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THE USE OF FOOTWARMERS IN OFFICES FOR THERMAL COMFORT AND ENERGY SAVINGS IN WINTER

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ABSTRACT
Personal comfort systems provide comfort by targeting heating or cooling to important parts of the human body, making tight ambient temperature control less important. This paper provides evidence that comfort is possible under cooler-than-normal ambient temperatures when occupants have personal control over a very local thermal condition—the warmth of their feet. During a six-month winter period in Berkeley California, office workers were given low-energy adjustable footwarmers and the room heating set point was gradually lowered from 21.1C (70F) to 18.9C (66F). Occupant surveys showed statistically equivalent thermal comfort for the original 'higher heating setpoint no-footwarmer' condition and the 'lower heating set point plus occupant-controllable footwarmer' condition. The overall reduction in heating energy varied between 38% and 75% depending on the setpoint reduction and outdoor conditions. The added plug load energy from the low-energy footwarmers was substantially less than the heating energy saved by lowering the heating set point (11-21W 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 designs or options will be needed in future applications.

HIGHLIGHTS
- Personal control of a footwarmer allows room heating setpoints to be lowered in winter without negatively impacting thermal comfort
- Energy saved by lowering room heating setpoints is far greater than the plug load added to power low-energy footwarmers

KEYWORDS
Thermal comfort, personal control, personal comfort system, energy savings, HVAC, room heating setpoint, footwarmer

INTRODUCTION

Despite the large amount of mechanical energy spent on space conditioning in offices, it is difficult to satisfy the full range of occupants' individual thermal requirements and preferences. In a uniform environment, 20% of occupants are typically dissatisfied at any temperature within the comfort zones set by standards [1]. In real buildings, the large dataset from the CBE occupant's satisfaction surveys shows that of all the 9 indoor environmental quality factors related to the workplace, temperature consistently receives the 2nd lowest rank [2]. 42% of occupants express dissatisfaction with their thermal environment as evaluated over time [3], well above the 20% dissatisfaction limit suggested by standards. So the current thermal comfort in buildings is not that wonderful. It represents the existing baseline, but not the ideal. If, for example, a new personally-tuned environmental control technology existed that allowed for 100% of occupants to be satisfied within the normal comfort zone that would clearly be a great improvement over the current maximum of 80%.

Building operators typically select thermostat setpoint ranges that are narrower than allowed for by standards in the hope that this action will minimize the number of thermal complaints from their occupants. However narrow ranges confer questionable comfort benefit [4] at high energy cost [5]. Simulations show that for each degree Centigrade that the thermostat heating setpoint is lowered or the cooling setpoint raised, the total heating+cooling HVAC energy consumption is reduced 10%. If the range is extended several degrees, savings of 40 -50% are possible. If the above personally tuned technology had the capacity to provide equivalent or better comfort outside the normal interior comfort zones, substantial amounts of HVAC energy might be saved.

A number of personal comfort system (PCS) devices have been developed to heat or cool thermally sensitive parts of the human body. Laboratory studies have shown them maintaining comfort for individual occupants under expanded ambient setpoint conditions. The cooling mainly depends on convective cooling of facial regions [6-10] or by cooled chairs [11-13], and heating is mainly tested with heated chairs [14,15]. Laboratory and field research have also suggested that the simple availability of personal thermal control options at occupants' workstations improves their thermal comfort and satisfaction [16-18].

There have been relatively few field studies of PCS, mostly in warm seasons [19,20]. The authors have found only one instance of 100% thermal satisfaction in a field study, in a building where the occupants had PCS systems [21]. The results of that study showed that occupants' comfort was better at higher temperature with PCS than the condition without PCS at lower ambient temperature. Though the study was limited, this was a promising finding. To date, no PCS field studies have evaluated associated HVAC energy savings.

The PCS device evaluated in this study originated from a fundamental laboratory study [6] that established the extent to which cool feet dictates the discomfort of the entire body in cool

environments [22]. Not only are warm feet essential for maintaining comfort in cool environments, but also feet warming is very effective at restoring comfort. Based on this, the authors developed energy-efficient footwarmers that focus radiant heat on the feet and ankles. In a subsequent laboratory study these footwarmers were tested in realistic office workstations in which subjects were performing tasks representing office work [7]. The encouraging findings suggested a winter field study in which an actual office is provided with footwarmers. While its interior temperature is systematically varied, its occupants would be repeatedly surveyed about their comfort. At the same time, the energy savings associated with lowering the indoor temperature setpoints would be quantified.

METHODS
Footwarmer description: Because there were no efficient footwarmers available on the market, the authors designed and fabricated 100 for use in field studies. In order to create a rapid warming effect, the design uses incandescent reflector bulbs as heat sources. The filament and bulb heat 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 allows the footwarmer to provide the equivalent of 9F (5K) of whole-body heating using roughly 30W at steady state [6-7, 22-23]. This heating effect compares favorably to the typical 750 - 1500W heater found in office environments. These 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 maximum 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 a small desktop nozzle fan 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 (Arduino in this study) for power control, temperature and power sensing, and providing internet connectivity for controls and research purposes. The internet connectivity allows research to monitor and download the ambient air temperatures and the fan and footwarmer uses by occupants remotely.
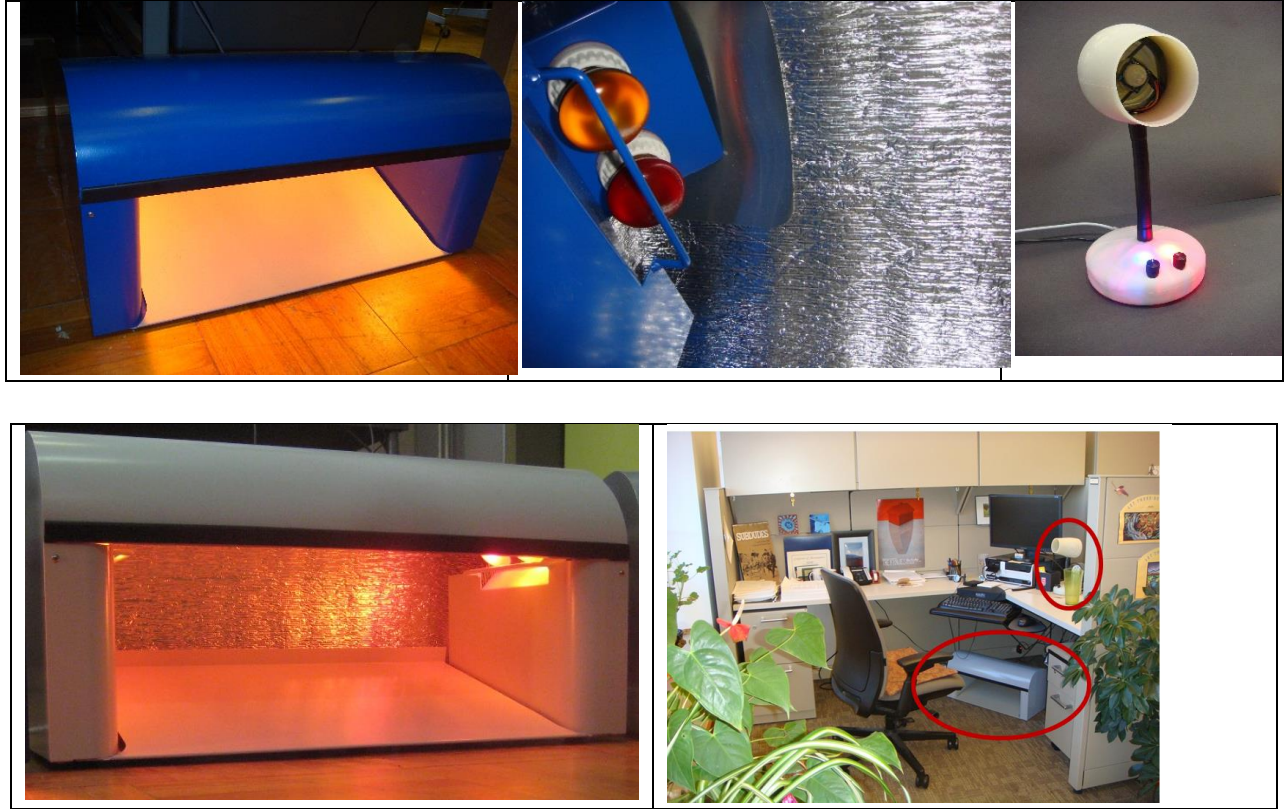
Figure 1 – PCS Fan and Footwarmer combination

Building description: The field study was conducted in a wing of a large office building on the University of California Berkeley campus, over the winter season of October 2012 - May 2013. The main façade of the office 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. None of the windows are operable. There are 16 occupants (8 females and 8 males) in the office all of whom participated in the study. About half of the occupants sit adjacent to windows and the other half are one workstation removed or in the room interior (Figure2).

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).

Figure 3 – Floor plan showing occupied workstations

Setpoint change and survey period: The time period available for this study, October 2012 through May 2013, is heating-dominated for buildings with low-to-medium internal loads (ASHRAE Climate Zone 3c and California Climate Zone 3). Temperatures and humidities are fairly moderate. The weather file from the nearby Oakland International Airport (OAK) contains 2909 heating degree days at base 65F (1616 at base 18.3°C) and 128 cooling degree days at base (28.2°C) annually.

The pre-existing heating and cooling setpoints for the office were 21.1°C (70°F) and 22.2°C (72°F). The base case condition for the study was the original heating setpoint of 21.1C with no footwarmer (period 1). We surveyed occupants' thermal comfort under the base case condition, then delivered the footwarmers and started to lower the heating setpoint. During a series of three-week periods during the 6-month study period, 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 steps to 21.1ºC. The first two weeks in each three-week period were designed to allow the subjects to adapt to the new setpoint, and repetitive occupant satisfaction surveys were performed in the third week. The third week is called "survey period". Figure 4 shows the timeline of the 12 survey periods for the study. 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.
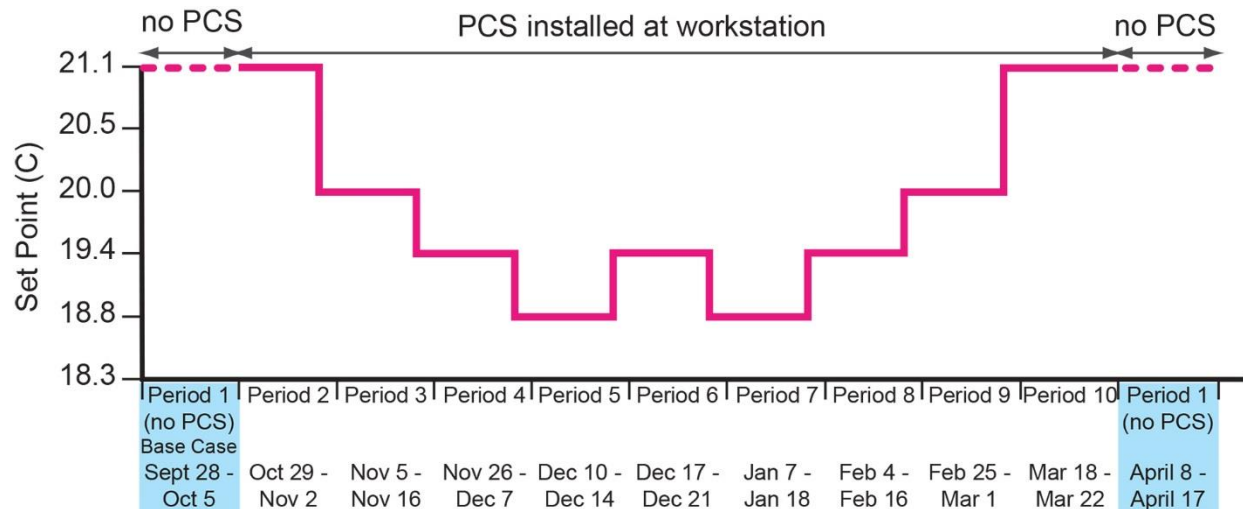
Figure 4 – Timeline showing progression of the heating setpoints for the 12 survey periods

HVAC system and energy monitoring: This wing of the building employs a single-duct VAV reheat system with separate setpoints for heating and cooling. Its HVAC system has Automated Logic controls, is BACnet compatible and its 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 calculating the energy consumption of the mechanical system. The thermostats were locked to prevent occupants from changing settings.

The energy consumption of the HVAC system was 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 building management system (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 [24] (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 later the PCS footwarmer units) to monitor workstation plug loads.

Occupant satisfaction survey: During the survey week, occupants were invited to take web-based "Right Now" survey three times a day 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 survey questions are presented in the Appendix. The three votes towards "Not at all acceptable" point are considered as "unacceptable". The survey also asked thermal sensation using the ASHRAE seven-point scale, and if they would prefer to be warmer, cooler or no change. The thermal sensation and thermal preference questions were also asked for the occupant's feet, to determine whether the footwarmer was producing enough heat.

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

RESULTS
Environment
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.
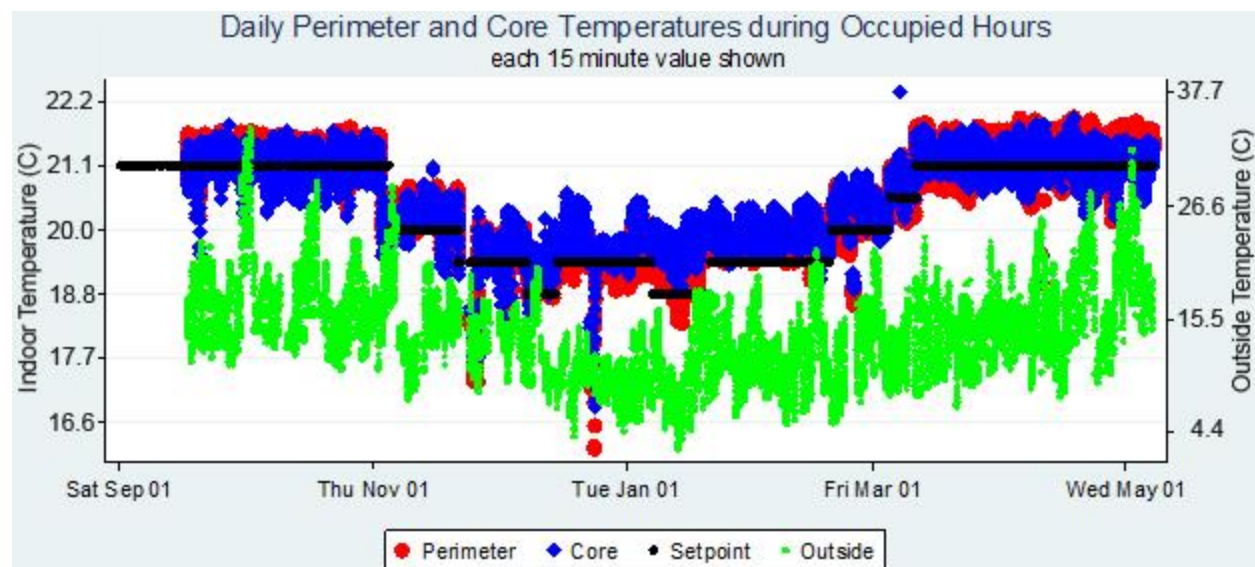

Figure 5 – Core, perimeter, setpoint and outdoor temperatures during the study (occupied hours)

The ambient air temperature setpoints shown by the black dots are the same values as shown 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. In general, the ambient air temperature followed the setpoints well. Most of the time, the air temperatures in the perimeter zone and the core zone are very similar, with slightly cooler temperatures in the perimeter zone in January.

Thermal Comfort Results

A walkthrough confirmed that the occupants did not have any portable heaters installed prior to being given the footwarmer for the study. Several portable fans were in use. The subjects spent most of the work day at their desks. 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.

During the study, four occupants didn't use the footwarmers — one felt that the radiation on the skin was irritating; three for ergonomic reasons regarding the position and design of the footwarmer, which will be described later. To understand the effect of the footwarmers on thermal comfort, the survey results described below are only from the 12 actual users of footwarmers (6 males and 6 females), unless otherwise noted.

"Survey period" in Figure 6 refers to specific weeks at several different setpoint temperatures as described in Figure 4. During these weeks the occupants received repeated "right-now" surveys. Each boxplot in the charts below represents the average survey results for each survey period.

Thermal acceptability. Figure 6 below shows the right-now survey results for each of the 12 survey periods 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. The numbers just above the x axis represent the number of votes of the boxplot above it and the acceptability in percentage (%) for that survey period. The median in each box is shown by a thick horizontal line and the mean is shown by a thick dot. The "*" represents the statistical significance of means between the base-case condition (Period 1) and any other period.

The comparison is done between the base-case condition (Period 1) and the rest of the periods when the setpoints were lowered and the occupants were given footwarmers. The medians of the thermal acceptability in Figure 6 remain the same throughout the study. The means are fairly constant too, with variation less than 0.5 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 remaining ten periods in which occupants had footwarmers and the setpoint was gradually lowered and raised. The variations in acceptability rates are not statistically different between the base case and the most of the remaining periods. The dissatisfied outliers (dots more than 1.5 times the interquartile range below the lowest datum within the range) are from one person who was in general dissatisfied with the thermal comfort in the office, but who said in the exit interview that the footwarmer had provided sufficient heat.
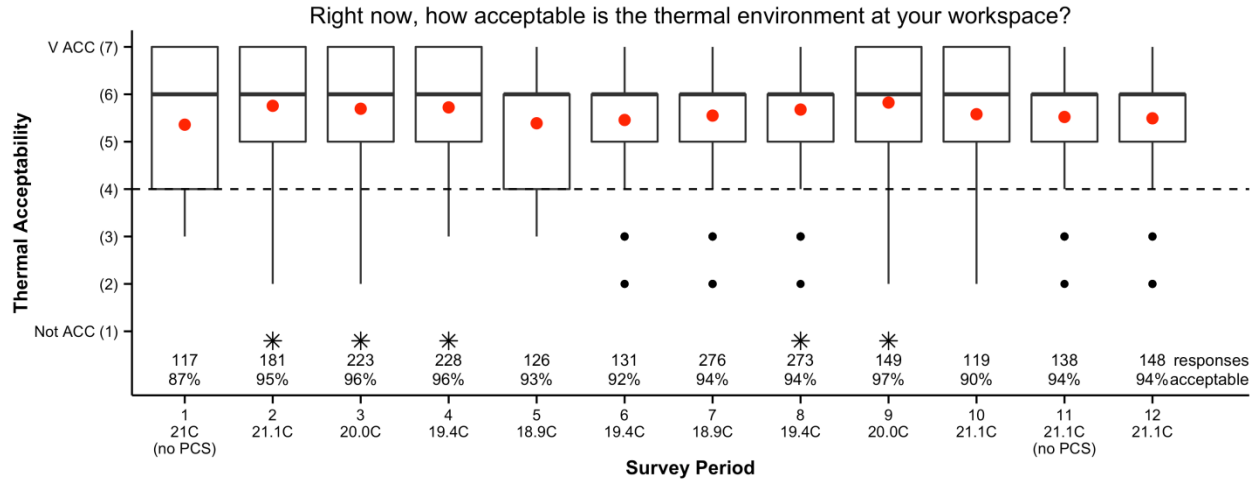
Figure 6 – Thermal acceptability

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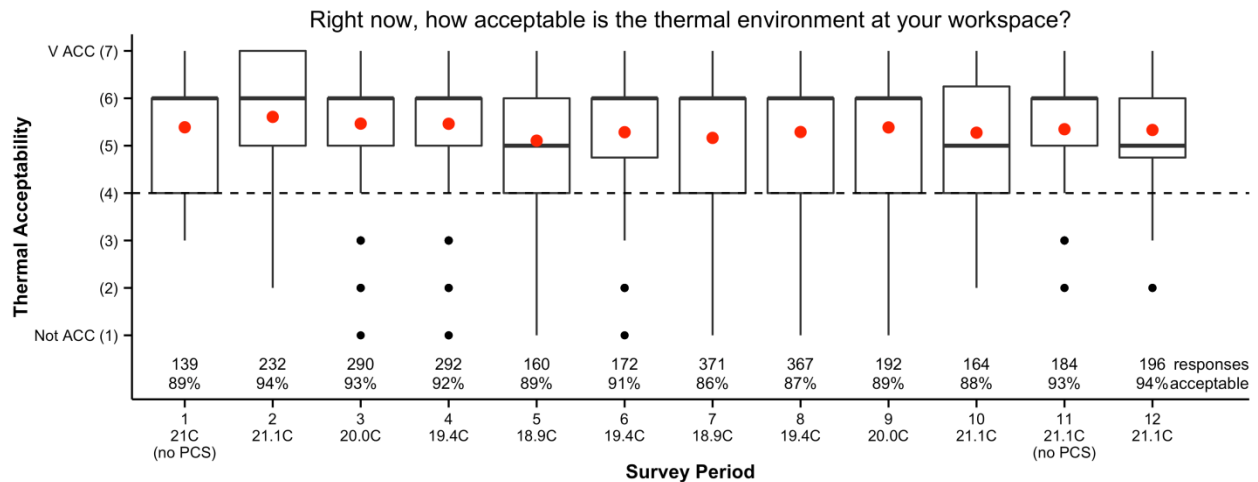

Figure 7 – Thermal acceptability for all 16 participants

Thermal sensation. Figure 8 shows that whole-body thermal sensation votes are 'slightly cool' in the base case conditions, improving in the direction of 'neutral' upon receiving the footwarmer at the same setpoint, dipping back towards 'slightly cool' as the setpoint is lowered, and then returning towards 'neutral' when the setpoint is 20°C and 21.1°C again. 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 at the lower temperatures, but it appears that this is not necessary for thermal acceptability with this local personal comfort system.

Comparing the 20°C and 21.1°C room temperatures at the beginning and end of the study, the thermal sensation was "slightly cool" at first, but was "neutral" at the end. This may indicate that people were adapting to cooler environments during the period that the room temperature setpoint was lowered.
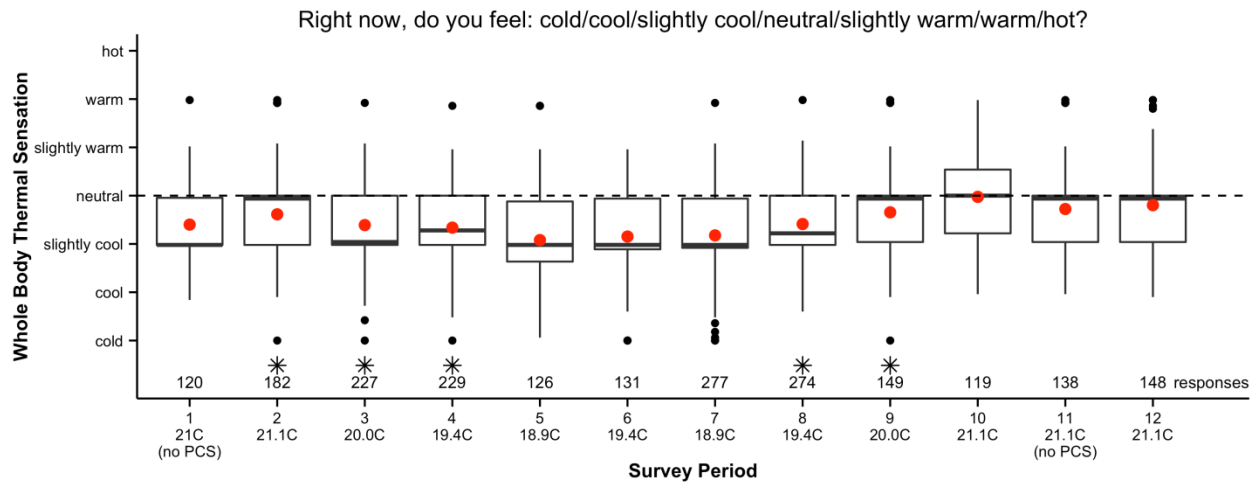

Figure 8 – Whole body thermal sensation

Feet thermal sensation. Feet thermal sensation responses are shown in Figure 9. The spread in the data is wider than for other questions, for both warm and cool feet thermal sensation. The warm outliers are likely due to the use of footwarmers. The cool outliers likely happened during the time when footwarmers were not used, because (as will be described below), almost all the occupants who were using the footwarmers during the time of the survey said that the footwarmer provided enough heating. As the setpoint temperature was lowered, the median and mean for the feet thermal sensation in each survey period remained close to neutral. This occurred even as whole body thermal sensation votes dipped towards slightly cool (Figure 8). This indicates that the footwarmer (or access to it) consistently kept most people's feet perception neutral even if their whole body thermal sensation was slightly cool.
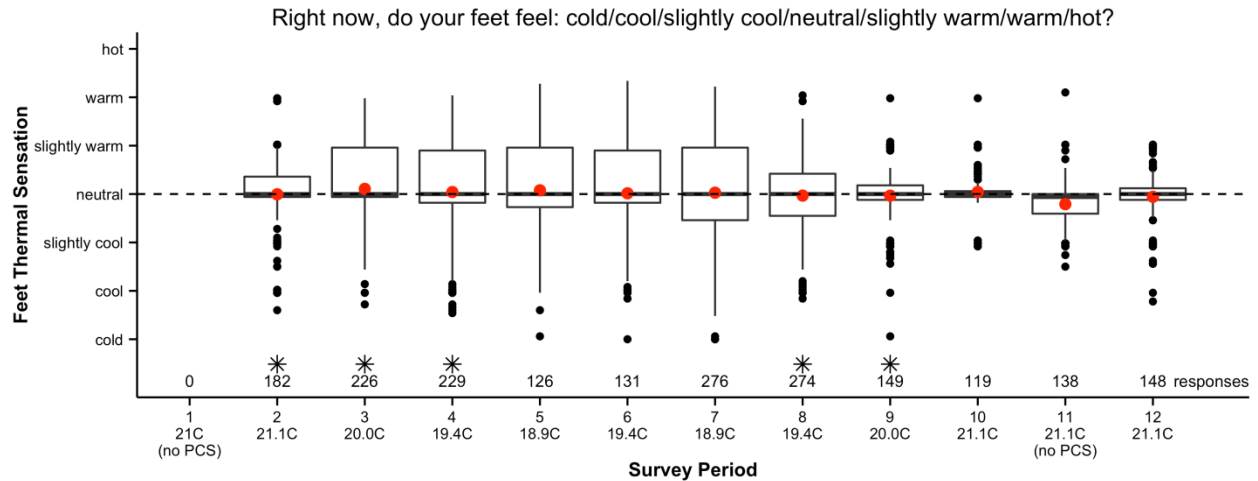
Figure 9 – Feet thermal sensation

Footwarmer performance. Figure 10 shows whether the footwarmers provide enough heating. The setpoints for the 12 periods are presented on the x axis. The green line represents the percentage of survey responses in which footwarmers were in use at the time of the surveys. The red line indicates when the footwarmer was providing enough heat and the blue line when the footwarmer did not. These percentages are also presented in the table below the chart. 47% and 51% of occupants were using the footwarmer at the lowest setpoint (18.8°C), meaning that about half people were not using the footwarmers during the time of the survey even at the lowest ambient temperature setting. The red line and green line are very close, meaning that for those people who were using the footwarmers, they felt that the footwarmer provided enough heat. Only 1 – 3 % of votes in each survey period indicated that the footwarmer did not provide enough heat. The data show footwarmer usage increasing as the setpoint was lowered, and diminishing as the setpoint approached the baseline of 21.1°C. Also, 13–20% of occupants used the footwarmer even when the room heating setpoint was at the baseline setpoint of 21.1°C, suggesting that a number of people found the footwarmer beneficial at the baseline temperature.
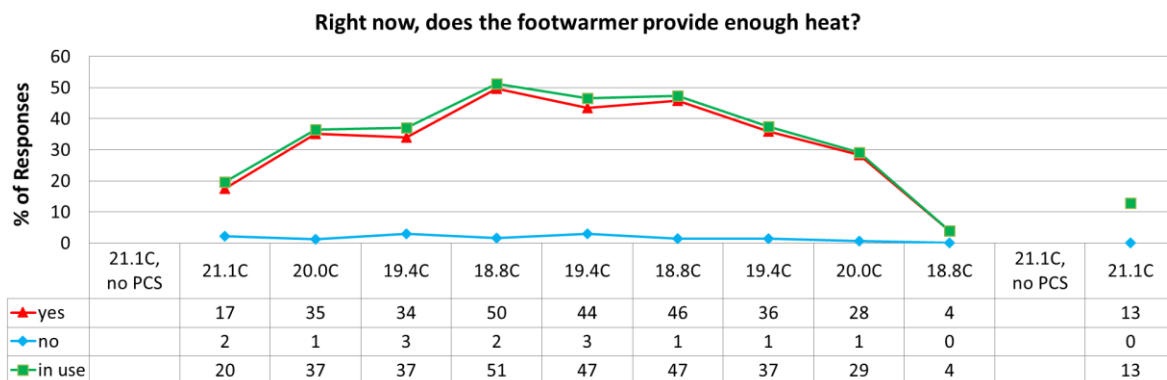

	21.1C, no PCS	21.1C	20.0C	19.4C	18.8C	19.4C	18.8C	19.4C	20.0C	18.8C	21.1C, no PCS	21.1C
yes		17	35	34	50	44	46	36	28	4		13
no		2	1	3	2	3	1	1	1	0		0
in use		20	37	37	51	47	47	37	29	4		13

Figure 10 – Performance of the foot warmer

Thermal sensation in mornings vs. afternoons. Figure 11 shows that there were no statistical differences in whole-body thermal sensation between mornings and afternoons.
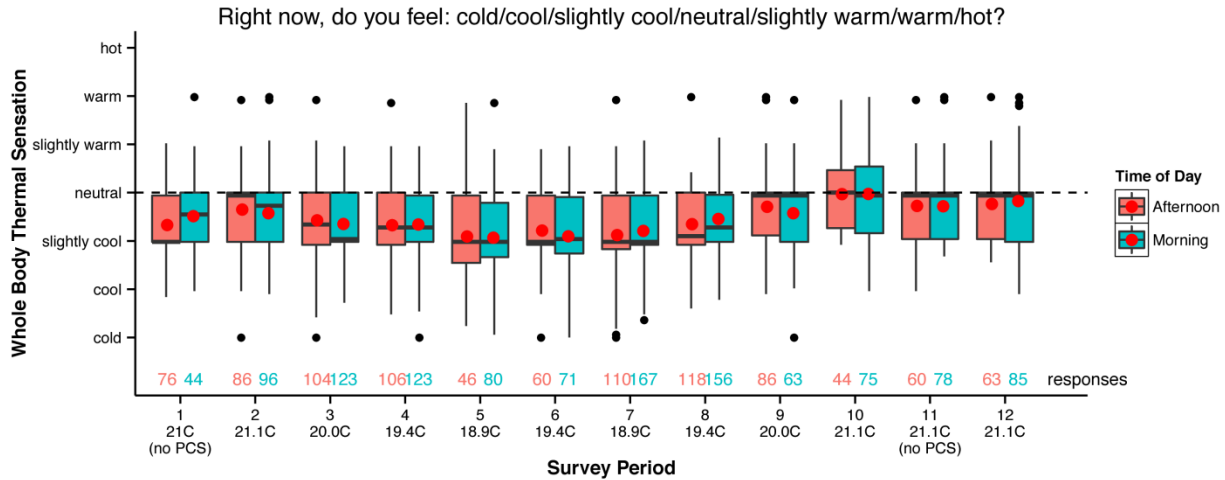

Figure 11 – Whole body thermal sensation - morning versus afternoon

Thermal sensation between genders. Figure 12 shows that males' whole-body thermal sensation was slightly cooler than females. The difference was statistically significant for most of the study periods (as represented by "*"). This could be caused by clothing difference between men and women in winter. Frequent visits to the study site revealed that women wore more insulating clothing (sweater, vest), while men normally wore a T-shirt + a long-sleeve shirt.
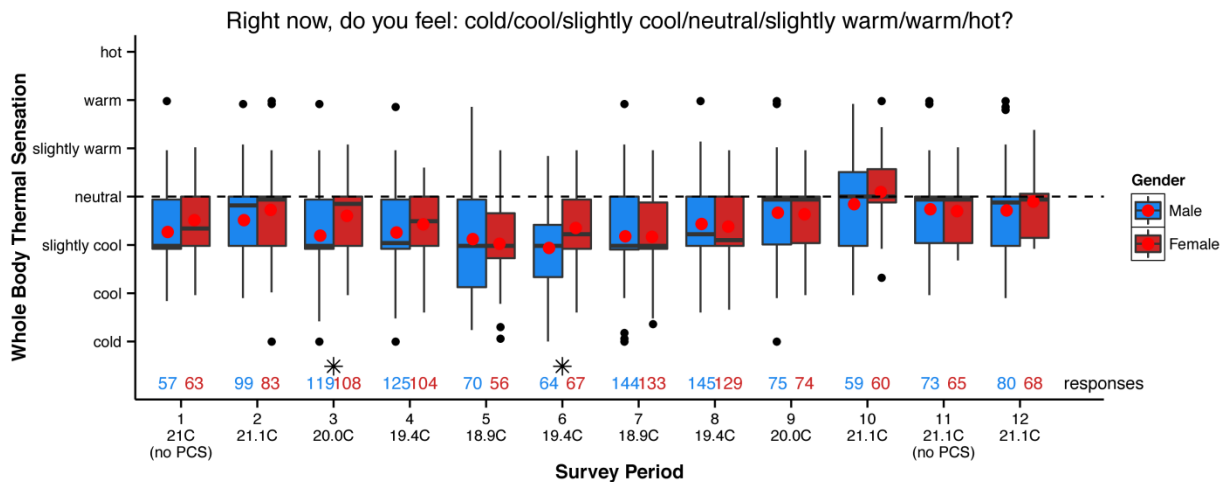

Figure 12 – Whole body thermal sensation – males versus females

Energy Performance Results

Using the power readings recorded at each workstation, a sample of average footwarmer power is shown in Figure 13.

People typically used the footwarmer at full power or not at all, as opposed to adjusting the power setting between 0-100%. Also, the footwarmer was used for short periods of time sporadically throughout the day. The footwarmer is only activated when the feet are inside pressing down on an occupancy-sensing pressure plate . Therefore it is always off when people are not at their desk, whether or not they have turned the footwarmer off.
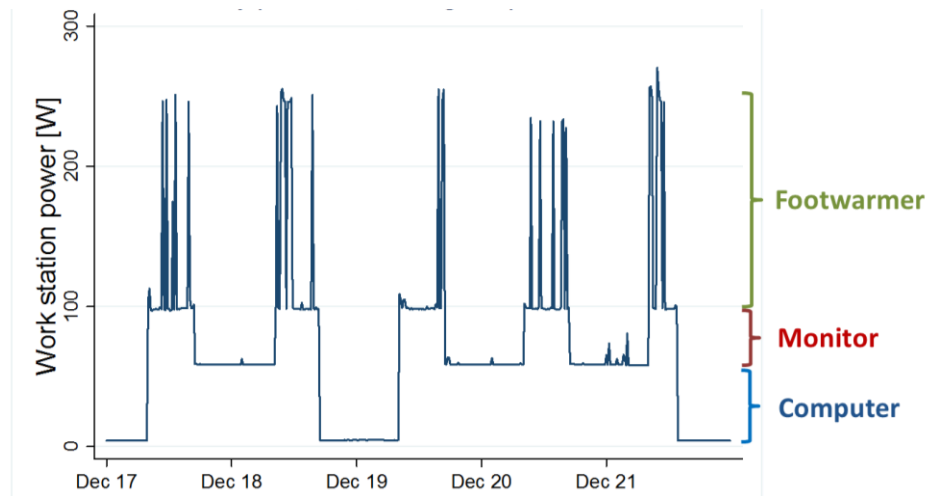

Figure 13 – Power consumption at the workstation

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 throughout 5 days of 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 may have adapted to the cooler zone temperatures later in the study and felt they needed less heat from the footwarmer to keep warm.
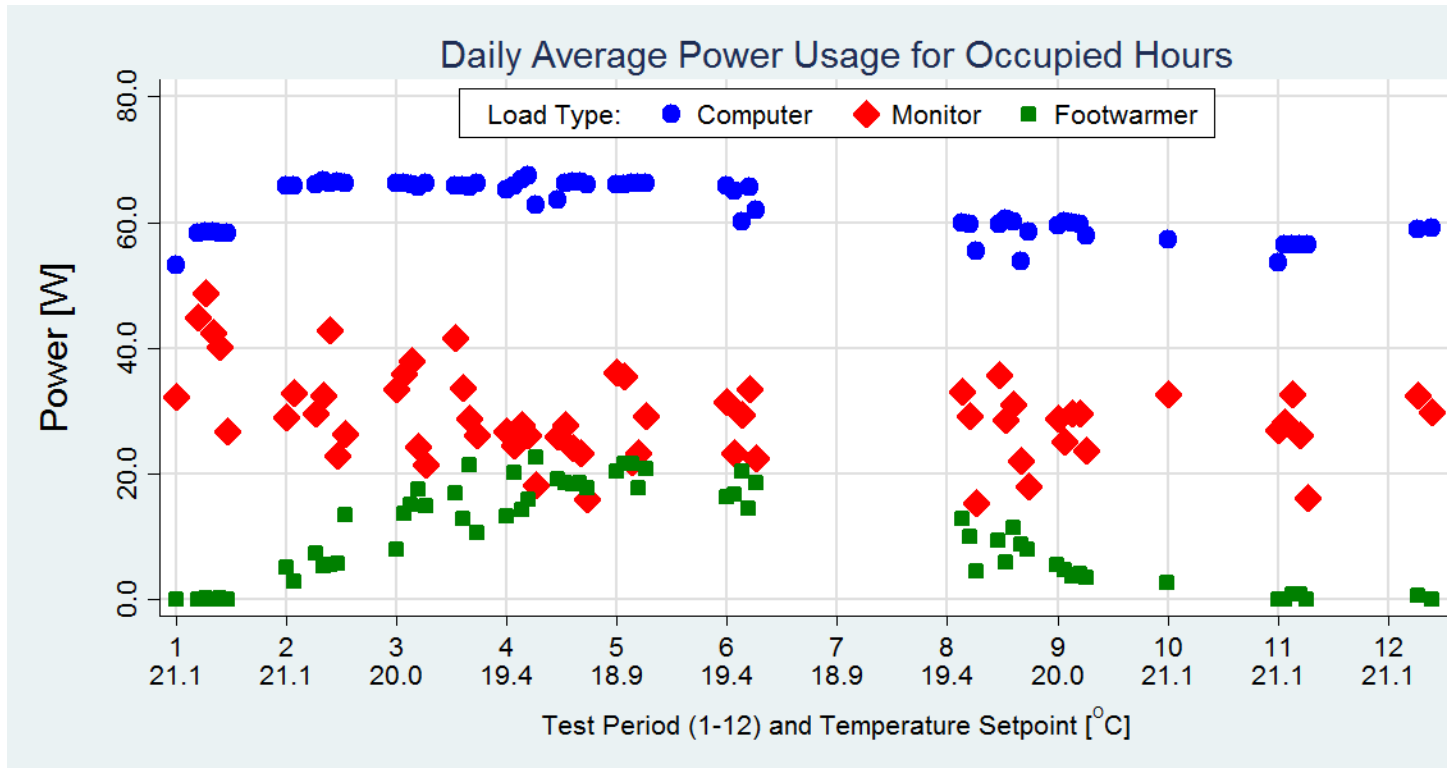
Figure 14 – Division of load for period 1 - 12

Figure 15 shows the room's central heating power decreasing as the outdoor temperature increases and lowers the temperature difference between indoors and outdoors. The figure also shows four lines indicating the median of the datapoints corresponding to each of the test setpoints. The balance point of the room (where each sloped line reaches zero power) ranges between 12 and 15°C. The shift in balance points is somewhat greater than the shift in interior temperature caused by setpoint changes. The balance point is more clearly defined at lower outdoor temperatures.
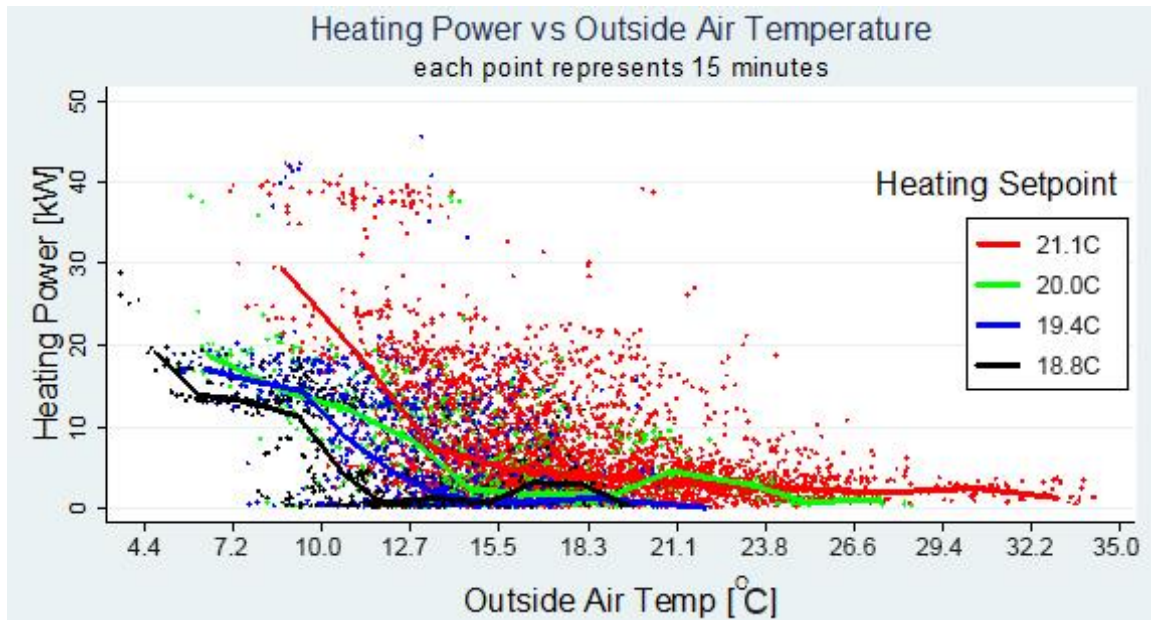
Figure 15– Heating power versus outdoor temperature

From 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 footwarmer and HVAC consumption per occupant on average, divided into two groups representing the relative cool versus cold outdoor conditions. It shows that the per-capita HVAC heating power was reduced by 38 – 75% depending on the setpoint and on the outdoor temperature range during which the setpoints were reduced. The reduction translates to 300-550W per occupant on average. The footwarmer power is almost negligible in comparison, averaging 3 (21.1°C) to 21W (18.8°C) depending on the room temperature (Figure 17).
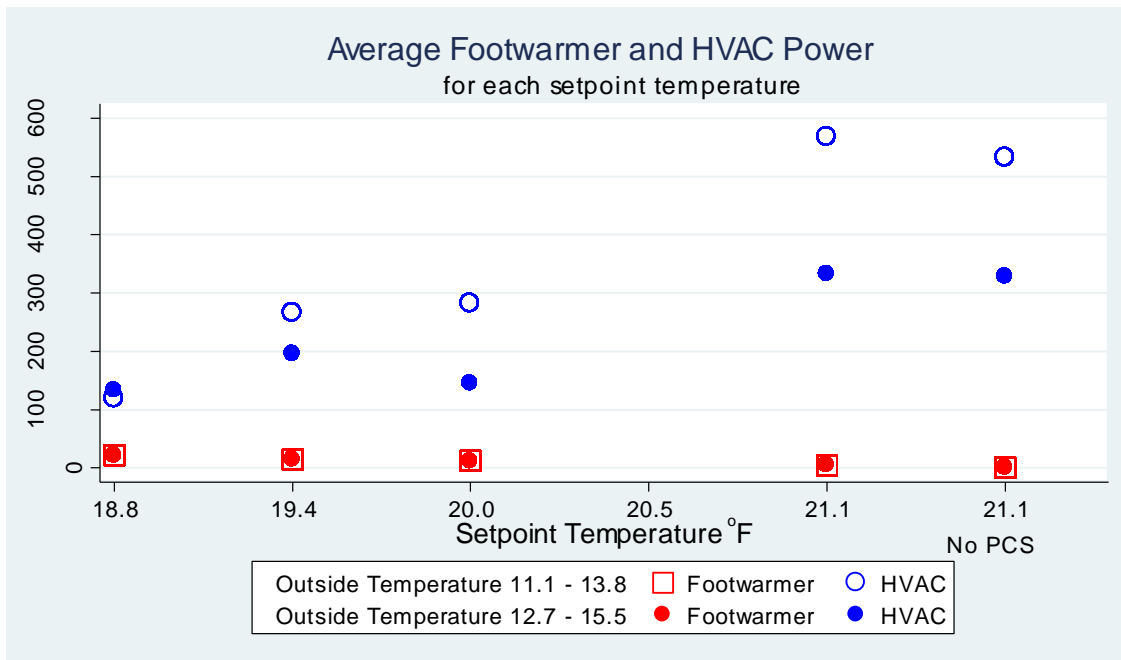
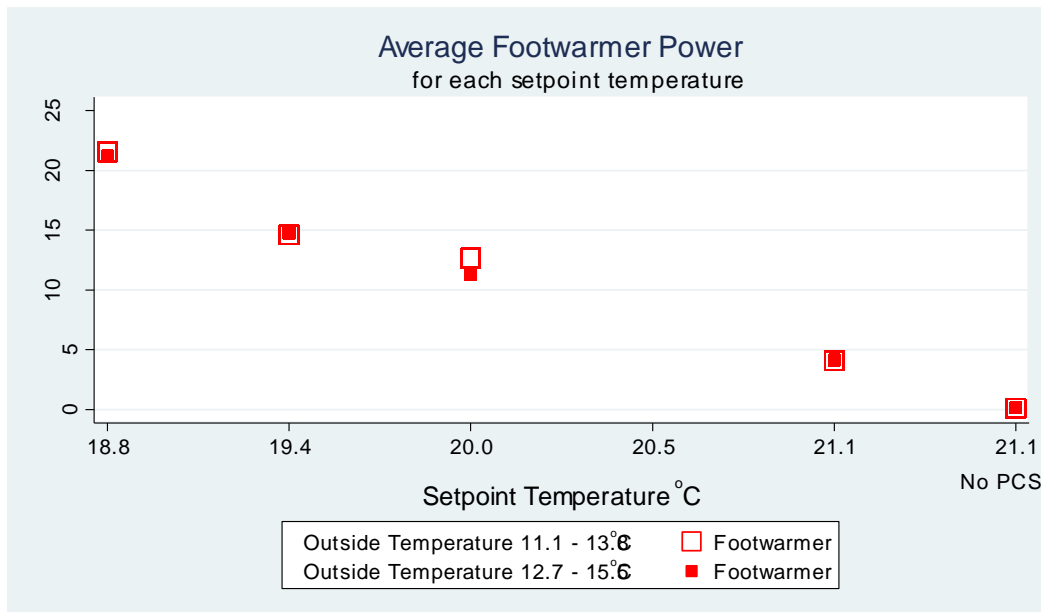Figure 16 – Average footwarmer and HVAC power per workstation

Figure 17, showing the 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 the footwarmer non-users said that they didn't use the device because they were not cold. Some footwarmer users found the footwarmer

ergonomics problematic due to the low front which could touch people's shins, suggesting that the ergonomic design of the footwarmer might be improved.

DISCUSSION

Despite some instances of overall cool thermal sensation , the footwarmers may be creating good acceptability through a spatial version of the theory of alliesthesia [6,22-23,25]. Alliesthesia posits that the greatest sensory pleasure occurs during stimuli that correct an imbalance in the body's homeostasis. For example warmed feet will create very high whole-body thermal comfort when the overall sensation is 'slightly cool' in a cool environment. The most comfortable environments might therefore contain some amount of non-uniformity. Spatial alliesthesia offers an alternate way of providing thermal comfort from the conventional isothermal neutral environment. A more non-uniform environment that focuses small amounts of corrective thermal stimuli on the occupant can be pleasant and may offer great opportunities for energy-efficiency.

Throughout the study (including pre-case reference condition, Period 1), whole-body thermal sensation was roughly 'slightly cool' (Figure 8). The feet thermal sensation was always neutral (Figure 9), and the overall thermal acceptability was also essentially constant throughout the study, well above the minimum 80% acceptable threshold set forth in ASHRAE Standard 55. People do not necessarily require a neutral thermal sensation to find the thermal environment of their workspace acceptable.

The measured energy savings (38% - 75%) from lowering the heating setpoint were considerably greater than predicted using EnergyPlus (28%) [5].

CONCLUSIONS

Occupants were provided with low-power footwarmers during a six-month test period in which their room setpoint was gradually reduced from 21.1C to 18.9C and then back up to 21.1C. Footwarmer use increased with lowered setpoints. For the large majority using the footwarmers, thermal acceptability improved with the reduced room temperatures. Including the 25% of occupants who chose not to use the footwarmers, there was no statistically significant difference in thermal acceptability 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 heating power savings from the reduced setpoints.

When retrofitting existing buildings for energy efficiency, adding personal comfort systems can be a way to achieve significant savings at low cost because they do not require any modifications to the envelope or mechanical system.

More detailed results of this study are available in reference [26].

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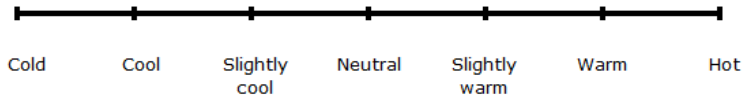
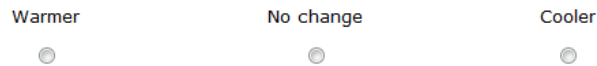**Appendix**

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*)

|———|———|———|———|———|———|

Cold   Cool   Slightly cool   Neutral   Slightly warm   Warm   Hot

You would prefer to be:

Warmer   No change   Cooler
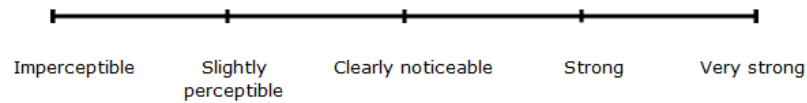
◎   ◎   ◎

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*)

|———|———|———|———|

Imperceptible   Slightly perceptible   Clearly noticeable   Strong   Very strong

You would prefer:

More air movement   No change   Less air movement

◎   ◎   ◎
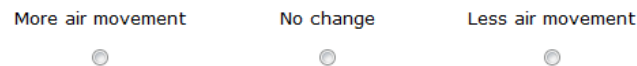
3. AIR QUALITY

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

Very acceptable 👍 ◉ ◎ ◎ ◎ ◎ ◎ 👎 Not at all acceptable

Survey questions 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 >>

Added questions about the footwarmer use after they were distributed