UC Berkeley
Indoor Environmental Quality (IEQ)

Title

Occupant comfort and behavior: High-resolution data from a 6-month field study of personal comfort systems with 37 real office workers

Permalink
https://escholarship.org/uc/item/9vv4z3gg

Authors

Kim, Joyce
Bauman, Fred
Raftery, Paul
et al.

Publication Date
2019

DOI
10.1016/j.buildenv.2018.11.012

Copyright Information
This work is made available under the terms of a Creative Commons Attribution-NonCommercial-ShareAlike License, availalbe at https://creativecommons.org/licenses/by-nc-sa/4.0/

Peer reviewed

Occupant comfort and behavior: High-resolution data from a 6-month field study of personal comfort systems with 37 real office workers

Joyce Kim[1*], Fred Bauman[1], Paul Raftery[1], Edward Arens[1], Hui Zhang[1], Gabe Fierro[2], Michael Andersen[2], David Culler[2]

[1] Center for the Built Environment, University of California, Berkeley, CA, USA
[2] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA, USA
* Corresponding email: joyce_kim@berkeley.edu

Abstract

Personal Comfort Systems (PCS) provide individual occupants local heating and cooling to meet their comfort needs without affecting others in the same space. It saves energy by relaxing ambient temperature requirements for the HVAC system. Aside from these benefits, PCS offers a wealth of data that can describe how individuals interact with heating/cooling devices in their own environment. Recently developed Internet-connected PCS chairs have unlocked this opportunity by generating continuous streams of heating and cooling usage data, along with occupancy status and environmental measurements via embedded sensors. The data allow individuals' comfort and behavior to be learned, and can inform centralized systems to provide 'just the right' amount of conditioning to meet occupant needs. In summer 2016, we carried out a study with PCS chairs involving 37 occupants in an office building in California. During the study period, we collected >5 million chair usage data-points and 4500 occupant survey responses, as well as continuous measurements of environmental and HVAC system conditions. The data analysis shows that (1) local temperatures experienced by individual occupants vary quite widely across different parts of the building, even within the same thermal zone; (2) occupants often have different thermal preferences even under the same thermal conditions; (3) PCS control behavior can dynamically describe individuals' thermal preferences; (4) PCS chairs produce much higher comfort satisfaction (96%) than typically achieved in buildings. We conclude that PCS not only provide personalized comfort solutions but also offer individualized feedback that can improve comfort analytics and control decisions in buildings.

Key words: Thermal comfort; occupant behavior; personal comfort system; Internet of Things; big data

Highlights:

- We upgraded PCS chairs with wireless communication and data reporting capabilities.
- We conducted a field study with 37 PCS users in a typical office building.
- We collected >5 M chair data points at 20-s intervals and 4500 survey responses.
- The use of PCS resulted in 96% thermal acceptability and 99% user satisfaction.
- PCS control behavior can dynamically describe individuals' thermal preference.

1. Introduction

Technological advances are accelerating innovations in buildings, helping us to reimagine how we provide thermal comfort in the built environment. Personalized yet customizable user-experience is no longer a requirement of just the online world. Buildings are also expected to provide smart comfort solutions that take occupant feedback and deliver a customized environment to meet the unique requirements of individual occupants. However, there is a limit to how much a centralized system can do to satisfy everyone with the traditional approach of providing uniformly conditioned air to relatively large, and often shared, spaces in a building with a single controlled set-point. Given this limitation, it should come as no surprise that more occupants are thermally dissatisfied than satisfied in office buildings with conventional HVAC systems [1,2], and this situation is not any better in "green" buildings [3].

https://doi.org/10.1016/j.buildenv.2018.11.012
https://escholarship.org/uc/item/9vv4z3gg

Personal Comfort Systems (PCS) offer an alternative or complementary solution to centralized systems by allowing a highly customizable microclimate zone in an occupant's workstation without affecting others in the same space. With PCS, individuals can use personal control to provide local heating and cooling to meet their comfort needs and desires. PCS comes in many different forms including fans [4,5], heated and/or cooled chairs [6–8], and foot warmers [9–11]. These devices specifically target sensitive body parts (e.g., head, feet) to leverage their influence over whole-body thermal comfort [12]. Applying local heating and cooling to sensitive body parts can not only restore comfort but also go beyond it in eliciting pleasure sensations (e.g., warm floors in the bathroom, or air movement on one's face in a warm environment), a process termed "alliesthesia" [13–16] which will be described later on. This shifts the focus of comfort provision from minimizing discomfort to providing delightful experiences [17,18]. Another benefit of PCS is the extended range of acceptable ambient temperatures, which allows central HVAC systems to operate in wider temperature setpoints, leading to potentially significant energy savings [19,20,13,21].

PCS provides a wealth of data that can be traced to specific individuals. With the introduction of Internet-connected PCS chairs by the Center for Built Environment (CBE), University of California, Berkeley [22], we now have access to a continuous stream of heating and cooling usage data, along with occupancy status and environmental measurements (e.g., air temperature, relative humidity) via embedded sensors. This presents a unique opportunity to learn individuals' thermal control behavior and comfort preferences. Such knowledge can enable intelligent comfort management in both new and existing buildings to provide 'just the right' amount of conditioning to meet occupant needs, in contrast to over-conditioning that results from tight setpoint management. The PCS chairs can communicate and interact with building automation systems (BAS) via Internet. Therefore, the intelligence built on PCS chairs can turn into actionable feedback for HVAC (heating, ventilating, and air conditioning) operations to optimize occupant comfort and energy use in buildings [23,24].

In summer 2016, we carried out the first field study with Internet-connected PCS chairs involving 37 occupants in an office building located in northern California [25]. To our knowledge, it is the largest field study ever conducted with PCS. The objective of this field study was to (1) evaluate the new capabilities of PCS chairs via human subject testing in a typical, real-world office environment; and (2) improve our understanding of occupant comfort and behavior through the analysis of PCS data. In this paper, we describe the field study methods and a novel dataset that measures continuous PCS usage and local environmental conditions. We then report the results of our field data analysis that examine the relationship between occupant behavior, comfort, and environment of PCS users. Lastly, we summarize key insights drawn from the analysis that would benefit comfort analytics and building controls, as well as areas for improvement for PCS chairs.

2. Methods

2.1 Internet-connected PCS chairs

The Internet-connected PCS chairs have the following technological components:

Chair hardware: As a starting point, we used the same physical chair previously developed by CBE [8,26] – a mesh-type office chair with fans and heating strips integrated into the seat and back in reflective plenums (Figure 1). The heating strips use a maximum of 14 W combined (seat and back). The fans use a maximum of 3.6 W (combined). A 86 Wh LiFePO4 battery powers the chair, which lasts for several days with typical use. The chair has a pressure switch in the seat, providing chair occupancy information. This switch is also used to conserve battery power by automatically turning off heating strips and fans when the chair is unoccupied. The previous heating and cooling settings are restored when the user returns to the seat. The maximum surface temperature of the heating strips is 40 °C, which is lower than the body's heat pain thermoreceptor threshold (43 °C), and the fans use ambient air, not cooled air, to create cooling effects. These features help to avoid potential discomfort that could result from overheating or overcooling.

Digital controller: Previous designs used an analog controller to enable local control of heating and cooling. We replaced this with a digital controller with new capabilities including: (1) supporting wireless telemetry and remote actuation via IEEE 802.15.4 radio and Bluetooth (an external antenna is added to the controller to improve signal range); (2) logging data locally upon losing wireless connectivity, and uploading it later; (3) measuring air temperature and relative humidity at the chair location as well as chair occupancy status via embedded sensors; (4) allowing separate control of the back and seat heating/cooling via individual rheostat knobs on a physical user interface (Figure 1); (5) indicating battery charge status via a LED light on the user interface; and (6) enabling a pulse width modulation signal to dissipate excess energy into the heating strips. Andersen et al. [22] and Kim [27] provide more details about the newly developed digital controller for PCS chairs.

Figure 1. PCS chair designed and developed by the Center for the Built Environment and the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley. The images show hardware and heating and cooling elements of the chair, the new controller with wireless connectivity, and the newly designed user interface that allows separate control of seat and back heating/cooling.

Network connectivity: The digital controller transmits data to a cloud server via a gateway device. There are two types of gateway devices that can be used for the chair connectivity: (1) a Bluetooth-enabled mobile phone, and (2) an 802.15.4 router. The use of mobile phones reduces deployment effort by avoiding the installation of local network infrastructure, and allowing flexible chair location through the wide coverage of a mobile phone's cellular networks. However, it requires the development of mobile applications to enable telemetry reporting via Bluetooth across various operating systems and devices. Also, real-time telemetry may not be guaranteed if the chair communication depends on the availability and network coverage of the chair user's mobile phone. An 802.15.4 router provides reliable real-time telemetry because its physical location and network configuration can be fixed. Once installed, the router can talk to multiple chairs allowing scalable field deployment. But it requires more upfront deployment effort due to the installation of local network infrastructure. For this field study, we used 802.15.4 routers for the chair communication to have control over wireless connectivity and data reporting during the field study. We installed a total of five border routers to cover 37 chairs spread across two separate floors.

Software suite: We developed the following online tools to support the chair deployment: (1) plotter, and (2) status dashboard [27]. The plotter allows query, visualization, and download of time-series data. The status dashboard provides real-time status monitoring of chair data streams. Both tools are built on the sMAP (simple Measurement and Actuation Profile) – an open-source software that enables accessing and storing time-series data and actuating connected devices, developed by UC Berkeley's Electrical Engineering and Computer Sciences Department [28].

2.2 Field study

The field study with Internet-connected PCS chairs took place in the San Mateo County (SMC) office building in Redwood City, CA, between April and October 2016. The site offers a real-world setting with typical office workers in which to conduct field experiments, which is quite a rare opportunity in academic research that often resort to university buildings, laboratory spaces, and student subjects. This location has a Köppen Csb climate zone (California climate zone 3, ASHRAE climate zone 3C) characterized by dry, warm summers and mild winters.

Building description: The SMC office building is a 5-story, 1,100 m^2 (120,000 ft^2) building, shown in Figure 2 (a). Constructed in 1999, the building houses the county government and administrative offices for approximately 400 county employees. It is predominately open plan with some enclosed offices and conference rooms along the perimeter. The perimeter zones have a window-to-wall-ratio of approximately 0.6 on the first floor and 0.45 on all other floors. The windows are not operable or externally shaded, but do have interior blinds.

HVAC system: The building has a conventional single-duct variable air volume (VAV) reheat with overhead air distribution system, served by two rooftop units with direct expansion coils and evaporatively cooled condensers. A gas-fired hot water boiler supplies hot water to the terminal reheat coils distributed throughout the building. The HVAC system in the building underwent a complete controls retrofit 18 months before the study period, which has brought it up to current industry best practice. The building has a Distech and Tridium/Niagara based BAS and two Internet-based building management software tools: Comfy and Trendr (https://www.comfyapp.com/product). Comfy provides an online solution for thermostat control that adjusts the zone temperature setpoints based on occupant votes via mobile devices/computers and generates immediate hot/cold responses from the building's HVAC system. Trendr facilitates web-based archiving and remote access to BAS trend data. The building's HVAC system is in operation only during the occupied hours (typically 6 am-6 pm), with some minor variability in starting time due to an optimal start algorithm, and is turned off otherwise.

Subject description: 37 occupants on the first and fifth floors of the building participated in our field study (17 males and 20 females). The majority (30 subjects) were in open-plan offices while 7 subjects had enclosed offices. Figure 2 (b) shows a participant in his office with a PCS chair. The study entailed having a PCS chair for a 12-week period and taking a series of surveys. We compensated the subjects $1 per survey, up to $15 per week. Due to limited chair availability, we staged the chair deployment in three phases to maximize the total number of subjects. The first phase was April – July with 10 subjects; the second phase was June – September with 17 subjects; and the third phase was July – October with 10 subjects.

Figure 2. (a) San Mateo County office building, the southwest façade. (b) A field study subject in an open-plan office, seated in a PCS chair.

2.3 Data collection

The field study produced the following data sets.

Background survey: All subjects completed a one-time background survey at the beginning of the study to provide information about personal characteristics (i.e., sex, age, height, weight), general thermal comfort satisfaction, and morning commute method (See Supplementary material for the survey questions).

Daily (right-now) survey: After a one-week adjustment period with their PCS chair, the subjects took short online surveys (less than 1 minute to complete) three times daily for 12 weeks. The survey included questions about their current thermal comfort (acceptability, preference), clothing ensembles, motivations for chair use if being used at the time of survey, and resulting satisfaction (See Supplementary material for the survey questions). We asked the subjects to primarily follow email reminders to take surveys, but allowed some flexibility in survey timing to accommodate their office schedules and responsibilities. We provided a web link to the survey in the email to ensure that they were easy to access. Depending on the participation rate, we extended the survey period for some subjects by a few more weeks to increase the total survey count per person. In total, we collected 4655 survey responses (averaging 125 surveys per subject with the 25-75th percentile range of 110-141).

PCS control behavior: We gave all subjects a PCS chair to use according to their comfort needs and desires during the study period. Each PCS chair recorded heating/cooling intensity (in a scale from 0 to 100%), heating/cooling intensity and location (seat, back), and chair occupancy at 20-s intervals. Figure 3 shows an example of this data for a single PCS chair. Note that the chair allows separate control of the back and seat heaters/fans; hence, simultaneous heating and cooling can be recorded (e.g., back heater and seat fan). In total, we obtained 5.1 million chair data points from 37 participants after aggregating the raw data into one-minute intervals.

Indoor environment: Each subject's local thermal environment was monitored continuously via environmental sensors using both the PCS chairs and independent data loggers. The chair's environmental sensor, located underneath the seat (about 0.5 m from the ground), recorded air temperature (±0.25°C accuracy) and relative humidity (±2.0% accuracy) at 20-s intervals. We provided redundancy by installing a HOBO data logger (Model U12-012, Onset, USA) in each subject's workstation near the breathing zone in a sitting position (about 1.0 m from the ground). The data logger recorded air temperature (±0.37°C accuracy), relative humidity (±2.5% accuracy), and globe temperature (±0.37°C accuracy) (only for perimeter offices) at 5-min intervals. We calibrated both chair and HOBO sensors in a climate chamber.

Outdoor environment: We obtained outside weather data from a nearby weather station via the National Centers for Environmental Information, National Oceanic and Atmospheric Administration website (https://www7.ncdc.noaa.gov/CDO/cdo). This dataset includes outdoor temperature, precipitation, and sky coverage measured at San Carlos weather station (WBAN 93231).

HVAC system: We also obtained measurements from the HVAC system using Trendr, which included the following data at 5-min intervals: room temperature (measured at the thermostat on the wall), supply airflow, damper position, heating output, and discharge air temperature in the 22 HVAC zones where the subjects were located.

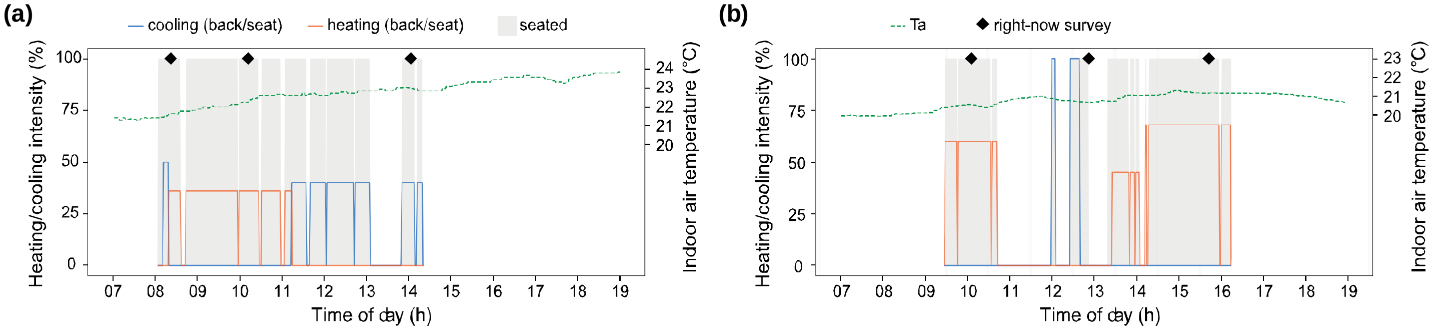


Figure 3. Examples of continuous PCS chair data of two different subjects between 7am and 7pm. Ta refers to indoor dry-bulb air temperature measured via the temperature sensor embedded in the PCS chair. The location of heating and cooling shown here refers to either the back or the seat of the chair. The diamond shape indicates the timing of right-now surveys submitted by the subject.

The UC Berkeley Committee for the Protection of Human Subjects (IRB-2011-04-3163) reviewed and approved these methods.

3. Results

The following sections report key findings from the field data analysis. We conducted all statistical analyses described in this paper in R (version 3.4) and RStudio (version 1.0.143).

3.1 Exposed environmental conditions

Table 1 summarizes the overall environmental conditions (indoor and outdoor) during the study period, excluding non-operating hours and weekends.

Table 1. Statistical summary of the field conditions (indoor and outdoor) during occupied hours excluding weekends and holidays.

Variable	Mean	Lower, middle, and upper percentiles (5 / 25 / 50 / 75 / 95)
Indoor[a]		
Air temperature (°C)	23.5	21.8 / 22.8 / 23.4 / 24.1 / 25.3
Globe temperature[b] (°C)	23.2	21.4 / 22.4 / 23.1 / 24.0 / 25.6
Relative humidity (%)	48.4	41.8 / 46.0 / 48.3 / 50.6 / 54.9
Outdoor		
Temperature (°C)	14.4	12.2 / 12.8 / 13.9 / 15.0 / 17.8

[a] Indoor conditions refer to the measurements taken at the subjects' workstations by data loggers located at approximately 1.0m from the ground (breathing zone in sitting position), not by the chair sensors located at 0.5m from the ground (underneath the chair seat pane).

[b] globe temperature is only measured in perimeter workstations.

The weather in Redwood City, CA during the field study period was mostly dry and sunny with mild to warm daytime temperatures. A comparison to the average long-term climate data confirmed that our measured temperatures were representative of this region's climate. The indoor air temperature remained mostly within a relatively narrow range of 22-25 °C during the occupied hours, largely unaffected by the outdoor conditions, primarily due to the relatively constant heating and cooling air temperature setpoints within which the HVAC system controls each zone. The difference between air (Ta) and globe (Tg) temperatures along the perimeter offices was small (mean (Ta-Tg) = 0.3 °C, standard deviation = 0.6 °C). Relative humidity was relatively uniform with little variations across different workstations (mean = 48%, standard deviation = 3.4%).

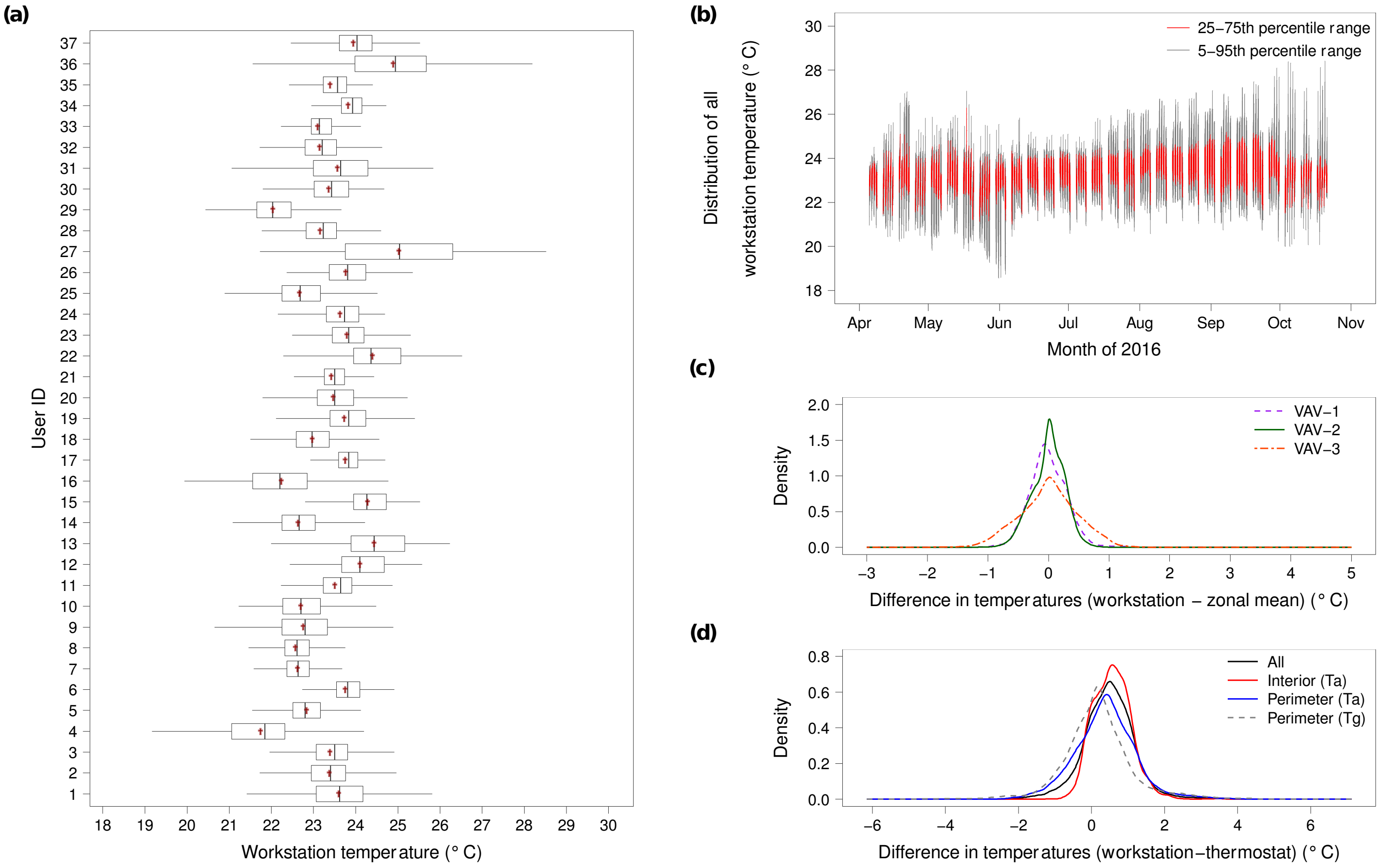


Figure 4. (a) Distribution of indoor air temperature measured by data loggers at each subject's workstation during occupied hours of the field study period. Red dots signify the mean values. (b) Hourly distribution of indoor air temperature across the subjects' workstations over the field study duration, shown in 25-75th (red line) and 5-95th (grey line) percentile ranges. (c) Density curves of the temperature difference between individual subjects' workstation and zonal mean within the same HVAC zone, as measured by data loggers. Only the zones with three or more subjects were shown in the plot. (d) Density curves of the temperature difference between the subjects' workstation, as measured by data loggers, vs. zonal thermostat. There were 19 workstations in Interior zones and 18 workstations in perimeter zones.

With distributed environmental sensing via PCS chairs and data loggers, we had high visibility into the subjects' local thermal conditions. Figure 4 (a) shows the distribution of air temperature at each chair location during the study period. The majority of the subjects experienced conditions that were within the 'comfortable' range according to the current standards (i.e., ASHRAE 55, ISO 7730, EN 15251); however, some were exposed to a wider temperature variation than others during the study period. Figure 4 (b) shows the distribution of indoor temperatures across different workstations occupied by the subjects within the building. On average, the difference in air temperature exposures by different subjects across the building was as much as 1.1 °C during the same hour based on 25-75th percentile range and 2.9 °C based on 5-95th percentile range. Note that this is wider than the 2 °C range between control setpoints on the HVAC system, typically 21 °C (heating) to 23 °C (cooling). When we examined the temperature distribution within HVAC zones with 3 or more subjects as shown in Figure 4 (c), we found that the subjects' local temperatures deviated more than ±0.2 °C from the zonal mean 50% of the time and more than ±0.4 °C 25% of the time even within the same thermal zones. These findings indicate that individuals may experience different thermal conditions even in the same moment depending on their location within the building, or even their location within the zone.

To understand how well the building's HVAC sensors capture temperature variations across different building spaces, we compared local temperature measurements to the zonal thermostat readings in Figure 4 (d). The discrepancy between the two readings across all chair locations was 0.5 °C on average with standard deviation of 0.8 °C. The measured temperatures in interior offices were often warmer than thermostat readings. This may be due to instrumentation measurement error (thermostats are uncalibrated), confounding effects of the thermal inertia of the massive surface upon which the thermostat is mounted, and equipment heat gain. Exterior offices were both cooler and warmer than the thermostat readings as they were exposed to solar heat gains or losses through the building envelope that are not always captured by thermostat sensors (since they are typically installed on interior walls). This shows that local temperatures and thermostat readings are not always in agreement, and depending on where the thermostats are located, temperature readings may not be representative of the conditions experienced by individuals in their local areas.

3.2 Thermal comfort assessment of PCS users

The daily thermal comfort assessment via online surveys consisted of two questions: thermal acceptability (4-point discrete scale) and thermal preference (3-point discrete scale) of the overall thermal environment considering both the surrounding ambient and chair conditions. We did not include the traditional thermal sensation question in the questionnaire because it could be confusing or misunderstood by PCS chair users, as discovered from interviews with the subjects during the beta-testing of PCS chairs [25]. Because PCS provided heating and cooling directly onto portions of their body, the subjects tended to report the sensation they felt from the chair's heating or cooling rather than assessing whole body sensation from the overall environment. As such, they often voted 'warm' or 'cool' sensation when the chair's heating or cooling was on, and they did not associate those votes with discomfort; in fact, they usually perceived them positively. Also, they considered 'neutral' as a void of warm or cool sensation and tended to not vote 'neutral' when they were using the chair's heating or cooling. To eliminate the source of confusion and misinterpretation, we removed this question from the survey for this field study. See Appendix A for a further discussion on the applicability of comfort scales for PCS users.

Figure 5 summarizes the results of the subjects' thermal comfort responses collected from daily surveys. PCS chair users had exceptionally high comfort satisfaction during the study period. Based on thermal acceptability, 96% of the votes found their thermal environment either 'acceptable' or 'slightly acceptable' over a range of air temperatures (21.9-25.3 °C based on 5-95th percentile range), far exceeding the 80% goal of the ASHRAE thermal comfort standard [29]. Furthermore, recent research showed that even this relatively low temperature satisfaction goal was only met in 44% of 144 surveyed buildings, indicating that actual temperature satisfaction is far lower than 80% in most buildings [1]. In this study, only 3.7% voted slightly unacceptable, and less than 1% voted unacceptable. This is similar to the result observed in an earlier laboratory study with 23 subjects using PCS chairs [8] that achieved over 90% comfort satisfaction over a wide temperature range of 18-29°C. Based on thermal preference, 70% of the votes indicated that subjects found their thermal environment sufficiently good – matching their preferred state and wanting 'no change' to the current conditions. 17% and 13% of the votes expressed subjects' desire to be cooler and warmer, respectively. Interestingly, the 'warmer/cooler' votes were mostly associated with the 'slightly acceptable' and 'unacceptable' votes in thermal acceptability as shown in Figure 5 (c). This indicates that a preferred thermal environment may be different from what is perceived as 'acceptable', and those in suboptimal comfort conditions know what they want in their thermal environment (i.e., warmer, cooler) to improve their comfort.

Note that 'unacceptable' and 'slightly unacceptable' votes were predominately want warmer due to overcooling in the office, and the chair heating alone was not enough to offset the discomfort caused by the surrounding ambient conditions.

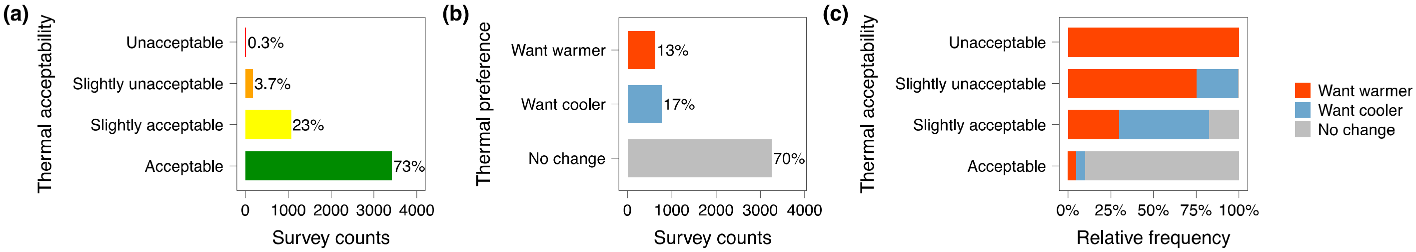


Figure 5. Distribution of thermal acceptability (a) and thermal preference (b) votes from daily surveys by all 37 subjects during the field study period. The total survey counts were 4655. (c) The relative frequency of thermal preference votes for each of the thermal acceptability categories.

Figure 6 (a) shows the distribution of thermal preference responses over the coincident indoor temperatures. The one-way analysis of variance (ANOVA) indicated statistically significant differences in the observed indoor temperatures between the three preference categories ($p < 2e-16$). The median temperature for 'want cooler' votes (23.7 °C) was slightly warmer than that of 'want warmer' votes (23.2 °C). Multinomial logistic regression on aggregated thermal preference votes with respect to indoor temperature in Figure 6 (b) showed that the probability of voting for 'no change' was the highest at 23.1 °C. The subjects were more likely to vote for 'want cooler' when temperatures were warmer. The opposite was true for 'want cooler' votes. However, such trends were not always observed when logistic regression was performed at individual levels, as shown in Fig. B.1. Within moderate temperature exposures, many did not follow changes in temperatures when voting for 'want cooler/warmer'. In fact, some subjects showed only certain preferences within the exposed temperatures that logistic regression only produced binary results (e.g., no 'want cooler' trends for User 7, 19) or did not converge at all (e.g., only 'no change' votes for User 15, 21). Also, the likelihood for voting for 'want cooler/warmer' varied quite a lot between individuals even under the same temperatures; therefore, temperature alone – even when measured local to the occupant – cannot explain individuals' thermal preferences within the range of exposed conditions.

Figure 6 (c) shows the distribution of thermal acceptability responses over the coincident indoor temperatures. The one-way ANOVA indicated statistically significant differences in the observed indoor temperatures between the four acceptability categories ($p < 1.51e-07$). Within the moderate temperature exposures observed in this field study, the subjects associated unacceptability mostly with cooler temperatures. The logistic regression curves for thermal acceptability vs. indoor temperature in Figure 6 (d) also show this. However, there were too few votes for 'unacceptable' and 'slightly unacceptable' (12 and 170 votes respectively out of the total 4655 votes) to make any meaningful conclusions about this trend. Most of the logistic regression at individual levels did not converge due to heavy imbalance between the acceptability categories; hence, we did not report the results in this paper.

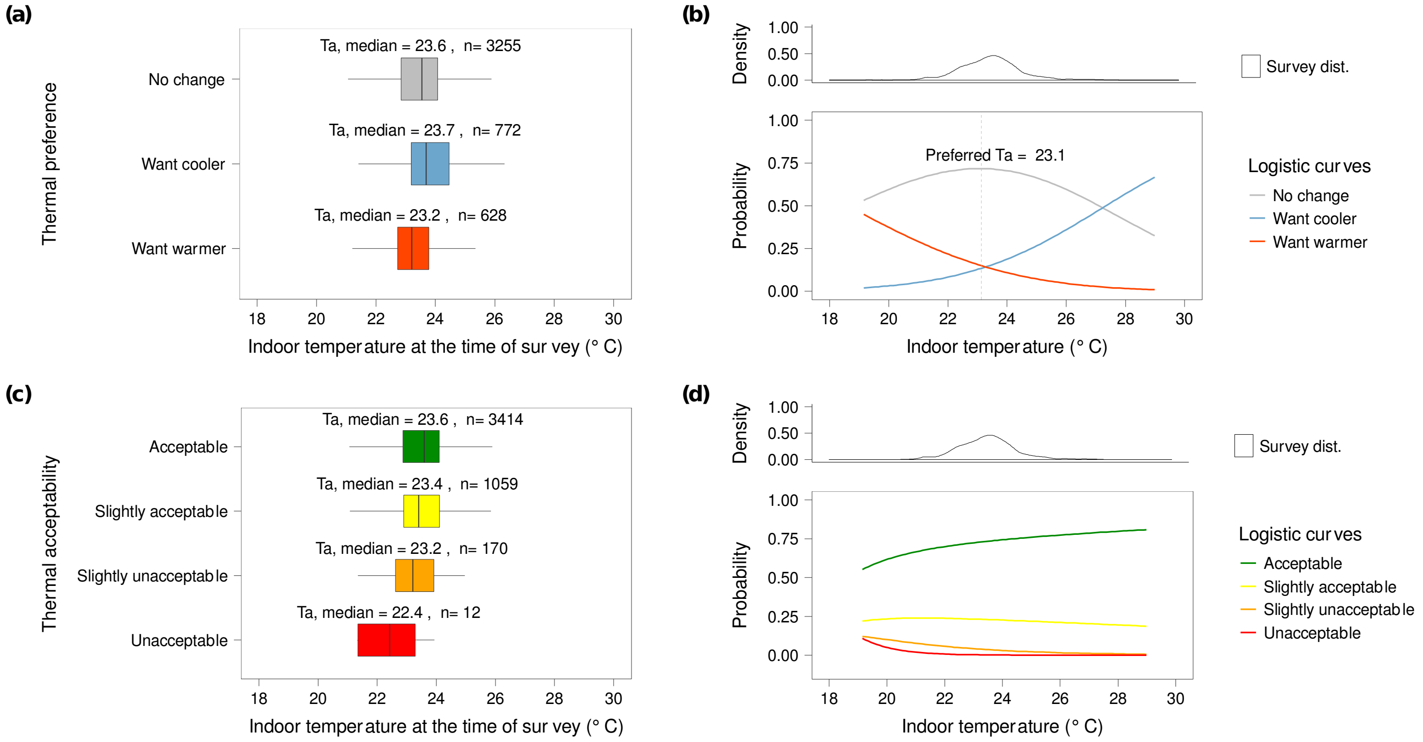


Figure 6. (a) Boxplots of the aggregated thermal preference votes (i.e., ‘no change’, ‘want cooler’, ‘want warmer’) from all subjects over coincident indoor air temperatures measured by data loggers. (b) Multinomial logistic regression curves for thermal preference categories over indoor temperature ($p < 2e-16$). The dotted line represents Preferred Ta, which is the temperature at which the probability of voting for ‘no change’ is highest. The distribution of thermal preference votes over coincident indoor temperatures is shown at the top. (c) Boxplots of the aggregated thermal acceptability votes (i.e., ‘acceptable’, ‘slightly acceptable’, ‘slightly unacceptable’, ‘unacceptable’) from all subjects over coincident indoor air temperatures measured by data loggers. (d) Multinomial logistic regression curves for thermal acceptability categories over indoor temperature ($p < 1.51e-07$).

3.3 PCS control behavior

Figure 7 shows the overall chair usage of each subject during the field study period. On average, chair heating and/or cooling were active 76% of the time during which the chair was occupied (daily mean/median chair occupancy = 4.0/4.8 h), indicating active chair usage by the subjects. However, individuals’ chair usage pattern varied widely. For example, some used the chair’s heating/cooling function more frequently than others while seated. Some subjects primarily used heating over cooling, or vice versa.

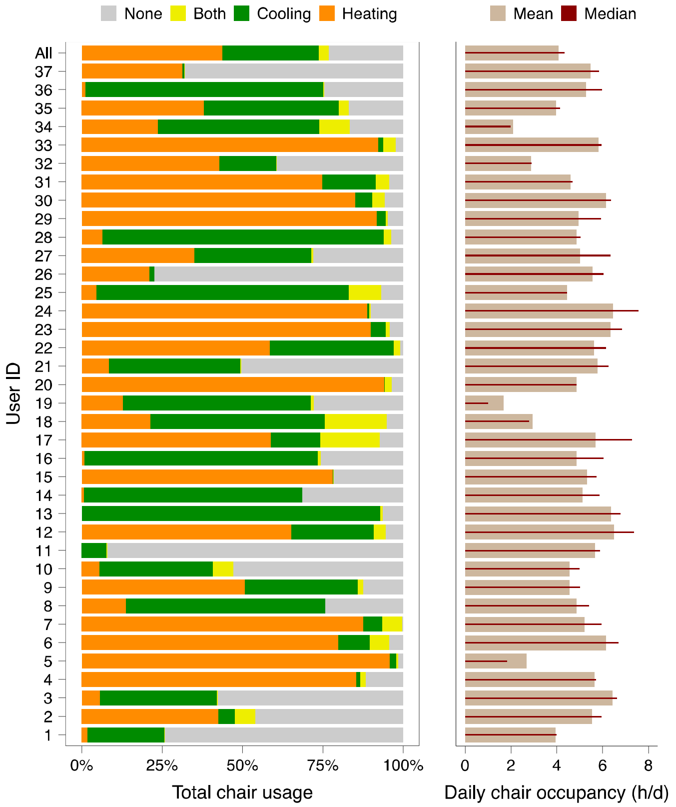


Figure 7. Distribution of relative PCS control mode usage (i.e., ‘heating’, ‘cooling’, ‘both’, ‘none’) and mean and median daily chair occupancy by all and each subject during the field study period.

We plotted the distribution of observed control modes against coincident indoor temperatures (Figure 8 (a)) to understand the relationship between the choice of control mode and exposed thermal conditions. The one-way ANOVA indicated statistically significant differences in the observed indoor temperatures between the four PCS control modes ($p < 2e\text{-}16$). Although the median temperature for different PCS control models did not vary by much, the likelihood for cooling usage increased at warmer temperature and heating usage increased at cooler temperatures, as shown in logistic regression curves (Figure 8 (b)). However, as shown in Figure 8, it is clear that temperature alone is not a very useful predictor of preferred control mode for a particular occupant, at least within the range of conditions to which they were exposed.

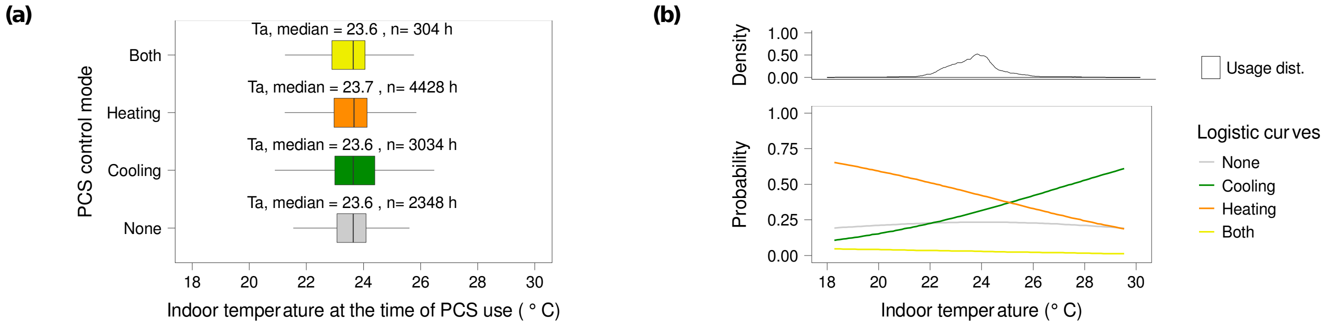


Figure 8. (a) Boxplots of the aggregated PCS control usage (i.e., ‘none’, ‘cooling’, ‘heating’, ‘both’) from all subjects over coincident indoor temperatures. (b) Multinomial logistic regression curves for PCS control modes over indoor temperature ($p < 2e\text{-}16$).

To understand what may trigger people to switch the chair’s heating/cooling ‘on’ from ‘off’ mode, we examined the subjects’ chair occupancy patterns and time of day (Figure 9). We only looked at the instances where the subjects intentionally activated heating/cooling, and excluded the instances where the chair automatically activated heating/cooling based on the previous setting remembered by the chair software. Our data show that intentional heating or cooling mostly occurred shortly after sitting in the chair (within 5 min of being seated), indicating that people's desire for heating/cooling may arise mostly during transitional periods. This is particularly prominent at the beginning of the office hours, during lunch hours, as well as in the late afternoon, where the occupants often selected cooling mode. This could be to offset people's heightened metabolic rate during a short period after arriving from their morning commute or lunch break or to get relief from the heat in the afternoon.

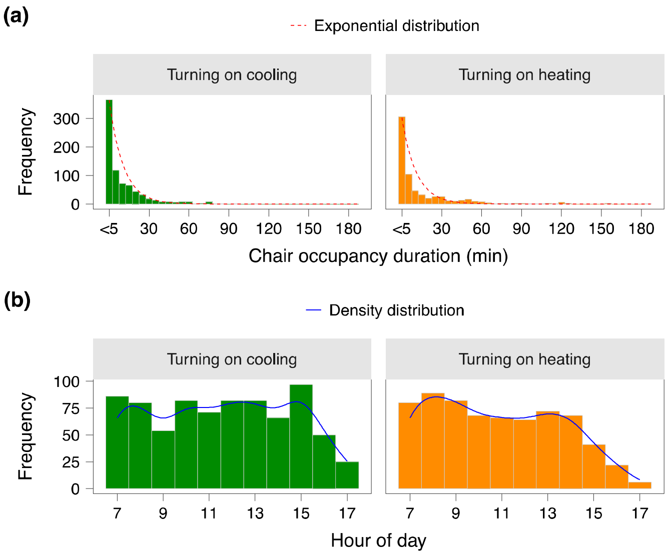


Figure 9. (a) Relative frequency of heating and cooling switch-on behavior by the subjects. Only the instances where the subjects intentionally turned on heating/cooling were plotted. We excluded the instances where the chair software automatically turned on heating/cooling based on the previously stored setting. (b) Relative frequency of heating and cooling switch-on behavior by hour of day.

In Figure 10 (a-b), we cross-linked thermal preference and acceptability votes with coincident chair control settings to better understand the relationship between the subjects' comfort perception and behavior. Note that we asked the subjects to consider both ambient and chair thermal conditions when voting their thermal preferences. As shown in Figure 5, the chair users were mostly comfortable with their environment, voting for 'no change' to their thermal conditions 70% of the time and 'acceptable' or 'slightly acceptable 96% of the time. They were actively using the chair to address their comfort needs and desire. The subjects sometimes wanted to be cooler (17%) or warmer (13%), and when this occurred, their choice of control mode provided some indication of what they preferred. When the subjects preferred a cooler environment, they used cooling mode more actively than heating mode. Similarly, when they preferred a warmer environment, they used heating mode more actively than cooling mode. In such cases, the room might have been warmer or colder than the chair's cooling/heating capacity, not allowing the subjects to reach their desired comfort levels. Or, the body might have been too warm or cold so that the chair's cooling/heating was not fast enough to offset discomfort. Note that some people used heating mode when they voted for 'want cooler'. This is because the subjects often used the chair's back heater for a therapeutic reason – to relieve back pain – while simultaneously cooling the seat. Some subjects preferred to be warmer/cooler but did not use the chair. According to the survey comments, this is because the subjects often forgot to use the chair or had busy schedules, drained battery, errors with the chair, etc.

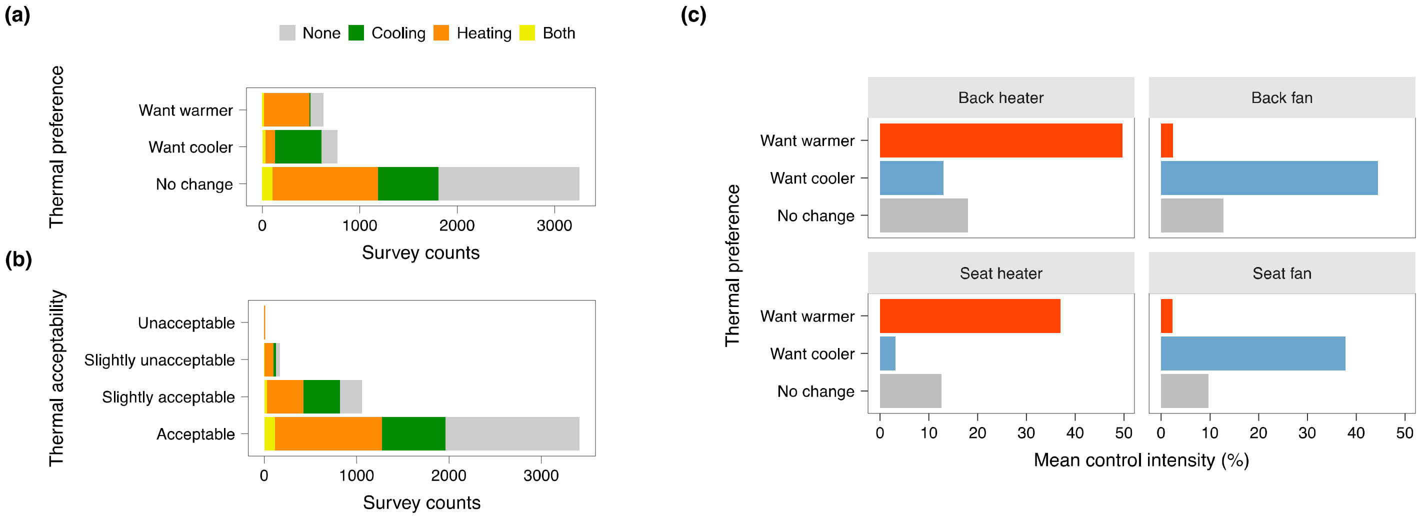


Figure 10. (a) Frequency of thermal preference votes from all subjects overlaid with coincident PCS control modes (i.e., 'heating', 'cooling', 'both', 'none'). (b) Frequency of thermal acceptability votes from all subjects overlaid with coincident PCS control modes. (c) Mean control intensity (recorded in 0-100%) of PCS heaters and fans across all subjects used at the time of survey for each of thermal preference categories (i.e., 'want warmer', 'want cooler', 'no change').

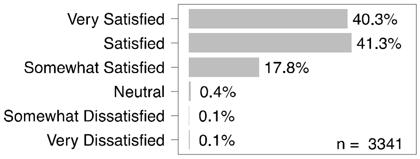
We further examined the chair data to find information that might help us to distinguish who wanted changes ('warmer/cooler') from no changes in their thermal environment. Figure 10 (c) plots the mean control intensity of chair fans and heaters used at the time of survey for each of the three preference categories. We observed that the subjects who expressed their desire for warmer/cooler tended to have a higher control intensity than those who were comfortable and wanted no changes to their thermal environment. It could mean that the subjects found the chair cooling/heating even at higher intensities to be tolerable without local discomfort, and local cooling/heating was sometimes not enough to offset the discomfort caused by their surrounding ambient conditions. This indicates that the level of chair heating/cooling intensity might be used to describe the direction of people's preferred thermal condition as well as the need for additional heating or cooling beyond what PCS is providing. The benefit of PCS data is that it can be traced back to individual occupants and be available continuously in real-time; hence, it can be used to predict individuals' thermal preference and inform HVAC control decisions.

3.4 User feedback on PCS chairs

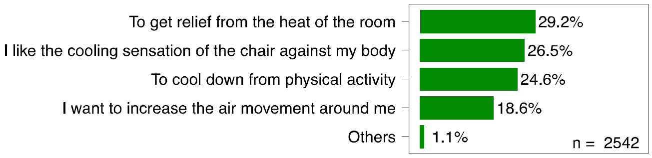
In addition to the core thermal comfort questions, we also included a few questions in the daily surveys to ask about people's satisfaction (a 7-point scale from 'very satisfied' to 'very dissatisfied') and motivation (multiple choices including 'other' with a text entry box) for PCS use. We developed the potential reasons for PCS use in the multiple choices based on the interview responses from chair users during the beta testing. The subjects could select more than one response to the multiple-choice questions or decline to select an answer.

The survey feedback showed that the subjects were highly satisfied with chairs' heating and cooling performance (Figure 11 (a)). The overwhelmingly positive rating – 99% satisfaction ('somewhat satisfied' to 'very satisfied') from daily surveys confirms this. There were some differences in people's motivation for chair cooling vs. heating (Figure 11 (b-c)). As for cooling, the subjects primarily used the chair to get relief from the heat in the room. They also used the cooling because they liked the sensation against their body or they needed to cool down from physical activities. As for heating, the pleasant sensation was the top reason for using the PCS chair, followed by a therapeutic reason to relieve back pain. Improving thermal comfort was ranked third in the list of reasons for heating use. Such outcomes provide field evidence of thermal pleasure associated with local heating and cooling; the concept of alliesthesia. Other reasons that motivated the chair use included staying alert, relieving hot flashes, etc.

(a) Satisfaction with PCS heating or cooling



(b) Reasons for cooling use



(c) Reasons for heating use

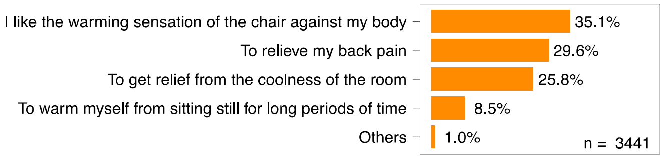


Figure 11. Distribution of (a) satisfaction rating with PCS heating or cooling, (b) reasons for PCS cooling use, and (c) reasons for PCS heating use. The data is based on the subjects' responses to the questions asked only when they were using their PCS chair at the time of daily survey. The subjects were allowed to select more than one in multiple choices for (b) and (c).

4. Discussion

Below we summarize key insights drawn from the data analysis, as well as areas for improvement for PCS chairs.

Variability in temperature conditions across different building spaces

Individual occupants are exposed to different temperature conditions even in the same moment depending on their location within the building. Our results from calibrated temperature sensor measurements showed that local temperatures varied as much as 2.9 °C (based on 5-95th percentile range) during the same hour across different building spaces. Even within the same thermal zones individuals' local temperatures varied more than ±0.4 °C from the zonal mean 25% of the time. This could be caused by the building's physical design (e.g., interior/perimeter zone), HVAC design (e.g., supply diffuser type and location), or other factors. Such variations in temperature exposure are difficult to capture or address using conventional HVAC systems as there is typically one temperature measurement (i.e., the thermostat) per zone covering a large area, and sometimes even several separate enclosed rooms. Depending on where the thermostat is located, temperature readings may not be representative of what is experienced by individuals in their local areas (on average, 0.5±0.8 °C differences observed) and temperature control may not be optimized for the majority's comfort. This is why relying on a single measurement for temperature control of the entire zone can potentially lead to discomfort. Modern buildings are becoming more extensible, capable of integrating various sensors via the Internet. Distributed sensing via connected sensors, such as the ones embedded in PCS chairs, can complement the building's existing sensing network and would allow more representative and robust temperature control due to increased visibility into local thermal conditions and redundancies in case any of the existing sensors go out of service. However, even with these sensors, a HVAC system will still lack the ability to independently address different users comfort needs within the same zone.

Individual differences in thermal preference and implications for HVAC system design

Occupants often have different thermal preferences even when they are all exposed to the same temperature, as shown in Figure 6 (b). Inter- and intra-individual differences in thermal comfort can lead to about one unit variance (±0.1) on the ASHRAE seven-point scale, which is equivalent to 3 °C in comfortable temperature [30]. This could be simply because of the differences in opinions, metabolic rates, clothing, or many other factors beyond temperatures. Regardless, differences in comfort preferences can lead to conflict among occupants over thermostat setpoints in shared spaces, and ultimately cause dissatisfaction with their environment. The challenge with conventional HVAC systems is that there is only one thermostat serving a large area, typically with multiple occupants, and individuals may not get to set the temperature according to their desire. Furthermore, as shown in Figure 4 (d), the thermostat measurement is a poor proxy for the thermal conditions where the occupant(s) are actually located within the zone. Providing PCS in the areas with conflicts in temperature preferences or unmet comfort needs can provide individuals with personal control over their immediate thermal environment and improve the overall satisfaction of building occupants. This field study showed very high thermal acceptability (96%) among PCS users in a mechanically-conditioned building with moderate temperature exposures (21.9-25.3 °C based on 5-95th percentile range). This is consistent with a previous study that improved thermal acceptability (from 44% to 88% on average) over similar temperature exposures (20.0-26.7 °C) after PCS deployment [31]. If the use of PCS would be able to maintain comfort at greater temperature ranges, central HVAC systems can deliver ambient conditions within a range in which the PCS can correct for each individual's thermal comfort needs, instead of a much narrower range that is a compromise for all occupants in that space. The extended range of temperature setpoints can also lead to significant energy savings in buildings [13,19–21][13,19–21]. Moreover, PCS provide fast-acting heating or cooling that can help to address immediate comfort needs of building occupants (e.g., cooling after walking up the stairs, warming after entering from a cold outdoor) with very minimal energy use [32]. Such responsiveness is not only impossible to achieve with conventional HVAC systems, as they condition the entire thermal zone, but also impractical due to substantial energy consequences and the needs of others occupying the same zone. Additionally, a HVAC system conditioning a zone have relatively long time constants, and therefore cannot respond quickly to short term, transient thermal comfort requests. As such, PCS can be used to provide complementary comfort solutions to traditional systems for greater satisfaction and reduced energy use.

Behavior as a predictor of thermal preference

When provided with thermal control, people use it to address their comfort needs; hence, the resulting behavior can be regarded as an expression of one's thermal preference. Our analysis of PCS control usage data confirms this. The choice of heating vs. cooling revealed adaptive actions taken by occupants to address their comfort (or other physiological) needs. On the other hand, the heating and cooling intensity indicated whether occupants wanted additional heating or cooling in their thermal environment. The benefit of PCS data is that it can be traced back to individuals and it is available continuously in real-time; hence, the data can be used to predict individuals' thermal preference dynamically [33]. Such predictions can act as an individualized comfort feedback for HVAC controls to provide 'just the right' amount of conditioning to meet occupant needs, in contrast to over-conditioning that results from tight setpoint management. One caveat is that not all chair use is motivated by thermal comfort, such as subjects using the chair's heating to relieve back pain. Hence, the predictive algorithm needs to be able to identify such situations and correctly predict those related to thermal comfort. Another alternative would be to add features to the chair controls so that an occupant could provide direct feedback on the ambient conditions as well as control their chair, with a minimal cognitive and tactile effort. For example, press down on a control dial if the ambient conditions are too warm, or some similar functionality.

Implications for temporal and spatial alliesthesia

This study, through the rich data collected from PCS users in a typical office building over a six-month period, suggests that PCS offers the possibility of bringing alliesthesial experience into everyday environment. There are two types of alliesthesia – temporal and spatial. The temporal form can be enhanced by the fast-responding heating and cooling afforded by PCS in non-steady state environments (e.g., during spatial or metabolic transitions). PCS users consistently activated heating and cooling within the first few minutes of sitting, especially right after morning commute, as shown in Figure 9. This suggests potential opportunity for PCS users to experience temporal alliesthesia – 24.6% of the PCS cooling use was attributed to cooling down from physical activity, as shown in Figure 11 (b). Even greater potential impact may be in the spatial form of alliesthesia, since PCS applies thermal stimulus to specific parts of the body. Studies have shown that applying local heating or cooling onto certain body parts can significantly influence the overall comfort and can also elicit pleasurable experience [34,16]. In fact, the survey results confirmed that one of the main motivation for PCS cooling and heating was the pleasurable sensation against their body – 26.5% of the PCS cooling use and 35.1% of the PCS heating use, as shown in Figure 11 (b-c). The chair heating or cooling could potentially be pulsed through a cycle assuring that both forms of alliesthesia operate continuously in steady state. This can not only be implemented with the remote actuation capability of the

Internet-connected PCS chairs but also can be fine-tuned to individuals' comfort needs and desires with the insights gained from the PCS data. As PCS becomes more diversified in its forms (wearables) and equipped with advanced technologies, opportunities await to map the effects of different combinations of heating and cooling across different body parts and develop alliesthesial models that can have practical significance for individuals' comfort experience in everyday environment.

Areas to improve Internet-connected PCS chairs

Overall, the field testing of Internet-connected PCS chairs was successful. The subjects were highly satisfied with the chair's heating and cooling performance, particularly when compared against thermal satisfaction typically reported in buildings. The communication system of the chairs mostly functioned well during the six-month study. Nonetheless, there are some areas for improvement, as listed below, that we identified from field inspections and user feedback.

- **Battery charging:** We noticed that our prototypes' LiFePO4 battery life decreased over time requiring more frequent charging. Because of this, many chair users left the charging cable connected to the battery all the time, presenting potential trip hazards and damage to the charger (e.g., broken plug). A larger capacity battery, or a battery with a longer life, or low power continuous wireless charging (currently under development by CBE) would improve this situation.
- **Data privacy:** Despite our strict data policy – removal of personal identifiers from the database and restricted access to core research personnel – a few subjects still expressed concerns about their organization potentially accessing sensitive personal data (e.g., chair occupancy). For PCS to be adopted as part of a building system, we think it is critical for organizations to develop rigorous data privacy measures to protect sensitive data and build trust with PCS users.
- **Control automation:** Survey responses indicated that occupants often forgot to use the chair's heating or cooling because of their busy schedules. This is particularly a problem when they first arrive at work in the morning. Software solutions such as pre-programming heating and cooling sequences or enabling a smart algorithm that learns and automates repetitive control behavior can help to address this problem.
- **Ergonomic diversity:** Modern offices encourage diverse furniture design to meet individuals' ergonomic needs and preference. The current PCS chair design with standard dimensions and adjustability has limitations to accommodate different workstation configurations and postures required by occupants (e.g., standing desk, high chair). Allowing greater adjustability and customizability beyond the standard design would be beneficial for mass market adoption of PCS chairs.
- **Combined PCS solutions:** Some subjects brought their own desktop fan and used it in combination with PCS chairs. Such combination is not only intuitive but also has scientific grounding, in that past research has shown that cooling is most effective when applied in the breathing zone and heating is effective when applied to feet [34]. Hence, offering a combination of complementary PCS devices, as demonstrated in [8] via the offering of PCS chairs and desktop fans together, can provide more effective heating or cooling than offering a single device alone.

5. Conclusions

The purpose of this paper is to report findings of the field study with new PCS chairs equipped with high resolution data logging and wireless communication capabilities. We conducted the field study in an office building located in northern California by recruiting 37 occupants to use PCS chairs according to their comfort needs and desires during the summer of 2016. During the study period, we collected over 5 million chair data points and over 4500 occupant survey responses, as well as continuous measurements of environmental and HVAC system conditions. The key findings of data analysis include the following:

- PCS chairs produced high comfort satisfaction, resulting in 96% acceptability in typical office environments (21.9-25.3 °C) and 70% wanting no changes to given thermal conditions. This is far higher than the minimum 80% satisfied requirement of ASHRAE Standard 55, which recent evidence suggest is only met in a small fraction of buildings in practice [1].
- The preferred air temperature with PCS chairs was 23.1 °C based on the survey analysis of all subjects. However, individuals often displayed different thermal preferences even under the same temperature conditions, indicating that indoor temperature alone is not a good predictor of thermal preference.
- The use of PCS chairs was often motivated by pleasurable sensation and short-term comfort needs (such as on first arrival), offering field evidence of both spatial and temporal alliesthesia via fast-responding local heating and cooling.

- Local temperatures experienced by individual occupants vary across different parts of the building (as much as 2.9 °C based on 5-95th percentile range), even within the same thermal zone (more than ±0.4 °C variations from the zonal mean observed 25% of the time). Such variations are not captured in conventional HVAC systems as most buildings only have one temperature measurement (i.e., the thermostat) per zone. Distributed sensing via connected sensors, such as the ones embedded in PCS chairs, can complement the building's existing sensing network and allow more robust and representative temperature control, though typical HVAC systems will still be unable to respond independently to the thermal comfort needs of an individual occupant.
- Individuals' PCS control behavior can be an indicator of their thermal preference. We found that the control modes indicate the type of thermal needs (i.e., heating, cooling) that occupants have while the control intensity indicates whether they want additional heating or cooling beyond what PCS is providing. This means that we can acquire information about thermal preference and acceptability while avoiding the need for occupant surveys. Hence, PCS control behavior can potentially be used as an individualized comfort feedback for HVAC controls.

Our findings demonstrate that PCS can provide comfort satisfaction far exceeding the 80% goal of the ASHRAE thermal comfort standard (Standard 55). At time of writing, a proposal is under review at ASHRAE to add a comfort control classification scheme to the standard, assigning control credit to buildings offering higher levels of PCS for their occupants. Such credits could be added to building rating systems such as LEED (Leadership in Energy and Environmental Design) or WELL; this study lends support to the benefits conferred by PCS control. In addition, Internet-connected PCS produces highly individualized data that can improve our understanding of occupant comfort and behavior. Since the software stack developed for the PCS chairs allows interaction between PCS and BAS on the same communication platform, the intelligence built on PCS data can turn into actionable feedback for HVAC controls. For future research, it would be useful to apply the findings from this study to comfort predictions, building IEQ (Indoor Environmental Quality) rating systems, and environmental controls to improve occupant satisfaction and energy performance in buildings.

Acknowledgment

This work was supported by the California Energy Commission Public Interest Energy Research (PIER) Buildings Program under Contract PIR-12-026 and the Center for the Built Environment at University of California, Berkeley. This work was also partially supported by ARPA-E (Advanced Research Projects Agency-Energy, Department of Energy) DELTA (Delivering Efficient Local Thermal Amenities) Program under Contract DE-AR0000529. We would like to thank the County of San Mateo and their staff, Andy Jain, Gary Behrens, and Win Maung, for their support and assistance through the field study. We also would like to thank Stefano Schiavon and Gail Brager for their expert feedback to improve our manuscript.

References

[1] C. Karmann, S. Schiavon, L.T. Graham, P. Raftery, F. Bauman, Comparing temperature and acoustic satisfaction in 60 radiant and all-air buildings, Building and Environment. 126 (2017) 431–441. doi:10.1016/j.buildenv.2017.10.024.

[2] C. Karmann, S. Schiavon, E. Arens, Percentage of commercial buildings showing at least 80% occupant satisfied with their thermal comfort, in: Windsor, UK, 2018.

[3] S. Altomonte, S. Schiavon, Occupant satisfaction in LEED and non-LEED certified buildings, Building and Environment. 68 (2013) 66–76. doi:10.1016/j.buildenv.2013.06.008.

[4] E. Arens, T. Xu, K. Miura, Z. Hui, M. Fountain, F. Bauman, A study of occupant cooling by personally controlled air movement, Energy and Buildings. 27 (1998) 45–59.

[5] S. Schiavon, B. Yang, Y. Donner, V.W.-C. Chang, W.W. Nazaroff, Thermal comfort, perceived air quality, and cognitive performance when personally controlled air movement is used by tropically acclimatized persons, Indoor Air. 27 (2017) 690–702. doi:10.1111/ina.12352.

[6] S. Watanabe, T. Shimomura, H. Miyazaki, Thermal evaluation of a chair with fans as an individually controlled system, Building and Environment. 44 (2009) 1392–1398. doi:10.1016/j.buildenv.2008.05.016.

[7] A.K. Melikov, G.L. Knudsen, Human response to an individually controlled microenvironment, HVAC&R Research. 13 (2007) 645–660. doi:10.1080/10789669.2007.10390977.

[8] W. Pasut, H. Zhang, E. Arens, Y. Zhai, Energy-efficient comfort with a heated/cooled chair: Results from human subject tests, Building and Environment. 84 (2015) 10–21. doi:10.1016/j.buildenv.2014.10.026.

[9] H. Zhang, E. Arens, D. Kim, E. Buchberger, F. Bauman, C. Huizenga, Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system, Building and Environment. 45 (2010) 29–39. doi:10.1016/j.buildenv.2009.02.016.

[10] H. Oi, K. Yanagi, K. Tabata, Y. Tochihara, Effects of heated seat and foot heater on thermal comfort and heater energy consumption in vehicle, Ergonomics. 54 (2011) 690–699. doi:10.1080/00140139.2011.595513.

[11] H. Zhang, E. Arens, M. Taub, D. Dickerhoff, F. Bauman, M. Fountain, W. Pasut, D. Fannon, Y. Zhai, M. Pigman, Using footwarmers in offices for thermal comfort and energy savings, Energy and Buildings. 104 (2015) 233–243. doi:10.1016/j.enbuild.2015.06.086.

[12] E. Arens, H. Zhang, C. Huizenga, Partial- and whole-body thermal sensation and comfort— Part I: Uniform environmental conditions, Journal of Thermal Biology. 31 (2006) 53–59. doi:10.1016/j.jtherbio.2005.11.028.

[13] H. Zhang, E. Arens, Y. Zhai, A review of the corrective power of personal comfort systems in non-neutral ambient environments, Building and Environment. 91 (2015) 15–41. doi:10.1016/j.buildenv.2015.03.013.

[14] G. Brager, H. Zhang, E. Arens, Evolving opportunities for providing thermal comfort, Building Research & Information. 43 (2015) 274–287. doi:10.1080/09613218.2015.993536.

[15] T. Parkinson, R. de Dear, Thermal pleasure in built environments: physiology of alliesthesia, Building Research & Information. 43 (2015) 288–301. doi:10.1080/09613218.2015.989662.

[16] T. Parkinson, R. de Dear, Thermal pleasure in built environments: spatial alliesthesia from contact heating, Building Research & Information. 44 (2016) 248–262. doi:10.1080/09613218.2015.1082334.

[17] L. Heschong, Thermal delight in architecture, MIT Press, Cambridge, MA, 1979.

[18] B. Erwine, Creating sensory spaces: the architecture of the invisible, Taylor & Francis, 2016.

[19] S.C. Sekhar, Higher space temperatures and better thermal comfort - a tropical analysis, Energy and Buildings. 23 (1995) 63–70. doi:10.1016/0378-7788(95)00932-N.

[20] M. Veselỳ, W. Zeiler, Personalized conditioning and its impact on thermal comfort and energy performance – A review, Renewable and Sustainable Energy Reviews. 34 (2014) 401–408. doi:10.1016/j.rser.2014.03.024.

[21] T. Hoyt, E. Arens, H. Zhang, Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings, Building and Environment. 88 (2015) 89–96. doi:10.1016/j.buildenv.2014.09.010.

[22] M.P. Andersen, G. Fierro, S. Kumar, J. Kim, E.A. Arens, H. Zhang, P. Raftery, D.E. Culler, Well-connected microzones for increased building efficiency and occupant comfort, in: Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, 2016.

[23] P. Zhao, T. Peffer, R. Narayanamurthy, G. Fierro, P. Raftery, S. Kaam, J. Kim, Getting into the zone: how the internet of things can improve energy efficiency and demand response in a commercial building, in: Pacific Grove, CA, 2016.

[24] T. Peffer, M. Pritoni, G. Fierro, S. Kaam, J. Kim, P. Raftery, Writing controls sequences for buildings: from HVAC industry enclave to hacker's weekend project, (2016). https://escholarship.org/uc/item/3671b82b (accessed March 26, 2018).

[25] F. Bauman, P. Raftery, J. Kim, S. Kaam, S. Schiavon, H. Zhang, E. Arens, K. Brown, T. Peffer, C. Blumstein, D. Culler, M. Andersen, G. Fierro, G. Paliaga, A. Pande, H. Cheng, J. Stein, Changing the Rules: Innovative low-energy occupant-responsive HVAC controls and systems. Final report to the California Energy Commission. CEC Contract PIR-12-026, Center for the Built Environment, Berkeley, CA, 2017.

[26] E.A. Arens, H. Zhang, W. Pasut, Heated and cooled chair apparatus, US9155398 B2, 2015.

[27] J. Kim, Advancing comfort technology and analytics to personalize thermal experience in the built environment, PhD Thesis, University of California Berkeley, 2018.

[28] S. Dawson-Haggerty, X. Jiang, G. Tolle, J. Ortiz, D. Culler, sMAP: a simple measurement and actuation profile for physical information, in: Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems, ACM, 2010: pp. 197–210.

[29] ANSI/ASHRAE, ANSI/ASHRAE 55-2013: Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, US, 2013.

[30] M. Luo, E. Arens, H. Zhang, A. Ghahramani, Z. Wang, Thermal comfort evaluated for combinations of energy-efficient personal heating and cooling devices, Building and Environment. 143 (2018) 206–216. doi:10.1016/j.buildenv.2018.07.008.

[31] F. Bauman, H. Zhang, E. Arens, P. Raftery, C. Karmann, J.D. Feng, Y. Zhai, D. Dickerhoff, S. Schiavon, X. Zhou, Advanced Integrated Systems Technology Development: Personal Comfort Systems and Radiant Slab Systems, 2015.

[32] W. Pasut, H. Zhang, E. Arens, S. Kaam, Y. Zhai, Effect of a heated and cooled office chair on thermal comfort, HVAC&R Research. 19 (2013) 574–583. doi:10.1080/10789669.2013.781371.

[33] J. Kim, Y. Zhou, S. Schiavon, P. Raftery, G. Brager, Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning, Building and Environment. 129 (2018) 96–106. doi:10.1016/j.buildenv.2017.12.011.

[34] H. Zhang, E. Arens, C. Huizenga, T. Han, Thermal sensation and comfort models for non-uniform and transient environments, part II: local comfort of individual body parts, Building and Environment. 45 (2010) 389–398. doi:10.1016/j.buildenv.2009.06.015.

Appendix A

Applicability of comfort scales for PCS users

Different comfort scales inform different aspects about thermal comfort of PCS users. Thermal acceptability describes the level of ‘acceptability’ of a given environment by the users while thermal preference describes what preferred condition would be if they can make changes to their environment. It is possible that even when people are not in their ideal state of comfort, they may still report their thermal condition as ‘acceptable’ – meaning it is tolerable or not bad enough to complain. We observed this in the survey results when the subjects in suboptimal comfort state (‘slightly unacceptable’ or ‘slightly acceptable’) expressed their desire to be warmer or cooler. From a building control perspective, both scales are useful as thermal acceptability informs about who is on the verge of discomfort while thermal preference informs about how to improve their condition. Such information can help HVAC systems to provide preventive or corrective control strategies to improve comfort satisfaction of building occupants. Thermal pleasure could be another comfort scale relevant to PCS users as it is a frequent reason for PCS heating/cooling use. This scale would address the concept of *alliesthesia* in thermal comfort assessment, shifting our focus from minimizing discomfort to creating delightful experience for occupants. Lastly, we think that the conventional version of the thermal sensation scale (7-point scale from ‘hot’ to ‘cold’) is not appropriate for PCS users as the local heating or cooling can cause confusion and misinterpretation of the scale. Further research is needed to design a sensation scale applicable to PCS users along with the appropriate survey question and understand its implications in building controls.

Appendix B

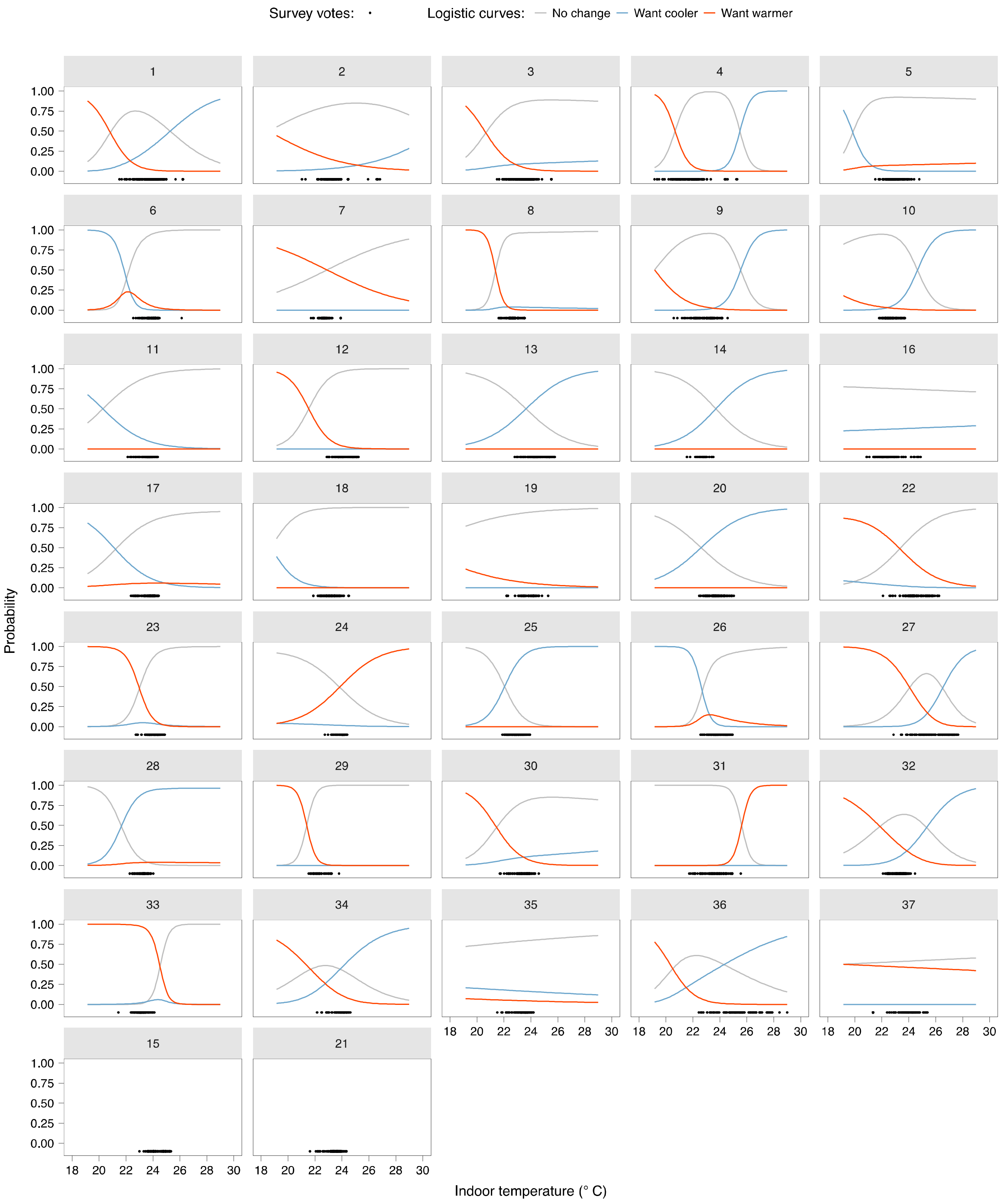


Fig. B.1. Multinomial logistic regression curves for thermal preference votes over indoor temperatures for individual subjects.