13.12 Workstation 14

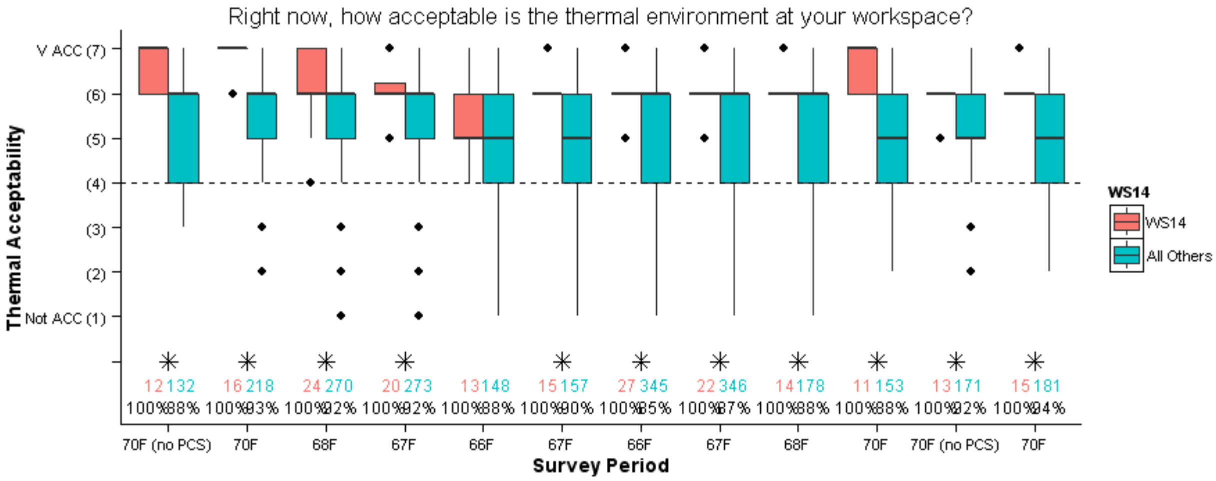

Figure 13.12-1 Workstation 14 Thermal Acceptability

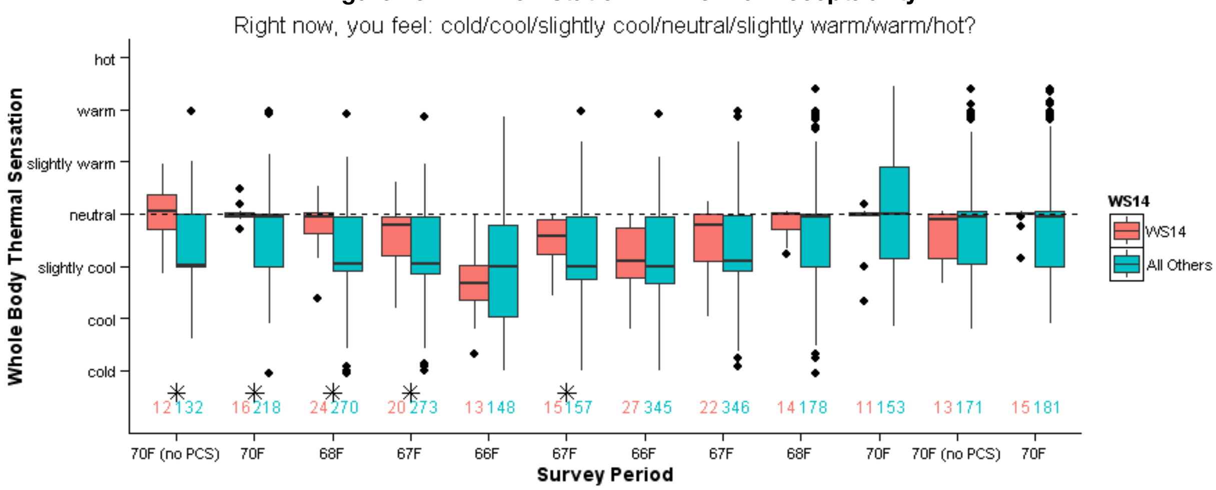

Figure 13.12-2 Workstation 14 Whole Body Thermal Sensation

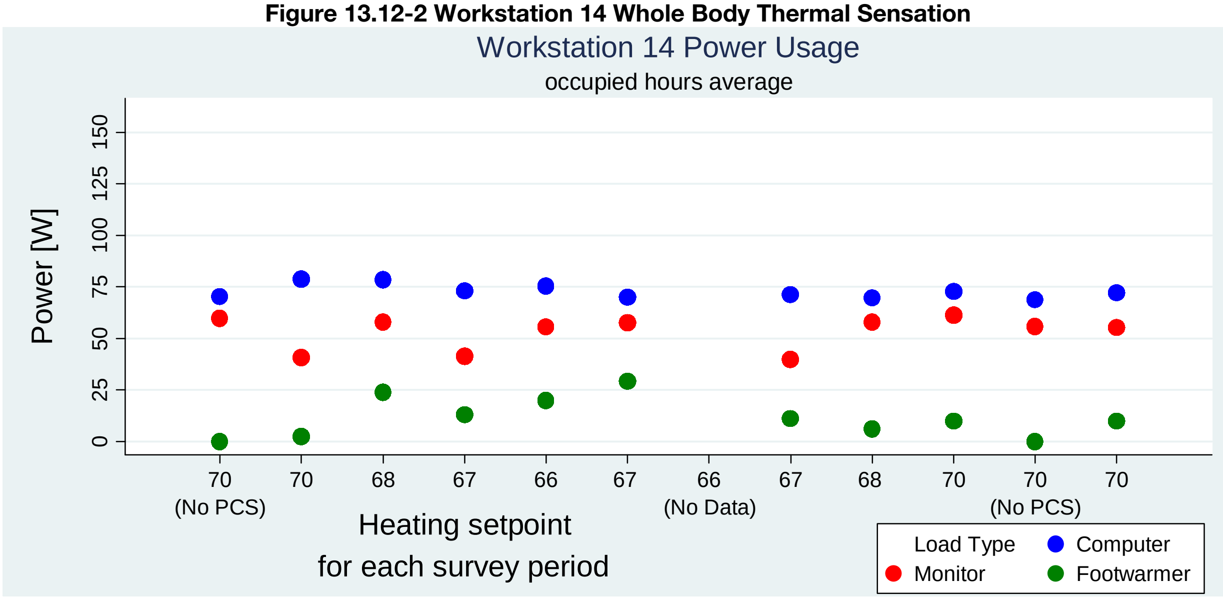

Figure 13.12-3 Workstation 14 Average Power

Workstation 14 Exit Interview Summary

2:15 pm, May 7th, 2013

- She used the footwarmer and said that footwarmer provided relief from her feet feeling cold. The footwarmer did give her more individual control though she always used it at full power. The footwarmer changed the way she sat at her desk since it raised her feet a little bit. She found the footwarmer effective for heating the bottom of her feet, but less effective in heating the top of her feet. The reflector helped this.
- She liked the study more as the study progressed. She didn't adjust her shoes or her clothes though she did take her shoes off when she used the footwarmer.
- There were just a few times when her feet were a little cold even when the footwarmer was on at full blast.
- She sometimes had a problem with the footwarmer hitting her shins. She didn't like having to take her shoes on and off.
- The footwarmer is under the desk so the aesthetics are not important.
- She never used the fan because she was never hot.
- She doesn't have any suggestions about the aesthetics of the fan, though she does find it a bit funny looking.
- She is at her desk about 90% of the time.
- She finds it breezier in this office compared to outside of the office. She does not notice a difference in her thermal comfort when she is at her desk compared to elsewhere in the office.

13.13 Workstation 15

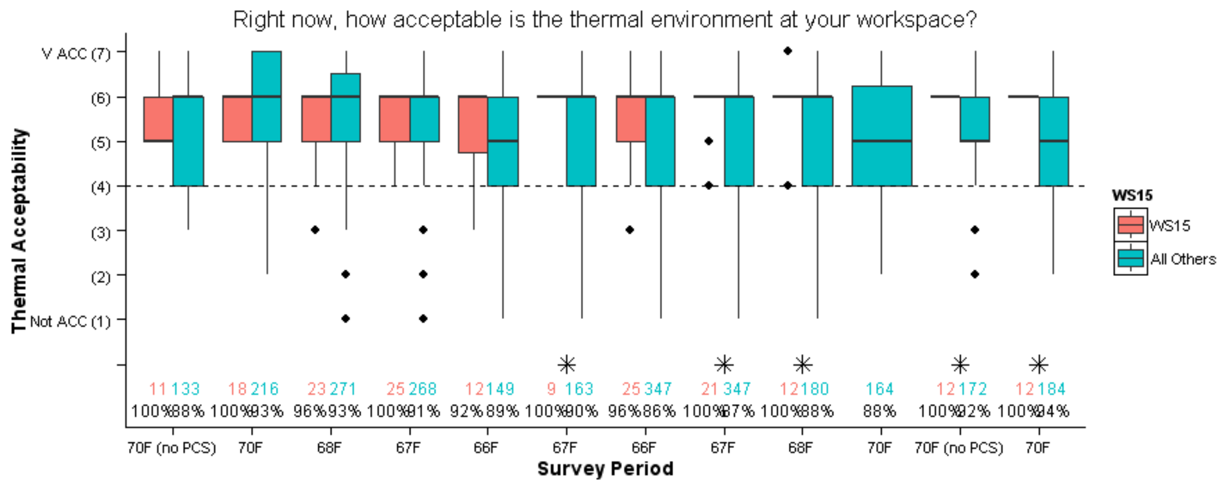

Figure 13.13-1 Workstation 15 Thermal Acceptability

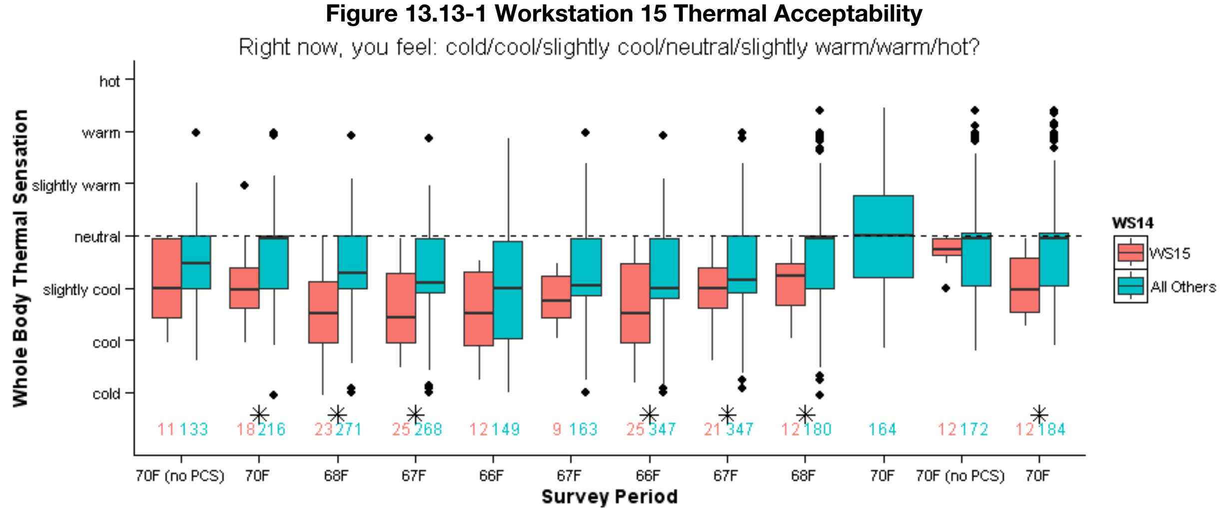

Figure 13.13-2 Workstation 15 Whole Body Thermal Sensation

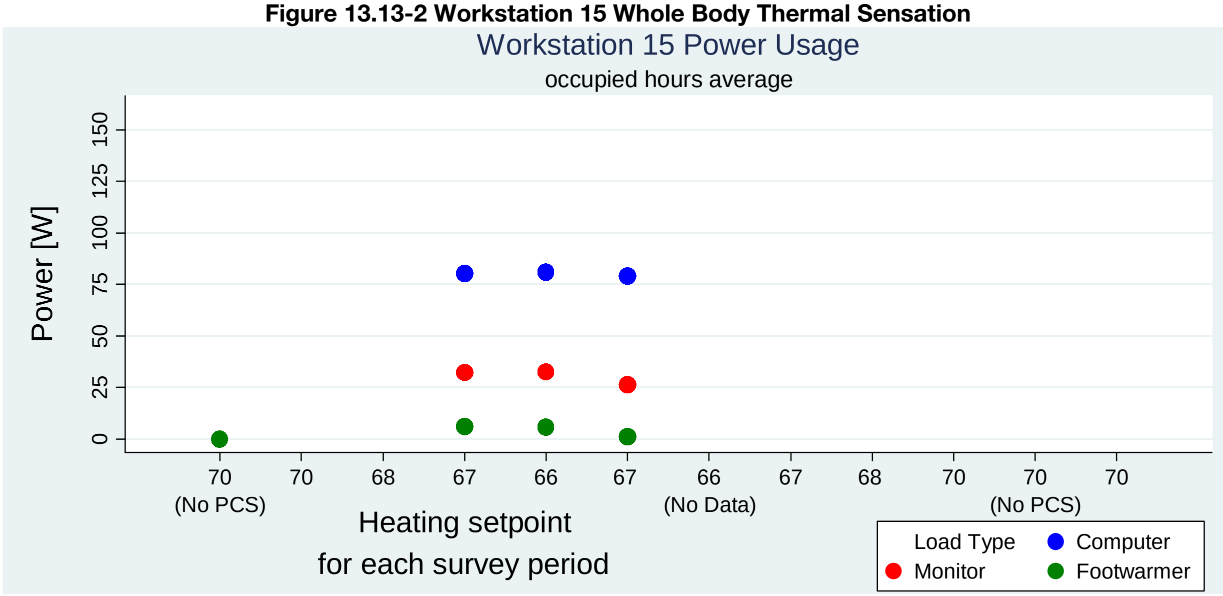

Figure 13.13-3 Workstation 15 Average Power

Workstation 15 Exit Interview Summary

1:30 pm, May 3rd, 2013

- Todd used the footwarmer and said that he liked having the footwarmer, the footwarmer gives him more individual control, and the footwarmer changed the way he sat at his desk. He used to site more with his legs extended. While using the footwarmer meant he had to change his posture, it wasn't uncomfortable and he liked having the footwarmer.
- Using the footwarmer meant that he had to adapt his posture. He didn't change his clothes or shoes and he never took off his shoes when he used the footwarmer. At first, he thought he was unlikely to use the footwarmer but he found it truly helpful as it got colder.
- There were never any specific or regular times in which the footwarmer did not keep him warm enough at his desk.
- He thought the footwarmer was comfortable and didn't require any change to the tilt. "Flat would have been nice if possible but that might be hard with shins."
- He hadn't thought about the aesthetics of the footwarmer. He wasn't really concerned with the aesthetics of the device.
- He uses the fan but not all that much. He never used it during the colder days. Sometime, he wanted more air flow but didn't want to use the fan. He feels some airflow from a nearby air filter. The fan is great for cooling off in the morning now that it's hot. He likes having air movement but he didn't think there was an air quality problem in the office. He liked that the fan is silent and he found the max setting to be ok. He said he liked the fan, he liked the feeling of air movement, the fan provided relief from feeling warm, and the fan gave more individual control.
- He never moved the fan during the study though sometimes he changed the angle to have it aim at his face. The fan didn't require any adaptation in behavior. He thought it was ok to have a small target area.
- There were not specific or regular times in which the desk fan did not keep him cool enough at his desk, but he didn't use it often. He found the fan adequate when he used it.
- Sometime the fan shot off. He would prefer if the fan could have a manual override to keep it constantly on.
- He thought the fan looked too much like it came from a lab. He found the fan a little rough looking.
- He is at his desk most of the time and he is always in his office.
- The conference room usually seems colder (most people think that). There is no control over the conference room temperature.

- He liked having candy as a treat for participating in the study. He didn't have anything negative to say about the research team. He is interested in the project and happy to participate. He found the study to be well executed.

13.14 Workstation 17

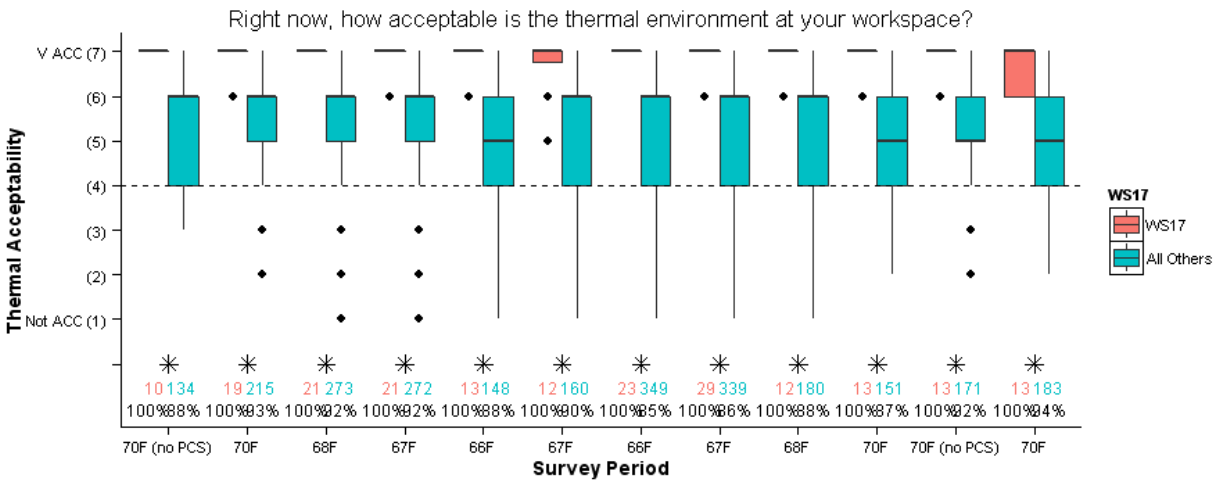

Figure 13.14-1 Workstation 17 Thermal Acceptability

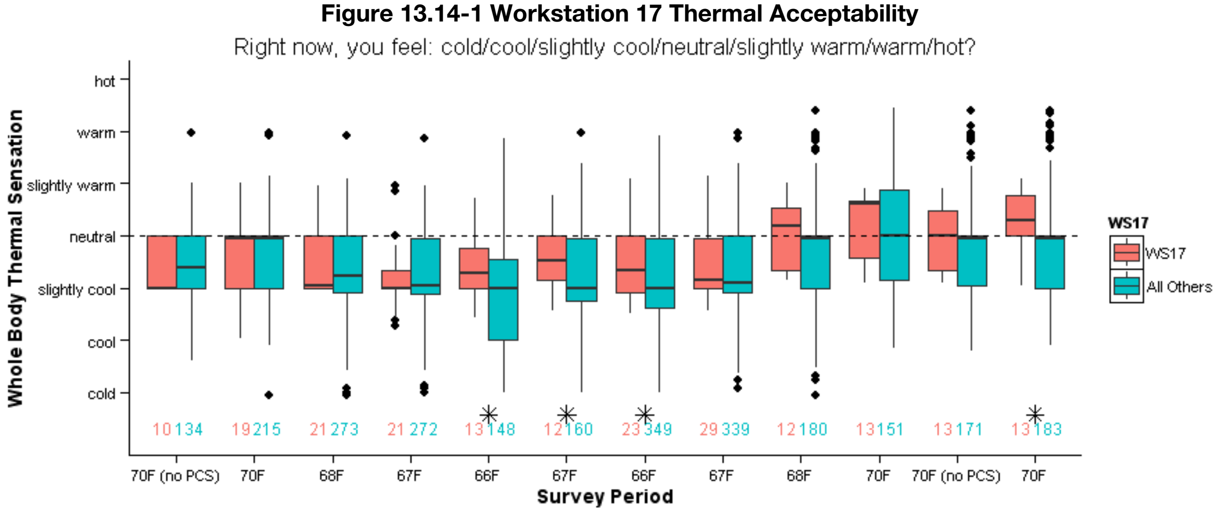

Figure 13.14-2 Workstation 17 Whole Body Thermal Sensation

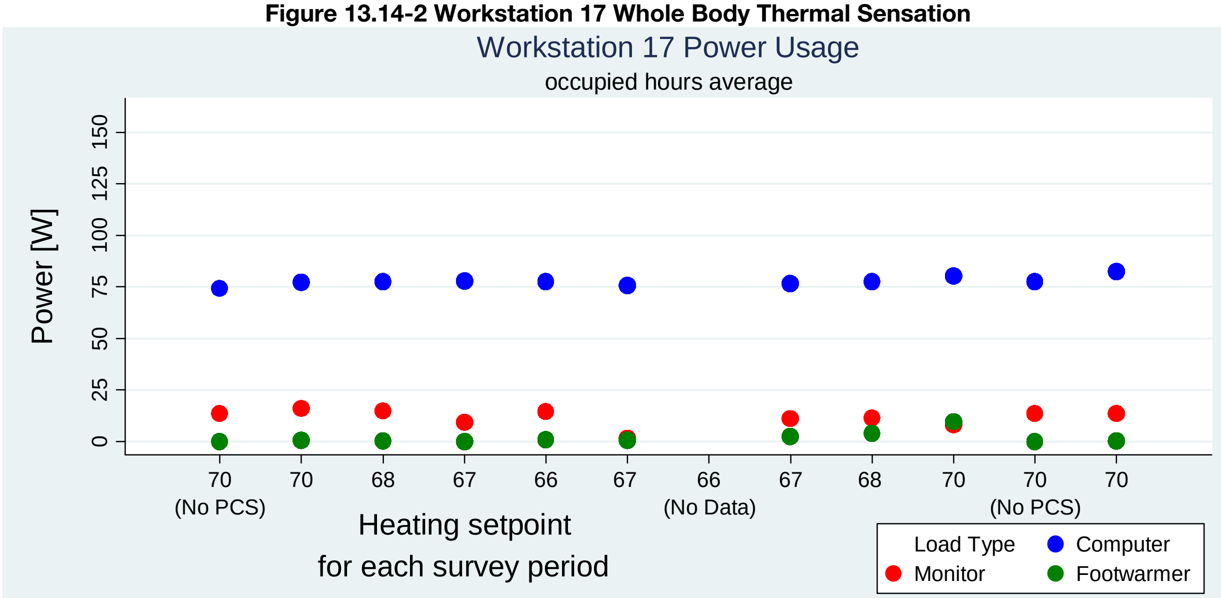

Figure 13.14-3 Workstation 17 Average Power

Workstation 17 Exit Interview Summary
1:15 pm, May 3rd, 2013

- He didn't like the footwarmer. He thought it was in the way so he moved it out of the way. However, his feet are always warm and he is rarely too cold. For this reason, he never used the footwarmer. He also tends to move around a lot at his desk, which makes it more inconvenient to have the footwarmer at his desk especially since he is never cold.
- He often uses the fan and sometimes uses an additional fan. He likes that the PCS fan is quiet and he usually has it on, however he likes a lot of air movement so he often has an additional fan for that purpose. Sometimes, the PCS fan was enough on its own though he always used it at full blast. He never found air quality to be a problem in the room. He liked that the fan has directed air movement, but it is just too weak for it to be his only fan all of the time. He said that the fan provides relief from feeling warm, the fan does not provide enough temperature relief, and the maximum setting on the fan is not strong enough. Unfortunately, his personal fan is louder, which is not ideal.
- Over the course of the study, he turned off his additional fan more and more. He liked the PCS fan increasingly as the study progressed. Some days, the weak power of the PCS fan was enough. He never moved the fan during the study but rather kept it pointed at his face.
- There were not specific or regular times in which the desk fan did not keep him cool enough at his desk.
- He thought the fan worked well in that the knobs were effective and the fan was easy to use. His only frustration is that the fan is not strong enough.
- He thinks the fan looks good.
- He didn't notice any difference in his thermal comfort between when he was at his desk, elsewhere in the office, or out of the office.
- He is at his desk about 85% of the time, while he is in another building the other 15% of the time.
- He found it easy to participate in the study and he thought the research team was responsive to feedback. He was often hot when coming into the office and he waited until he cooled down to take the survey. It was a little confusing how to answer if the fan provides enough cooling if the 2nd fan was in use.

13.15 Workstation 20

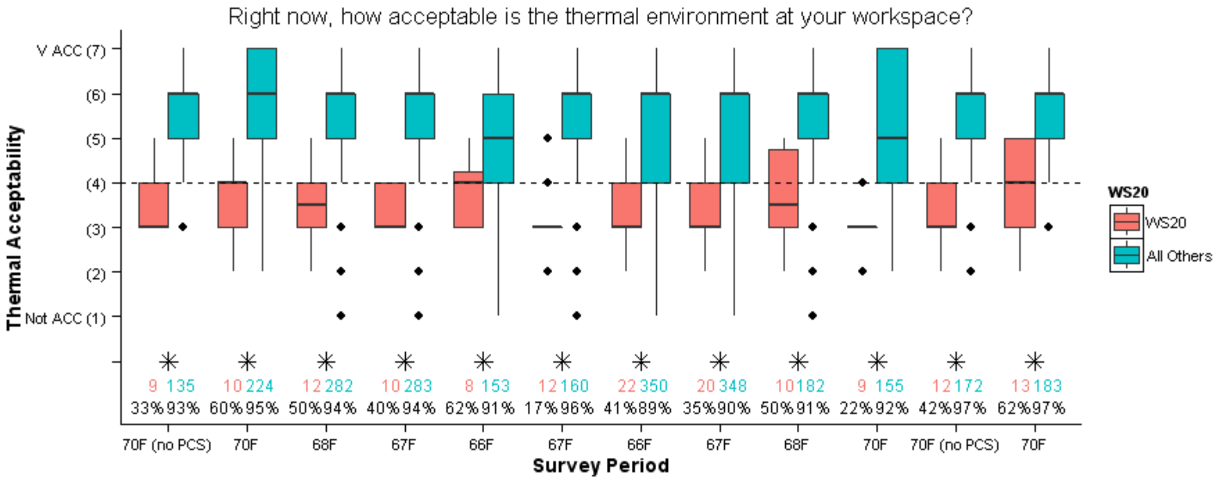

Figure 13.15-1 Workstation 20 Thermal Sensation

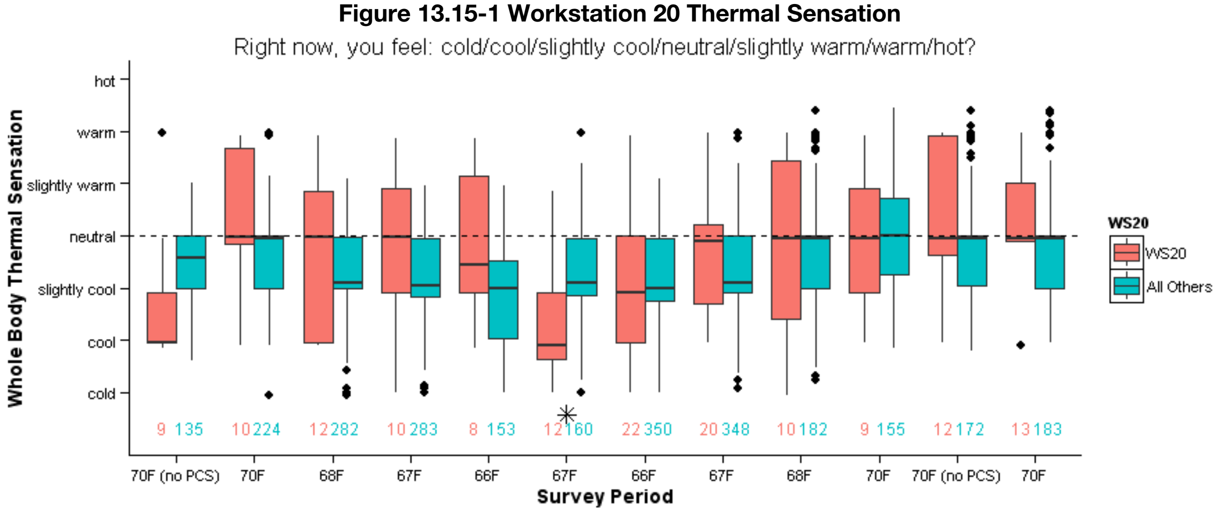

Figure 13.15-2 Workstation 20 Whole Body Thermal Sensation

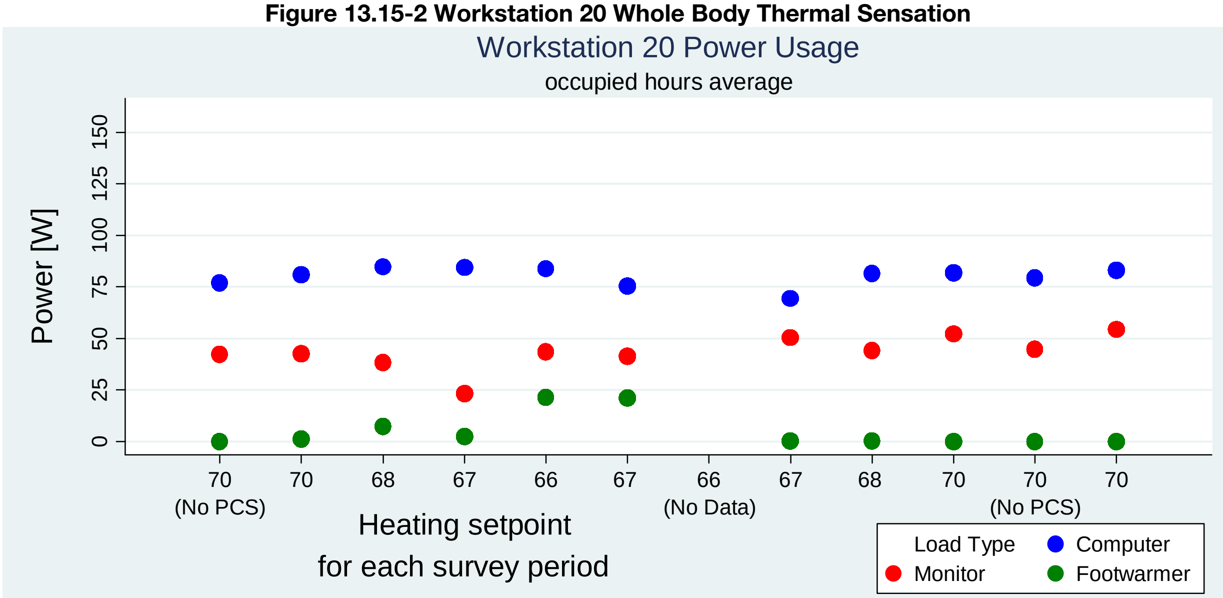

Figure 13.15-3 Workstation 20 Average Power

Workstation 20 Exit Interview Summary
11:15 am, May 9th, 2013

- It seems like the heat turns off at 4:30, which is frustrating because he usually works until 6:30. It was especially great to have the footwarmer during this time. He thought that the maximum setting was strong enough.
- He typically moved the footwarmer out of the way when he didn't want to use it.
- He didn't change his behavior during the study. He liked the footwarmer more and more throughout the study as it got colder. Now that it's warmer, he doesn't use the footwarmer anymore.
- He would like the footwarmer to be easier to move out of the way when it is not in use.
- He doesn't have any opinions the aesthetics of the footwarmer.
- He stopped using the fan because he was annoyed but the sound of the fan when it switched on and off. It is hot at his desk when it is sunny and he would use the fan if it didn't make noise turning on and off.
- He is rarely outside of his office and he estimates that he is at his desk 95% of the time. He doesn't have an opinion about the rest of the office because he is mostly at his desk. The conference room sometimes gets too cold and he usually brings a sweatshirt if he has a meeting in the conference room.
- Regarding the survey, he thought that some of his survey responses were skewed because sometimes he was hot from just having walked up the hill to the office. If he was hot from having walked up the hill, there was no way to reflect that in the survey.

13.16 Workstation 24

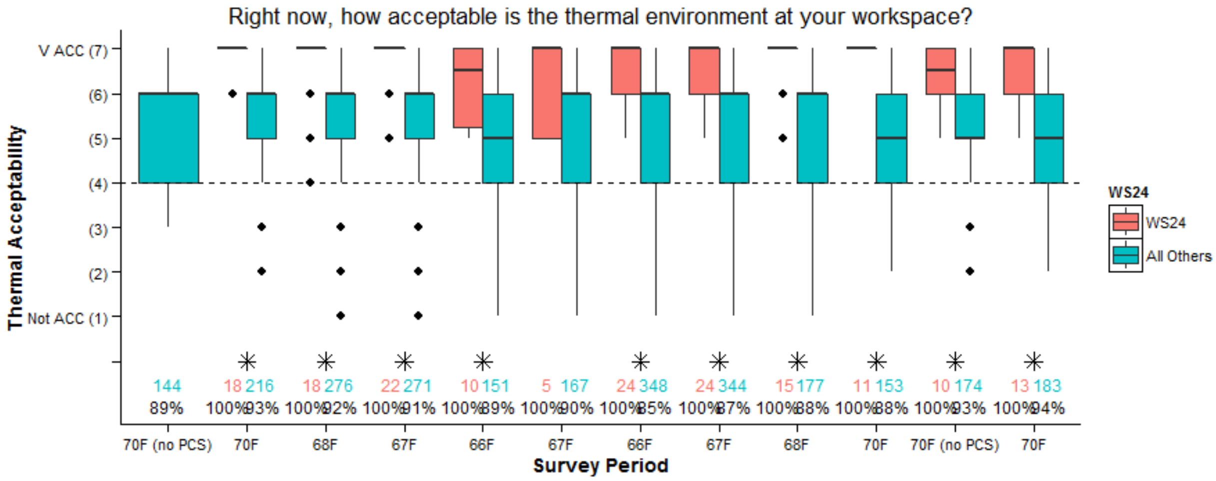

Figure 13.16-1 Workstation 24 Thermal Acceptability

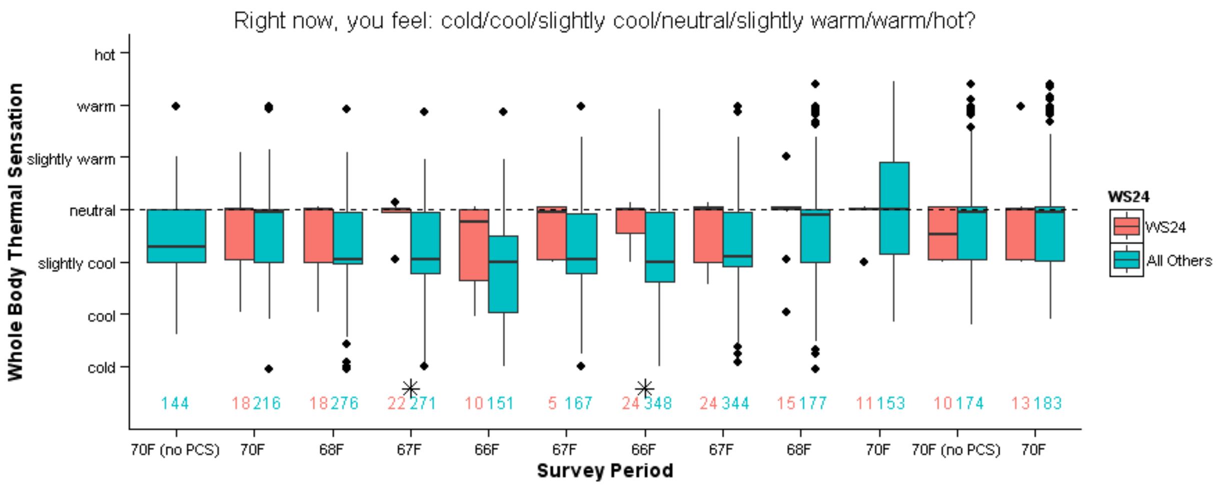

Figure 13.16-2 Workstation 24 Whole Body Thermal Sensation

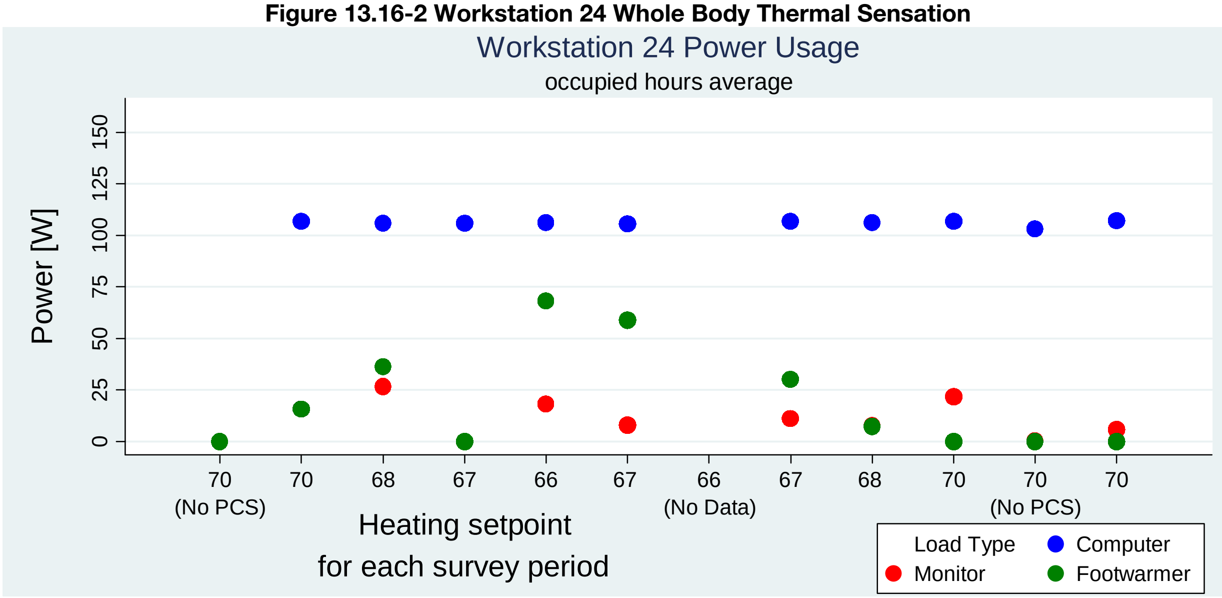

Figure 13.16-3 Workstation 24 Average Power

Workstation 24 Exit Interview Summary
10:15 am, May 14th, 2013

- He uses the footwarmer all the time and he likes having it. The footwarmer provides relief from feeling cold and heating feet is effective for feeling warm all over. The maximum setting on the footwarmer is not strong enough since there were a few cold days when he would have liked to have more heat from the footwarmer. The footwarmer gives more individual control and it makes you sit more upright. This change in ergonomics is a good long term change for him because he tends to slouch. Sitting upright is less preferable for him but he knows that it is better. In general, he thinks footwarmers are a great idea.
- He doesn't wear his shoes when using the footwarmer, which he used more when it got colder during the winter.
- He would like to be able to stick his feet into the footwarmer a bit further.
- He doesn't have any suggestions for the aesthetics of the footwarmer. He wasn't concerned about the footwarmer's aesthetics since no one sees it.
- He hardly ever used the fan. He usually doesn't use fans because they generally tend to dry out his contacts. He used the PCS fan a few times when it felt stuffy. Nothing in particular to this fan led him not to use it. He generally has a fan phobia due to the issue with his contacts.
- The fan looks fine and he thinks it is stylish.
- He is at his desk almost all of the time, estimated at 95%.
- He is more comfortable at his desk than when he is elsewhere in the office. He is mostly cold when he is not at his desk, especially when he is in the conference room.
- The study was not intrusive and did not bother him.