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USING FOOTWARMERS IN OFFICES FOR THERMAL COMFORT AND ENERGY SAVINGS

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ABSTRACT

An office equipped with personal footwarmers was maintained at cooler-than-normal indoor temperatures in the winter, producing great energy savings. The occupants' thermal comfort was not affected. The footwarmers provide individual heating control over a segment of the body that most strongly influences comfort perception when one is cool overall. If cooler ambient indoor temperatures could be made comfortable, savings in central heating energy would be possible. During a six-month winter period in Berkeley California, knowledge workers with low-energy footwarmers experienced a lowering of room heating set point from 21.1°C (70°F) to 18.9°C (66°F). Surveys showed equal thermal comfort in the original 'higher heating setpoint no-footwarmer' condition and the 'lower heating set point plus occupant-controllable footwarmer' condition. Heating energy was closely monitored throughout. It dropped 38% to 75% depending on the setpoint reduction and outdoor conditions. The added plug load energy from the low-energy footwarmers was much less than the central heating energy saved by lowering the heating set point (3-21W vs 500-700W average power per occupant during occupied hours). A few subjects had ergonomic issues with the particular footwarmers used, so usage was not universal. Additional foot- and leg-warmer design options would help.

HIGHLIGHTS

- Personal foot warmers were tested for energy and comfort in an office building
- Footwarmers enabled cooler rooms in winter without affecting thermal comfort
- Energy saved by lowering setpoints greatly exceeded electricity used by footwarmers
- Efficient footwarmer design used only 20W per person to offset 2K (4°F) cooler room

KEYWORDS

Thermal comfort, personal comfort system, footwarmer, heating setpoint, HVAC energy savings

INTRODUCTION

Roughly 10% of the world's energy is spent to heat and cool the interiors of commercial buildings. This is done to create a range of indoor temperatures that assure comfortable and productive occupants. The temperature range has a significant impact on the amount of energy used. A narrow range requires more heating and cooling, often simultaneous. For each degree Celsius that the thermostat heating setpoint is lowered or the cooling setpoint raised, a building's total (heating+cooling) HVAC energy consumption is reduced 10%, and savings of 40 -50% are possible [1]. If it were possible to have equivalent comfort outside the conventional interior temperature range, substantial amounts of HVAC energy might be saved with no loss in performance.

Personal comfort system (PCS) devices have been developed that cool or heat thermally sensitive parts of the human body to provide thermal comfort in a wider range of ambient conditions. They also improve comfort psychologically by making thermal control personally available [2-5]. PCS cooling mostly takes place through convective cooling by fans [6-12] or through cooled chairs [13-16]. PCS heating has been provided by heated chairs [17-21], a lower body warming enclosure [22], radiant panels in the kneehole [8] and footwarmers [7,8,21]. The literature on personal comfort systems has been recently reviewed and the comfort effectiveness of numerous systems compared [23].

Most PCS testing has been done in laboratory thermal chambers on student subjects. There have been relatively few field studies of PCS in actual buildings, and these only during warm seasons [10,24-25]. One of these found 100% thermal satisfaction in a building when the occupants had been given PCS in their workstation [26]. Though the study was limited in scope, finding 100% of the occupancy satisfied is a unique result in comfort field studies. The study also found that in summer occupants' comfort was better at slightly higher temperatures with PCS than without PCS at lower ambient temperature. To date, there has been no field study in which PCS was heating occupants, or which determined HVAC energy savings associated with using PCS.

The PCS device evaluated in this study originated from a fundamental laboratory study [6] that determined how cool feet dictate the discomfort of the entire body in cool environments [27]. Not only are warm feet essential for the perception of comfort in cool environments, but feet warming is also very effective at restoring comfort once one is cool. Based on this, the authors developed footwarmers that focus radiant heat on the feet and ankles. Emphasis was placed on making them energy-efficient. They were laboratory tested in realistic workstations in which subjects performed tasks representing office work [7].

The encouraging findings from the laboratory study suggested that an actual office with footwarmers should be tested for an extended period in winter. Office workers would be repeatedly surveyed about their comfort as the interior temperature is systematically varied. At

the same time, the HVAC energy savings associated with lowered office temperatures would be quantified. The field study would provide evidence about potential benefits and drawbacks of footwarming in an actual functioning office.

METHODS

Footwarmer description: Because there were no efficient footwarmers available in the market, the authors fabricated 100 for use in field studies (Figure 1). In order to create a rapid warming effect, the design uses four incandescent reflector bulbs as heat sources. The filament and bulb heat up almost instantly, and the radiation is focused on the top of the feet and ankles where shoe and clothing insulation is least. Non-absorbed radiation is retained to the extent possible within a reflective (low-emissivity) insulated enclosure. The feet are placed through an opening in the front. The increased radiation intensity and air temperature within the enclosure provide the equivalent of 9°F (5K) of whole-body heating, using roughly 30W at steady state [7]. This heating effect compares favorably to the typical 750 - 1500W heater found in office environments. Typical heaters are inefficient because they dissipate radiation, do not confine locally warmed air, and create cool convective currents at foot level that counteract the effect of radiant warming.

The footwarmer maximum power depends on the bulbs selected. In these tests, the total power was 160W. The amount of power is continuously controllable by the user from zero to maximum. The controls are positioned in the base of an associated small desktop nozzle fan (for ventilative cooling) that is linked to the footwarmer through a communications cable. The setup and controls are seen in Figure 1. The knob with the blue light on the left controls the fan speed while the knob with the red light on the right controls the heating level of the footwarmer. Both the footwarmer and fan have occupancy sensors assuring shut-off when unoccupied; the footwarmer using a pressure switch in the floorplate, and the fan using a passive infrared sensor mounted on the fan hub.

The fan base houses a microprocessor (in this case Arduino) for power control, temperature and power sensing, and for providing internet connectivity for controls and research purposes. The internet connectivity allows researchers to remotely monitor and download the ambient air temperatures and the occupants' fan and footwarmer usage.



Figure 1 – PCS fan and footwarmer combination

Building description: The field study was conducted in a wing of the office annex to the University of California Berkeley library (Figure 2), over the winter season of October 2012 - April 2013. The main façade of the wing faces north, with minimal solar gain in winter. There is one window on the west façade, 10 windows on the north façade, and three windows on the east façade. The windows are single-glazed and not operable. There were 16 occupants (8 females and 8 males) in the office all of whom were asked to participate in the study. Nine occupants were located adjacent to windows, three were one workstation removed from the window, and four were in the room interior (Figure3). The occupants were all middle-aged knowledge workers who spent long periods at their computers.



Figure 2 – Building east facade and interior cubicles

PCS footwarmers were installed at the 16 occupants’ desks to allow occupants to supplement the warmth during winter when ambient air temperature was lowered (Figure 3).

Temperature was measured in several locations. As described above, the small desk nozzle fan associated with each footwarmer unit has a temperature sensor to monitor ambient temperature next to the occupant at desktop level. In addition, there are seven thermostats in the room accessible through the building management system (BMS). The locations of the thermostats are marked by a red letter “T” in Figure 3.



Figure 3 – Floor plan showing occupied workstations

Setpoint-change and survey period:

The study period is heating-dominated for buildings with low-to-medium internal loads (ASHRAE Climate Zone 3c and California Climate Zone 3). The annual weather file from the nearby Oakland International Airport (OAK) contains 1616 heating degree days at base 18.3°C, and 128 cooling degree days at base 28.2°C.

The office's ambient indoor temperatures are controlled by its heating and cooling thermostat setpoints. The pre-existing setpoint range was 21.1°C (70°F) to 22.2°C (72°F). These established the study's base case condition without footwarmers.

Figure 4 presents the timeline of the study. To start the study, the occupants responded to repeated surveys in the base case condition during the week of September 28-October 5, indicated in the figure as Period 1. Following this, there was a gap in time during which the occupants received an onsite demonstration of the footwarmers, had the devices installed in their workstations, and were given a week to become familiar with them. The with-footwarmer surveys then took place over the next six months in Periods 2 through 10, and again in Period 12.

Period 2 also used the base case temperature setpoints. The occupants were surveyed three times per day from October 29-November 2. Late in the afternoon of the last day, the setpoint was changed. A gap of several days ensued in order for occupants to adapt to the new condition prior to initiating the next set of surveys (Period 3). This pattern was followed throughout the subsequent periods. Occupants were not notified about the setpoint changes, or informed that the research team was adjusting ambient temperature as part of the study.

In Periods 3 through 10 over the next six months, the heating setpoint was lowered from 21.1°C (70°F) to 20°C (68°F), 19.4°C (67°F), and 18.9°C (66°F), and then raised by the same steps back to 21.1°C. The survey periods ranged from one to two weeks. In instances when the occupancy was discovered to be low due to vacation or business trips, the survey period was expanded to two weeks to obtain more respondents. The length of gaps also varied, to compensate for holidays.

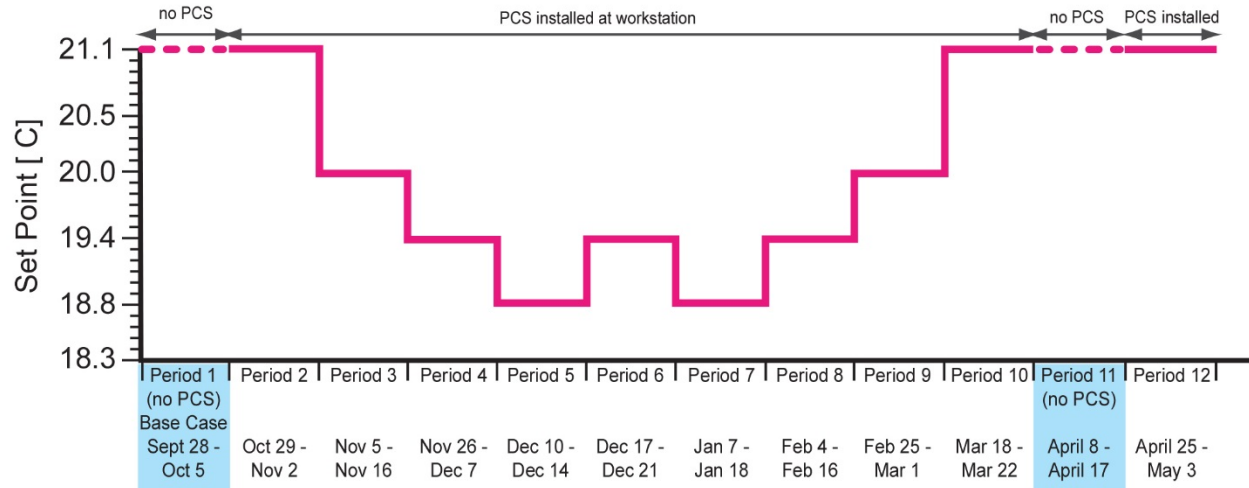


Figure 4 – Timeline showing progression of the heating setpoints for the 12 survey periods

HVAC system and energy monitoring: The building has a single-duct VAV reheat system with separate setpoints for heating and cooling. Thermostats are locked to prevent occupants from changing settings. The BMS is Automated Logic and is BACnet compatible. Data were accessed and exported through the UC Berkeley Simple Measurement and Actuation Profile (sMAP) software (<http://www.cs.berkeley.edu/~stevedh/smap2/>). sMAP makes it possible to record and remotely access numerous streams of climate and building performance data for monitoring the interior temperatures and calculating the HVAC energy consumption.

The energy consumption of the studied wing was monitored and calculated using an airside energy balance. The inputs to the calculations were: 1) the airflow through all 5 VAV boxes in the study area, 2) the supply air temperature reaching the VAV boxes, 3) the diffuser discharge temperature entering the zone, and 4) the temperature of the occupied zone. The airflow recorded through the BMS was calibrated with a flowhood for all 5 VAV boxes under 3 flowrates. The flowhood method, developed at Lawrence Berkeley National Labs (LBNL), is similar to the FlowBlaster Capture Hood Accessory commercialized by The Energy Conservatory [28] (TEC 2013).

The research team installed power-metered powerstrips in each workstation, and connected all workstation electricity consuming devices to this powerstrip (the computer, monitor, lighting, and footwarmer units) in order to monitor workstation plug loads.

The fresh air supply during work-hours is very constant, around 42%. It is zero during evenings and weekends.

Occupant satisfaction survey: During the survey week, occupants were invited to take web-based “right now” survey three times a day (9AM, 11AM, and 2PM), but only if they had been at their workstation for at least 15 minutes and had not submitted a survey within the last two hours. The survey asked questions such as: “Right now, how acceptable is the thermal environment at your workspace?” Occupants answered using a seven-point scale ranging from “Very acceptable” to “Not at all acceptable”. The seven-point scale and the entire set of survey questions are presented in the Appendix. Based on the approach in ASHRAE Standard 55 Appendix K2.2 [29], the three votes toward the “Not at all acceptable” point are considered as “unacceptable”. The survey also obtained whole-body thermal sensation using the ASHRAE seven-point scale, and a selection of three check boxes reported whether occupants preferred to be warmer, cooler or no change. Finally, thermal sensation and thermal preference were obtained specifically for the occupant’s feet, to determine whether the footwarmer was producing enough heat.

It was not possible to repeatedly request information about individuals’ clothing insulation. Frequent site visits by the researchers revealed that the occupants wore informal clothing (no jackets or ties) appropriate for the winter season. Women wore more insulating clothing (sweater, vest) than men, who normally wore a long-sleeve shirt with a T-shirt. Shoes were solid (no sandals) for both genders.

A walkthrough inspection confirmed that the occupants did not have any portable space heaters installed prior to being given the footwarmer for the study. Several portable desk fans were in use and were allowed to remain.

At the end of the study (April 2013), each participating occupant had a one-time interview with a researcher. The purpose of this “exit survey” was to get people’s opinions about the footwarmer. Each interview took about 15 minutes.

RESULTS

Environment

Outdoor temperature. The winter 2012-2013 was atypically warm. Table 1 presents the monthly mean, averages of all the daily maximum and minimum temperatures for each month of the study. The monthly mean temperature ranged between 9.7 (January 2013) to 17.1 (October 2012).

Table 1. Monthly mean, monthly average maximum and minimum outdoor air temperatures.

	Oct-2012	Nov-12	Dec-12	Jan-13	Feb-13	Mar-13	Apr-13
Mean T	17.1	14.1	10.1	9.7	11.2	12.9	14.9

Mean T_{\max}	23.2	19.0	13.9	14.8	16.8	18.7	21.3
Mean T_{\min}	11.1	9.1	6.3	4.6	5.6	7.1	8.7

Indoor temperature. Figure 5 shows the perimeter temperature, core temperature, setpoint, and outside temperature every fifteen minutes during occupied hours (8 AM – 6 PM) throughout the study.

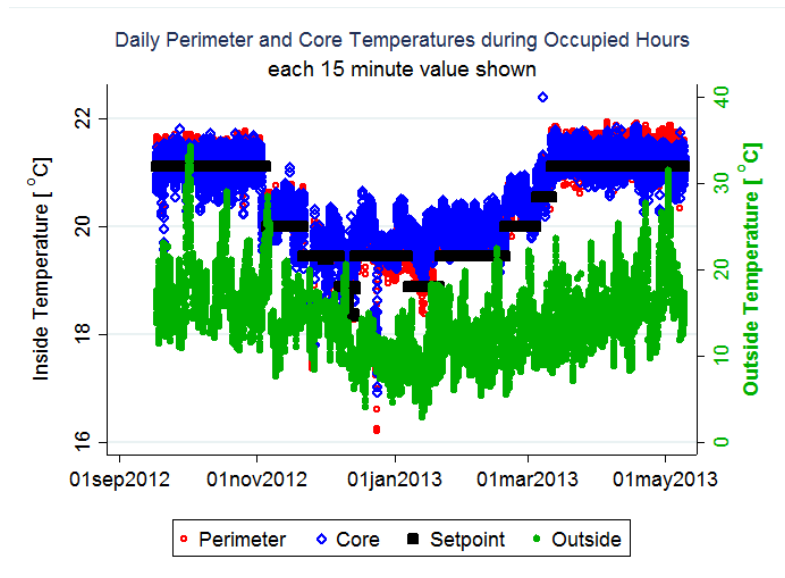


Figure 5 – Core, perimeter, setpoint and outdoor temperatures during the study (occupied hours)

The black dots are the setpoint temperatures shown above in Figure 4. The decrease and then increase in setpoint temperature followed the seasonal decrease and increase in temperatures as the seasons transitioned from late fall, to winter, and to early spring. The ambient air temperature in the core and perimeter zones followed the setpoints within a degree C.

The detailed values are summarized in Table 2. MS Windows anomalies on the diverse workstation computers prevented the download of temperature data monitored in many of the desktop nozzle fans. Temperatures measured by the fans were used whenever available, and the nearest thermostat temperatures when not. Thermostat readings were calibrated with a hand-hold thermometer.

The temperature distribution in the room is very uniform. The perimeter zone and the core zone are close, with slightly cooler (0.2K, see Table 2) temperatures in the perimeter zone in December and January (Period 6 and 7).

Table 2. Daily average outdoor, perimeter, and core zone temperatures, and their standard deviations (8 AM – 6 PM)

period	Outdoor				Perimeter				Core			
	avg	std	min	max	avg	std	min	max	avg	std	min	max
1	20.5	6.3	11.0	34.2	21.4	0.2	20.8	21.7	21.2	0.2	20.3	21.5
2	17.1	2.9	10.7	23.2	21.4	0.2	20.4	21.8	21.2	0.2	20.2	21.7
3	15.8	4.6	7.7	28.4	20.4	0.2	19.9	20.8	20.3	0.2	19.7	21.1
4	14.2	1.9	8.5	17.4	19.7	0.3	17.4	20.1	19.6	0.3	17.8	20.3
5	11.7	3.4	6.2	20.6	19.3	0.3	18.3	19.9	19.4	0.3	18.0	20.3
6	10.8	2.2	4.1	14.8	19.9	0.2	19.1	20.2	20.1	0.2	19.5	20.7
7	10.2	3.4	2.9	18.2	19.4	0.3	18.4	20.0	19.7	0.3	19.0	20.3
8	12.3	3.4	5.4	22.3	19.8	0.2	19.1	22.2	20.0	0.2	19.4	20.5
9	14.9	3.0	8.2	22.1	20.5	0.2	20.0	20.8	20.5	0.2	20.0	20.9
10	14.2	2.4	7.1	19.0	21.5	0.2	20.7	21.8	21.4	0.2	20.9	21.7
11	17.8	3.9	8.9	25.3	21.5	0.2	20.7	21.9	21.2	0.2	20.8	218.0
12	17.8	4.1	10.4	26.6	21.5	0.2	20.7	21.8	21.2	0.2	20.3	21.6

Thermal Comfort Results

There were a total of 2774 recorded surveys during the study. The survey responses were evenly distributed throughout the workday and across each survey period.

Some extraneous factors affected the study. After the onset of the study, four occupants stopped using the footwarmers — one stated that her skin was sensitive to by IR radiation; and others cited ergonomic reasons regarding the position and design of the footwarmer, or that they didn't need it. Because the study objective was to understand the effect of generic footwarming on thermal comfort, and because at least three of the four objections raised by this group related to this specific design and could be corrected in the future, the main focus of the analysis was on the 12 people (6 males and 6 females) who actually used the footwarmers. However the two groups (user and total) were compared as described later.

Thermal acceptability. Figure 6 below shows the 'right-now' survey results for the user group for the question, "Right now, how acceptable is the thermal environment at your workspace?" The x axis shows the setpoints for the 12 survey periods, following the same order as shown in Figure 4. Each boxplot summarizes the results for one survey period. The numbers above the x axis give the number of survey votes in the period and the percent of occupants voting acceptable in the period. The box contains half the data and its height the interquartile range. In the box, the median is denoted by the thick horizontal line and the mean by the red dot. The "*" in a survey period indicates that there is a statistically significant difference (t-test, $p < 0.05$) between the mean of the base-case condition (Period 1) and the mean of that survey period.

The medians of the thermal acceptability in Figure 6 remain constant throughout the study. The means are fairly constant too, varying less than half a scale unit. The thermal acceptability votes for the pre-existing base case condition are 87% (Period 1) and 94% (Period 11), and between 90% and 97% for the ten periods in which occupants had footwarmers and the setpoint was

below the base case temperature. These are good scores for thermal acceptability surveys in buildings. The variation in acceptability rates from the preexisting base case is statistically significant for about half of the periods in which setpoints were changed, always in the positive direction. Most of the dissatisfied outliers (dots falling more than 1.5 times the interquartile range below the lower border of the box) came from one person who wished to express general dissatisfaction with the thermal comfort in the office, but who said in the exit interview that the footwarmer had provided sufficient heat.

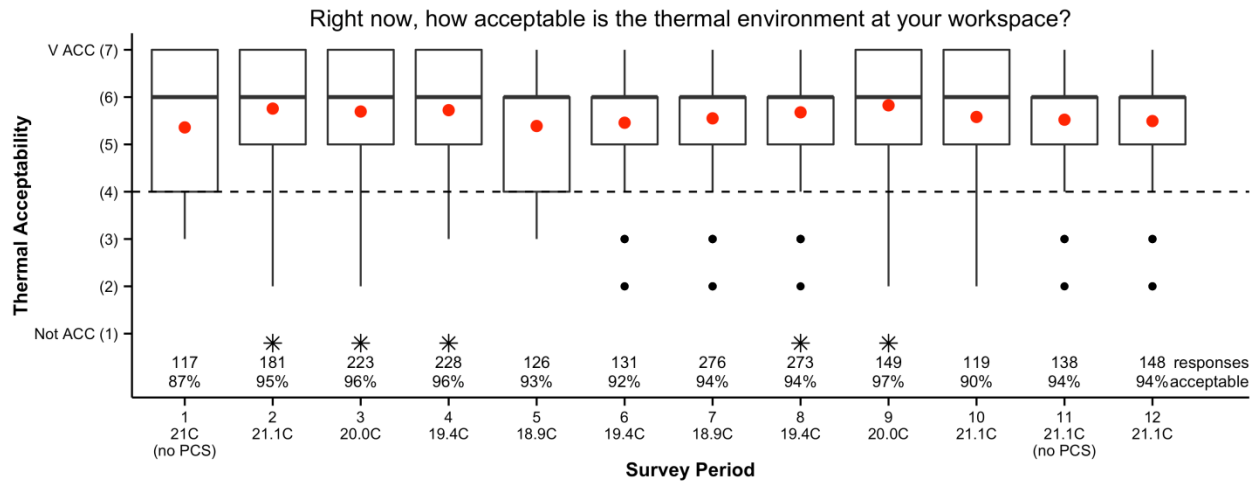


Figure 6 – Thermal acceptability results for footwarmer users (* indicates a significant difference from Period 1)

Figure 7 presents the thermal acceptability results for all the 16 survey participants (12 footwarmer users and 4 non-footwarmer users). There are no statistically significant differences between the base case and the periods in which setpoints were lowered, and overall the acceptability is good. However it is clear that the four non-users lower the acceptability ranges seen in Figure 6. The thermal acceptability votes for all 12 survey periods range from 86-94%.

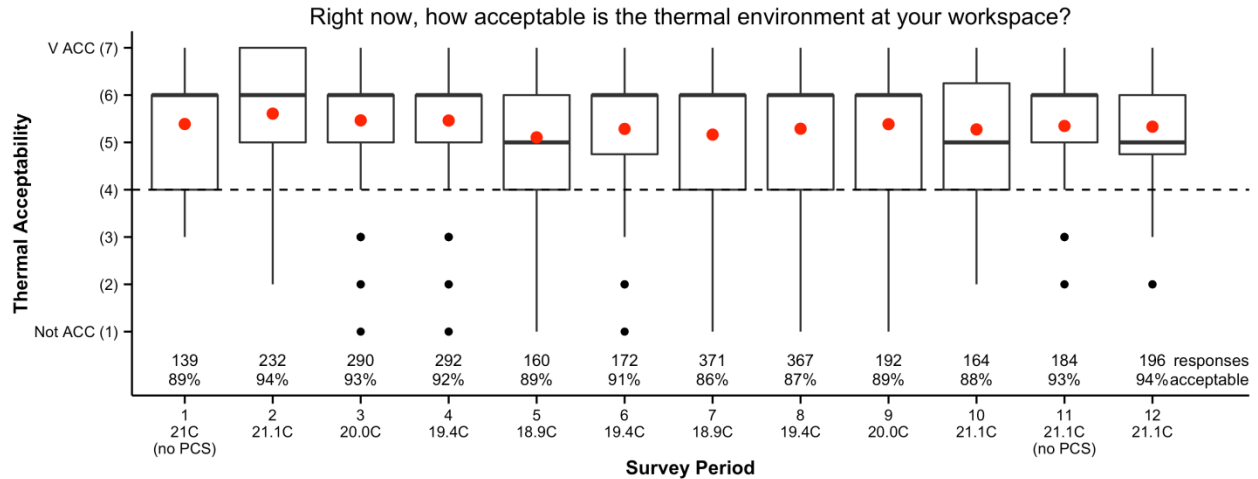


Figure 7 – Thermal acceptability results for all 16 survey participants

There is large variation in thermal acceptability votes among occupants, though individuals' votes throughout the study tend to be internally consistent [30].

Thermal sensation. Figure 8 shows that whole-body thermal sensation votes are near 'slightly cool' in the base case condition, improving in the direction of 'neutral' upon receiving the footwarmer (with setpoint unchanged), dipping back towards 'slightly cool' as the setpoint is lowered, and finally returning towards 'neutral' as the setpoint is returned to 20°C and 21.1°C. The slightly cooler thermal sensations do not impact the thermal acceptability of the workspace (Figure 6) under either the pre-existing or footwarmer conditions. The footwarmer does not raise whole-body sensation in the lower temperatures, but as shown in Figure 10 below, it maintained a neutral sensation for the feet during these periods. Because whole-body discomfort in cool environments is dominated by cold sensation in the feet, the footwarmer counteracts this by removing the source of discomfort directly. With footwarmers keeping the feet neutral, it appears that whole-body neutral sensation is not necessary for thermal acceptability.

Comparing the 20°C and 21.1°C room temperatures at the beginning and end of the study, the thermal sensation is closer to "slightly cool" at first, but is closer to "neutral" at the end. This might indicate that people were adapting to cooler environments during the period that the room temperature setpoint was lowered, or during the winter season generally. However, the differences are very small, and this could also be caused by people adjusting clothing.

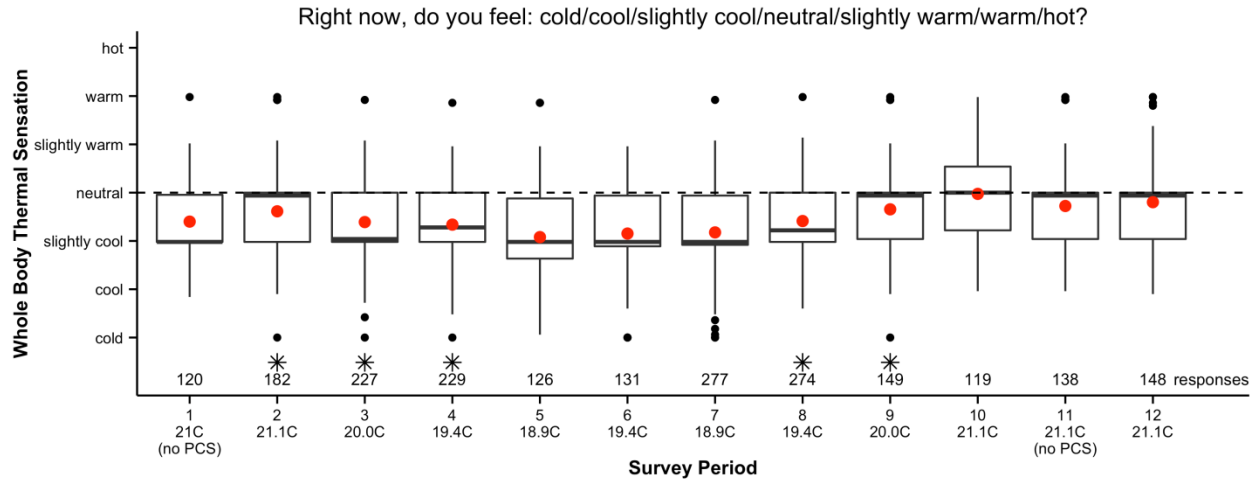


Figure 8 – Whole body thermal sensation

As with the thermal acceptability votes, thermal sensation depends greatly on the individual occupant. If one considers the range of all four quartiles in each box plot, the variation is quite large. Each individual occupant's acceptability and thermal sensation votes for the 12 study periods are presented in [30].

Footwarmer performance. Figure 9 examines whether the footwarmers provided enough heating. The setpoints for the 12 survey periods are presented on the x axis. The green dots represent the percentage of survey responses in which footwarmers were in use *at the time of the surveys*. The red dots indicate that the footwarmer was providing enough heat and the blue dots indicate that it was not. These percentages are also presented in the table below the chart.

51% and 47% of occupants were using the footwarmer at the time they were surveyed during the two recurrences of the lowest setpoint (18.9°C). This means that about half people were *not* using the footwarmers (when surveyed) even at the lowest ambient temperature. Among footwarmer users (green dots), there is no pattern or large difference in footwarmer use between the genders (percentages in brackets in the bottom row of Figure 9). The red and green lines are very close, meaning that for most instances where people were using the footwarmer, it was providing enough heat. Only 1 – 3 % of votes in each survey period indicated that the footwarmer was not providing enough heat. The data show footwarmer usage increasing as the setpoint was lowered, and diminishing as the setpoint returned to the baseline of 21.1°C. 4–20% of occupants used the footwarmer even when the room heating setpoint was at the baseline setpoint of 21.1°C.

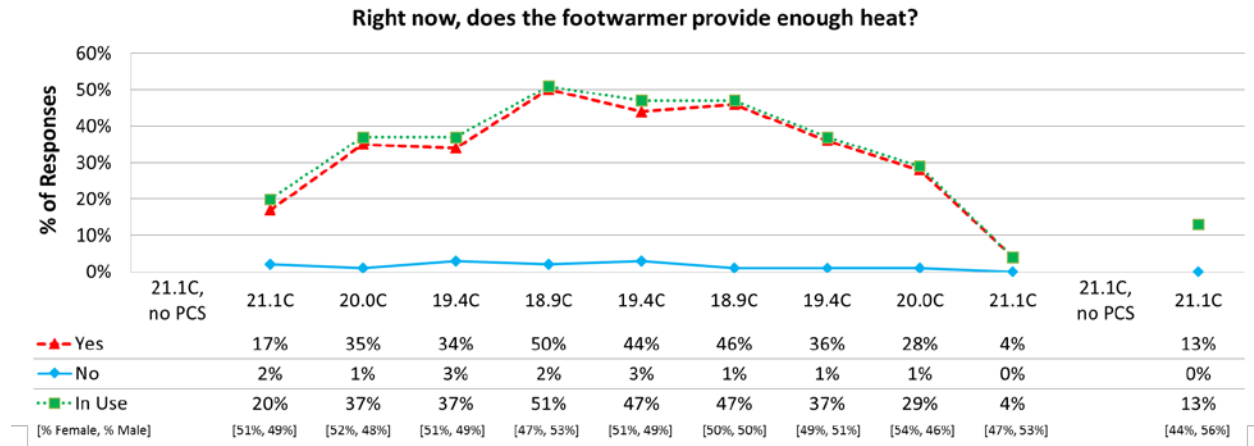


Figure 9 – Performance of the foot warmer

Feet thermal sensation. Feet-specific thermal sensation responses are shown in Figure 10. The spread in the data is wider than for other questions, for both warm and cool feet thermal sensation. The warmest votes are likely from footwarmers in use. The coolest votes appear to have happened at times when footwarmers were not being used, because (as described above), almost all occupants who were using a footwarmer during the time of the survey indicated that it provided enough heating. As the setpoint temperature was lowered throughout the winter, both the median and mean for the feet thermal sensation in each survey period remained neutral. During the coolest periods, there was a slight skew toward ‘slightly warm’. At these same periods, the medians and means of whole-body thermal sensation votes were ‘slightly cool’ (Figure 8). One can conclude that the footwarmer (or access to it) consistently kept most people’s feet perception neutral even as their whole body thermal sensation was slightly cool.

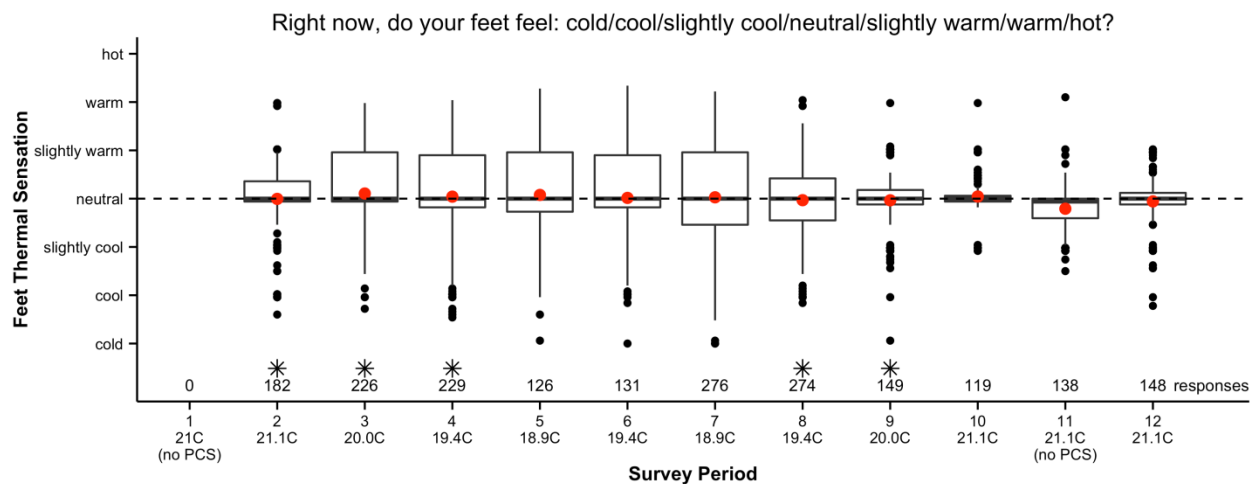


Figure 10 – Feet thermal sensation

Thermal sensation in mornings vs. afternoons. There are no statistically significant differences between the whole-body thermal sensation votes obtained in mornings versus afternoons (Figure 11).

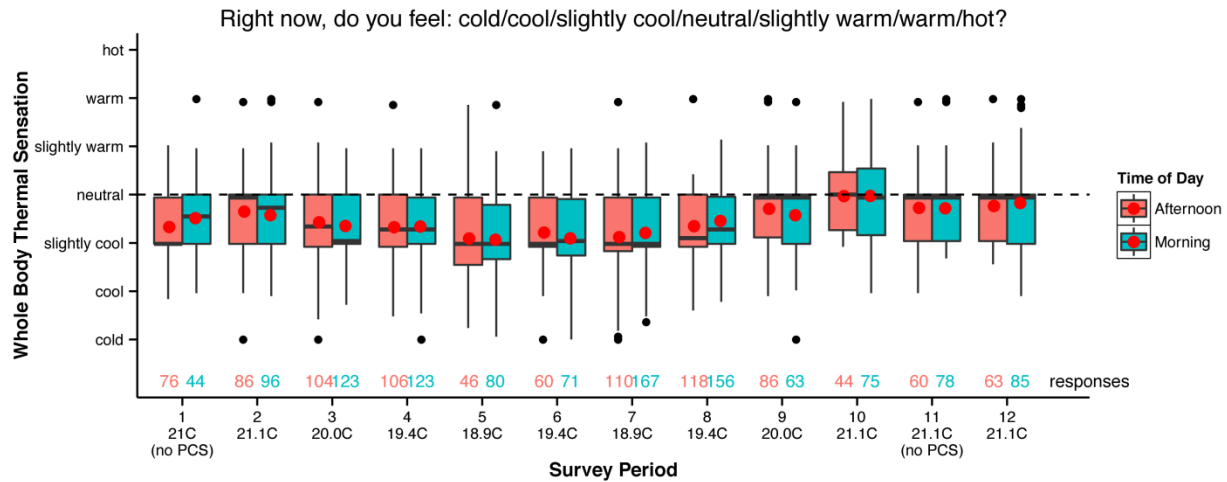


Figure 11 – Whole body thermal sensation - morning versus afternoon

Thermal sensation between genders. Figure 12 shows that males' whole-body thermal sensation is consistently slightly cooler than that of females, but the difference is statistically significant in only two of the twelve periods. Any finding of cooler males is the opposite of what is usually observed in building surveys. The result might be attributable to the generally higher level of clothing worn by women in this office, as mentioned earlier.

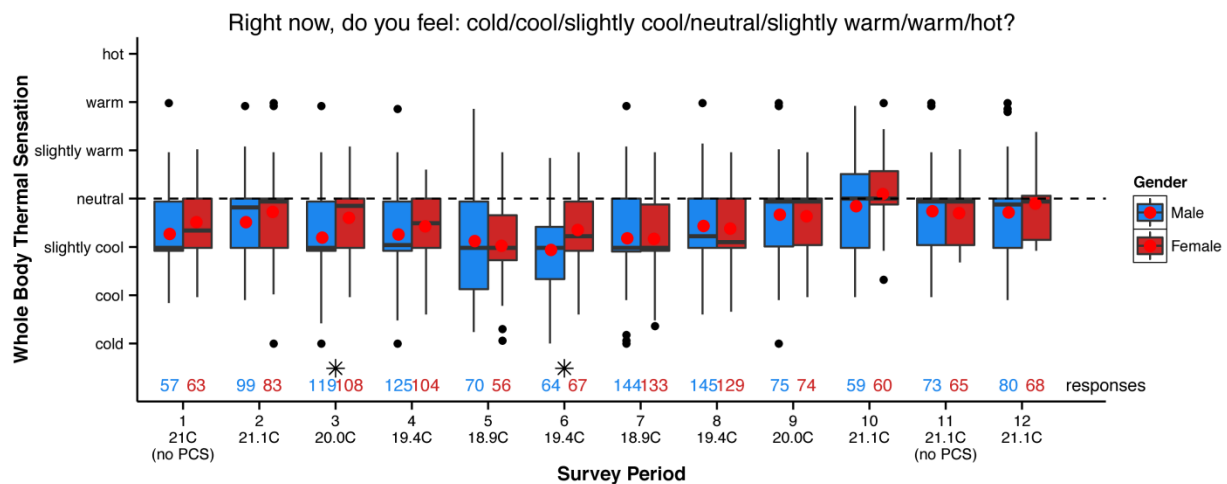


Figure 12 – Whole body thermal sensation – males versus females

Energy Performance Results

Figure 13 gives an example of a workstation's monitored power consumption, in which footwarmer usage is clearly visible. This turned out to be a common result: rather than adjusting the control knob between 0 and 100%, occupants left the setting at full power, and adjusted the warming of their feet by moving them in and out of the footwarmer. Since the footwarmer is only powered when the feet are inside contacting its floor plate, the outcome is a form of pulse-width power modulation. This usage merits further investigation.

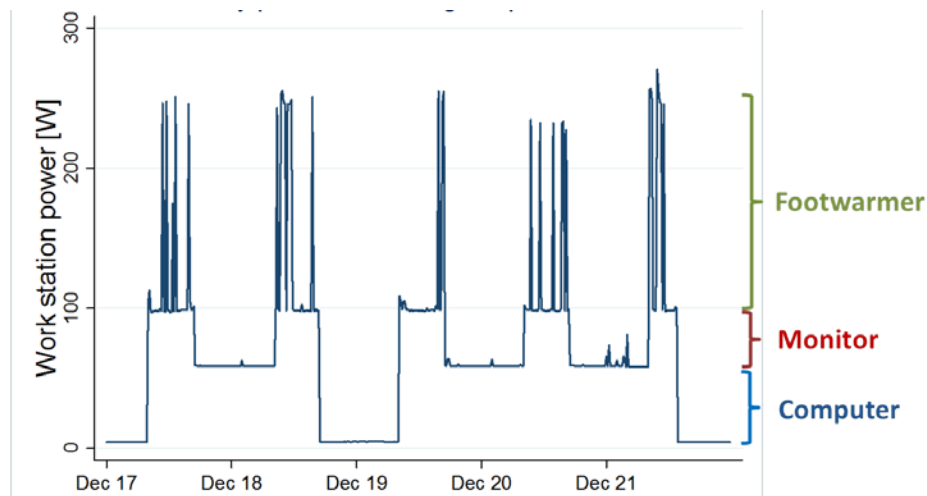


Figure 13 – Power consumption at the workstation

Figure 14 shows no change in the average footwarmer power within 5 days in any particular survey period. This suggests that people did not adapt to the cooler environment over the course of 5 days within a survey period but rather used a similar level of footwarmer heating for each particular setpoint. However, footwarmer usage was slightly higher in the first half of the study suggesting that people may have adapted to the cooler zone temperatures during the course of the study, or that they thermally adapted over the course of the winter itself.

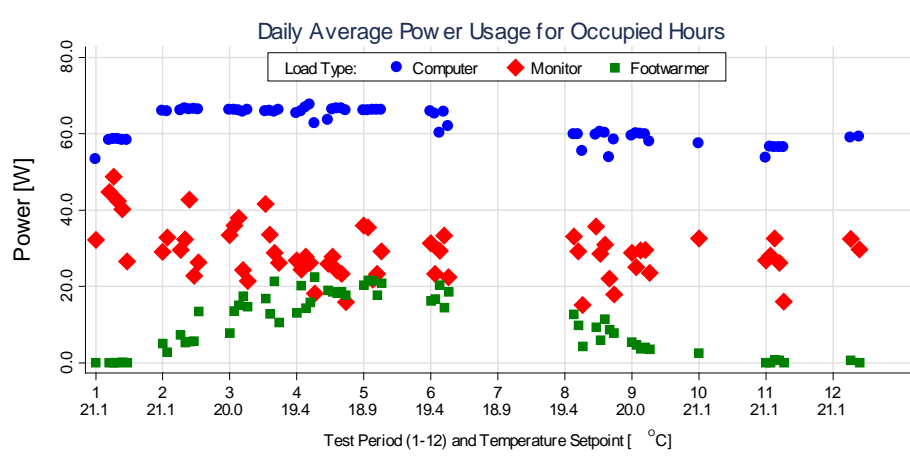


Figure 14 –Plug loads for period 1 - 12 (The gap in period 7 are due to a data loss)

Figure 15 shows the office’s use of central heating power, as affected by the outdoor temperature and by the thermostat setpoint. Each colored point is a measured condition representing 15 minutes. The four lines give the medians of the data for the four setpoint test conditions. The balance point of the room, where internal loads equal heat losses through the envelope and ventilation system, occurs where each sloped line reaches zero power. It ranges between 12 and 15°C. The shift in balance points appears slightly greater than the shift in interior temperature caused by the setpoint changes. The balance point is more clearly defined at lower outdoor temperatures.

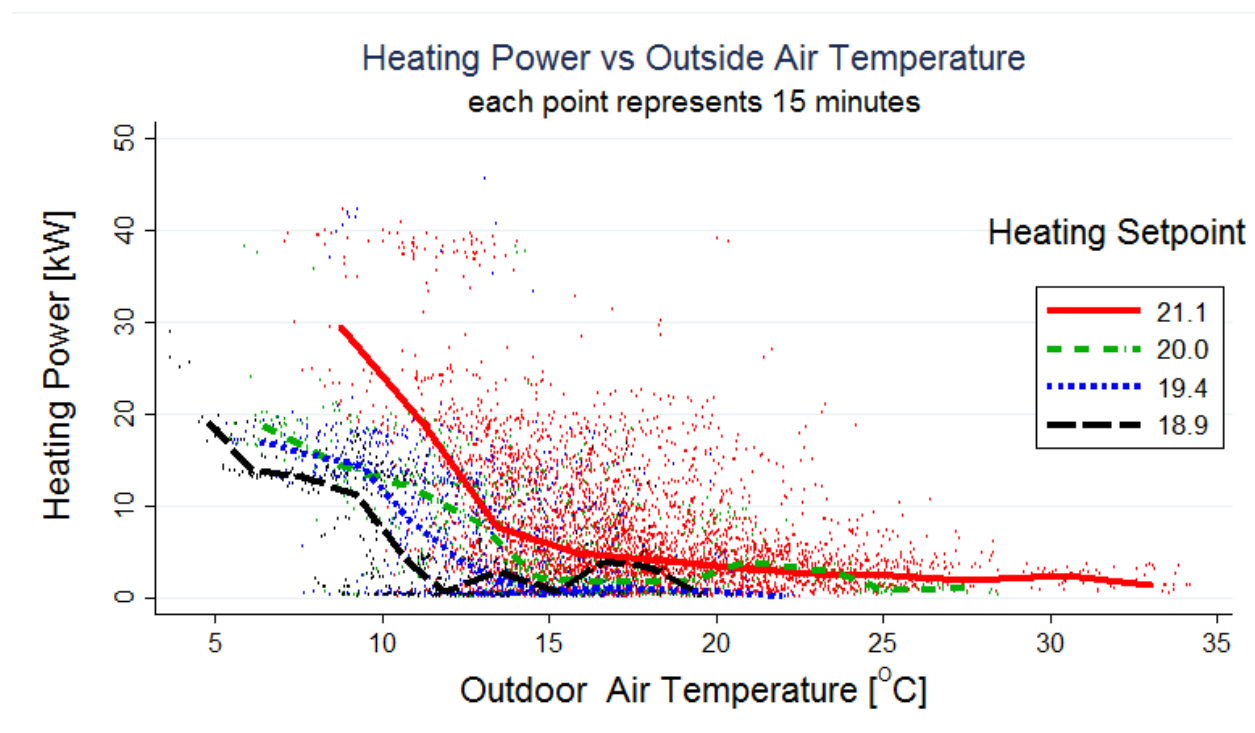


Figure 15– Heating power versus outdoor temperature

By measuring the footwarmer power and the HVAC heating power, it is possible to calculate the overall change in per-capita power from the pre-existing 21.1°C base-case. Figure 16 shows the average energy use of the 12 footwarmers and the average HVAC consumption of the room with its 16 occupants (per occupant), separated into cool versus colder outdoor temperature ranges. The X-axis represents the lower setpoint values for the 12 study periods, the same values as shown in Figures 4 and 6 through 12. It shows the per-capita HVAC heating power being reduced by 38 – 75% depending on the setpoint and on the outdoor temperature. The reduction ranges from 200W to over 400W per occupant on average. In comparison, the average footwarmer power use is very small, from 3W to 21W depending on the room temperature (21.1°C and 18.8°C respectively; Figure 17).

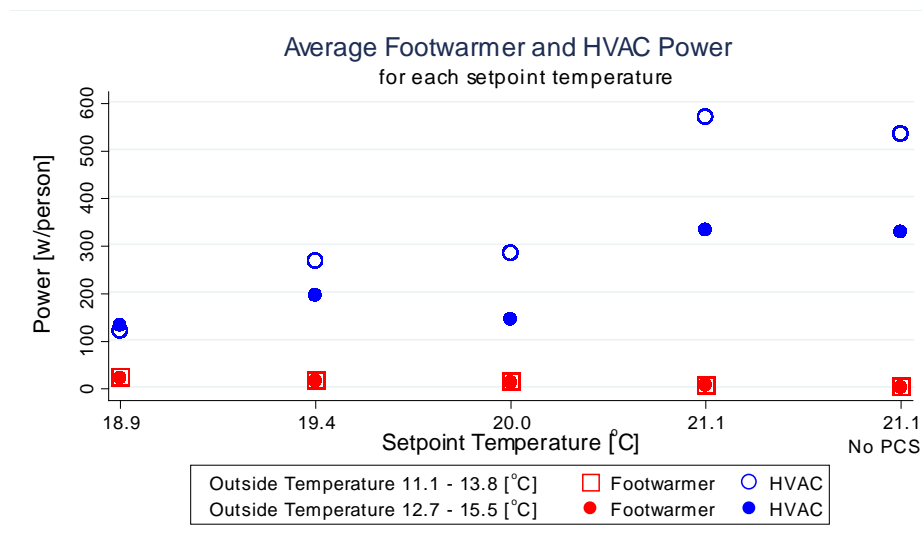


Figure 16 – Average footwarmer and HVAC power per workstation

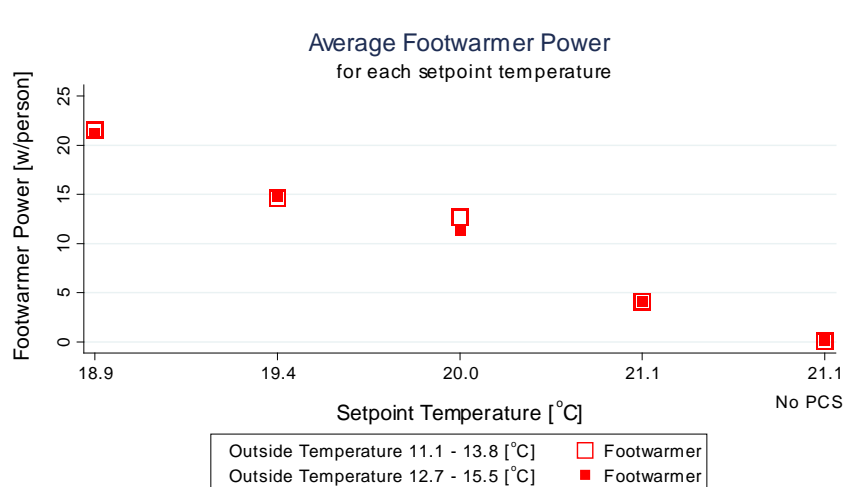


Figure 17 - Increase in footwarmer power with decreasing setpoint

Exit Survey Results

Comments from the 12 footwarmer users indicated that the footwarmers provided the desired amount of warmth throughout the study. Some of them said that they didn't use the device often because they were not cold. Some footwarmer users and the 4 non-users found the footwarmer ergonomics problematic. The front upper edge which could touch people's shins was noted, suggesting that the shape of the footwarmer might be improved, or that the front edge could be softened. One short-legged person needed a way to raise the footwarmer above the floor, and to be able to adjust its tilt.

DISCUSSION

Corrective power: throughout the study (including the base-case reference condition in Period 1), whole-body thermal sensation remained between ‘neutral’ and ‘slightly cool’ (Figure 8), and the feet thermal sensation was neutral (Figure 10). The occupants’ thermal acceptability remained essentially constant, and well above the 80% threshold prescribed in ASHRAE Standard 55 (Figures 6 and 7). This establishes that the footwarmers’ ability to offset the effects of cooling the ambient surroundings (termed their ‘corrective power’ [22]) is at least the difference between 18.9°C (66°F) and 21.1°C (70°F), or 2.2K (4°F). The full extent of their corrective power was not determined in that the base-case thermal sensation was already slightly lower than neutral, and the lowest temperature tested may not have been the lowest one acceptable to the occupants.

Simulated savings: this study’s measured energy savings can be compared to a nationwide set of EnergyPlus simulations of office building energy use as a function of indoor setpoints [1]. The simulations used the DOE Medium Office reference model with its system sized for its climate. For the San Francisco climate, the simulations predicted a 28% saving from the lowered heating setpoints used in this study. This compares to the 38% - 75% saving measured here. The reference model is a modern and better insulated building than the test building, which presumably explains some of the difference. Although smaller, the 28% simulated savings from adjusting the heating setpoint 2.2K is still very significant.

Time at workstations: the time of people perform work in their workstations vary. The occupants in this building stated in interviews that they are in their workstations 90% of the time. If they had stayed less (say 45%, common in some offices), how would these results differ? First, there would clearly be less energy used by the footwarmers themselves. The per-person footwarmer energy use in this study would be halved to 1.5 – 10.5W. Second, during the times occupants are away from their footwarmers but still within the building, their comfort might be reduced. The amount would depend on the nature of the absence. Laboratory studies that included 10- and 15-minute break periods from PCS did not show reduced comfort during the breaks, partly due to the warmth produced by the exertion of standing and moving [9]. However if the absent occupant has gone to sit somewhere else for a period of time, such as in a conference room, some form of PCS or independent room temperature control may need to be provided to maintain comfort.

Study limitations: there are several limitations to the study design and its accomplishments:

Although the study continued for half a year, and about 2774 individual survey responses were received, the number of occupants involved is fairly small (16), with only 12 of them providing footwarmer use and performance data.

The study could not compare the effects of lowered setpoint temperatures with and without footwarmers. The study site is an important building in the library, and it would not have been possible to lower the building's setpoints without offering the occupants some remediation. The occupants had important jobs, performing high-level curatorial, design, editing, and computer programming tasks. It was clear that if even a few of them had complained about the cold, the study would have been shut down. So the study was not designed to determine the percentage of the occupants that would have accepted the lowered temperature in the absence of footwarmers.

The primary objective was instead to confirm that footwarmers would provide comfort to this type of occupancy over a long period of time, within the ranges of temperature tested. The approach was to slowly lower the ambient temperature and monitor the comfort responses to see that we were not going too far. By keeping comfort essentially constant throughout the test sequence, the study confirmed that the expanded indoor temperature range was feasible in an actual building.

Those subjects who did not use the footwarmer found the environment almost as acceptable as those who did. This might be expected because any population will have a range of tolerance to cold, and the more tolerant occupants may have found no need to use the footwarmers. But this cannot be proved from the data because some of these occupants cited ergonomic issues for not using the footwarmer.

Although the study could not prove this, it is unlikely that the entire occupancy could have been subjected to the study's lowered temperatures without footwarmers, while continuing to vote that the temperature was acceptable. There are two observations supporting this assertion. First, the linear increase in average footwarmer power at lowered temperatures (Figure 17) indicates that occupants were actively and systematically using the footwarmers in response to the room conditions. They would not have done this without a comfort impetus. Second, the occupancy's interpersonal variation in cold sensitivity is seen to be significant. Cold-sensitive individuals determine the need for heating, not those who are cold-adapted. When the testing reached the 18.9C setpoint, some of the female footwarmer users were observed to have significantly increased their clothing (vest or jacket). The research team decided at this time not to further lower the setpoint, lest these presumably coldest individuals begin to complain. So the lower limit for this occupancy was not definitely determined, but evidence was provided that this range was practical.

The survey intentionally did not ask questions about other body parts than the feet, such as the hands, even though the hands are also sensitive to discomfort in cool environments [6,33,39]. It is important to limit the number of repeated questions so that respondents do not become fatigued with the questioning, which will affect the accuracy of the responses. One might argue that after many repeats of the survey, the subjects know that they are only being asked about

their feet and whole-body sensations and acceptability. It is then likely that their hand sensations will then be embodied in their whole-body responses. However this cannot be proven by this study.

The weather in this study was mild compared to many continental temperate climates, and the building less insulated compared to many modern buildings. Can these results be compared to colder climates and more insulated buildings? This can be done conceptually using the buildings' balance points, where their internal loads equal their heat losses through envelope and system. The study building has a relatively high balance point temperature (12-15°C depending on indoor setpoint temperature, Figure 15). The outdoor temperatures though mild were cold enough to require central heating throughout the study. In the cooler periods the footwarmer-lowered setpoints produced greater savings both relatively and absolutely (compare the open circles to the solid dots in Figure 16). It is not possible to project how these observed savings would have continued to increase had the outdoor temperatures been colder than they were. We also cannot generalize to savings from footwarmer use in a better insulated building in a colder climate. At the limit, if the balance point of a building's perimeter zones is below the outdoor temperature, there will be no need for heating, and therefore no savings from footwarmers. But in most climates the balance point of even large well-insulated buildings is higher than the outdoor temperature in winter, so heating is needed and lowering the indoor setpoints will save energy.

CONCLUSIONS

This appears to be the first study of a personal heating system in an office building, in which both comfort and energy savings were quantified. The occupancy had a representative age distribution and was performing skilled knowledge work.

Occupants were provided with low-power footwarmers during a six-month winter test period in which their room setpoint was gradually reduced from 21.1°C to 18.9°C and then back up to 21.1°C. Footwarmer use increased with lowered setpoints. Including the 25% of occupants who chose not to use the footwarmers, there was no statistically significant difference in occupants' thermal acceptability votes throughout the test sequence. The overall energy savings ranged from 38-75% during typical outdoor temperatures. The added plug load from the device was small in comparison to the savings in central heating power from the reduced setpoints.

This study does not establish a limit to the indoor temperature range that would be acceptable with these footwarmers, but it does provide evidence that the tested range is practical for long-term implementation in a real building occupied by workers engaged in white-collar work.

Efficient personal heaters used in conjunction with a lowered heating setpoint are a significant retrofit opportunity. Their cost is relatively low because they do not require any modifications to the envelope or mechanical system, and the savings are substantial. The design of the footwarmers tested in this study could be improved to enhance their ergonomics, based on feedback received from some occupants. Other occupants however were very attached to them and did not want to give them back at the end of the study.

ACKNOWLEDGEMENTS

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Appendix

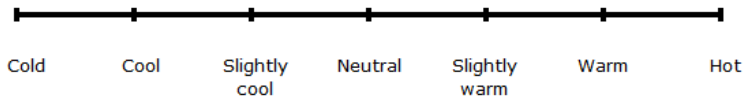
Online survey questionnaires

1. THERMAL ENVIRONMENT

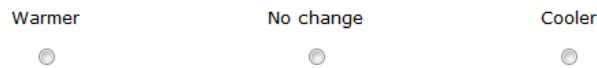
Right now, how acceptable is the thermal environment at your workspace?

Very acceptable    Not at all acceptable

You feel: (Please mark anywhere on the scale)



You would prefer to be:

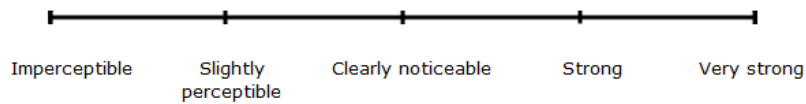


2. AIR MOVEMENT

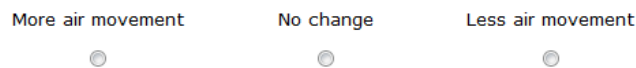
Right now, how acceptable is the air movement at your workspace?

Very acceptable    Not at all acceptable

The air movement feels: (Please mark anywhere on the scale)



You would prefer:



3. AIR QUALITY

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

Very acceptable    Not at all acceptable

Survey questions answered before footwarmers were distributed (base case condition)

Right now, does the desk fan provide enough cooling?

Yes No Not in use

Right now, does the footwarmer provide enough heat?

Yes No Not in use

Your feet feel: (Please mark anywhere on the scale)

—————
Cold Cool Slightly cool Neutral Slightly warm Warm Hot

5. COMMENTS ABOUT THE ENVIRONMENT PROVIDED BY THE PERSONAL COMFORT

If you have additional comments about your Personal Comfort System, click [here](#)

Submit >>

Questions answered after footwarmers were distributed