Title
Leveraging ubiquitous computing as a platform for collecting real-time occupant feedback in buildings

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Abstract

Building occupants represent a rich source of information for evaluating environmental design practices and building operations. This paper presents a scalable diagnostic technology for collecting real-time Indoor Environmental Quality (IEQ) feedback from building occupants: an interactive desktop polling station. The device demonstrates the potential of ubiquitous computing, a model of human-computer interaction in which information processing is integrated into everyday objects, to engage occupants in providing IEQ feedback in real work environments. Example data from a field study of a high-performance office building are presented demonstrating the applicability of multiple devices to acquire detailed feedback over daily and seasonal variations in climatic conditions. Sample results show how polling station data can help identify the frequency and magnitude of discomfort with the spatial and temporal granularity needed to assess, validate, and improve the performance of environmentally responsive building technologies, controls, and design strategies. Analysis of repeated-measures subjective assessments paired with concurrent physical measurements is performed to demonstrate how existing standards and assumptions for occupant comfort could be evaluated and refined using detailed occupant feedback from buildings in use. Results are discussed regarding implications for improving decision-making for the design, certification, and operation of environmentally responsive buildings.

Keywords: Ubiquitous computing, post occupancy evaluation, real-time feedback, indoor environmental quality, human-factors.

1. Introduction

Beyond energy, efforts are increasing to differentiate “intelligent,” “high-performance,” “sustainable,” or “green” buildings from standard practice on the basis of enhanced Indoor Environmental Quality (IEQ). However, in contrast to the technological sophistication of tools and services available to monitor and assess building energy performance, efforts to assess and validate IEQ objectives in buildings in use are far less developed. Claims of acceptable or enhanced IEQ are often based on compliance with green building rating system criteria (e.g. LEED Environmental Quality credits) achieved prior to occupancy, or through computational simulations comparing predicted IEQ outcomes to criteria specified by consensus-based standards (e.g. ASHRAE Standard 55). Claims are rarely based on occupant feedback and physical measurements validating that performance in use matches design intent. Consequently, there is a limited body of evidence that can be used to inform the operations or retrofitting of projects in use or to refine standards and design best practices.

As efforts increase to implement environmentally responsive design strategies outside of conventional mechanical conditioning and illumination regimes (e.g. daylighting, passive cooling, natural ventilation), systematic feedback is needed to ensure that acceptable environmental conditions are consistently provided for occupants. Field measures and surveys present a strong body of evidence that the most applicable sensors for ensuring comfort are building occupants (Loftness et al., 2009). Web-based occupant surveys are an example of a scalable method used to measure and benchmark “overall” levels of occupant comfort and satisfaction with a range of IEQ factors. The U.C. Berkeley Center for the Built Environment (CBE) has developed a 68-question occupant survey that has been applied to assess and benchmark over 593 buildings ranging in size from 100 to 2.5 million square feet (CBE, 2012). However, web-based surveys typically sample each occupant only once, and record an overall assessment. Because environmentally responsive design strategies often result in indoor conditions that are less homogeneous and more dynamic than in conventional, mechanically controlled environments, repeated real-time subjective measures at the resolution of individual workspaces can help to provide feedback with sufficient spatial and temporal granularity to identify precisely “when” and “where” design strategies are working and not working. Further, subjective responses paired with concurrent physical measurements can help to identify and model the physical conditions associated with discomfort as well as those preferred by occupants. Acquired systematically, detailed occupant feedback data can be utilized to inform design guidance, identify and prioritize retrofit needs, improve operations, simulation assumptions and building controls. However, unlike physical sensors, which are constantly available and can be sampled at regular intervals, occupants performing real work tasks have limited attention available to participate in human-factors assessments. Therefore, the level and quality of user-interaction with diagnostic instruments must be considered to avoid survey burnout or fatigue.

To address these issues, this paper presents a novel diagnostic technology for collecting real-time IEQ feedback data in the field: an interactive desktop polling station developed to enable repeated measures of occupant subjective assessments paired with physical measurements of IEQ. The devices explore the potential of ubiquitous computing, a model of human-computer interaction in which information processing is integrated into everyday objects, to better enable human factors assessments to be conducted in real work environments. The objective of this technology is to enable the measurement of IEQ performance indicators with the level of spatial and temporal granularity needed to assess, validate, and improve the performance of environmentally responsive building technologies, controls, and design strategies.

2. Participant engagement

The desktop polling station addresses the challenges of acquiring repeated IEQ feedback from building occupants in real work environments by exploring the process of data collection as user interface and user interaction design problems. With the commercial success of the personal desktop computer, the graphic user interface (GUI) (i.e. screen, keyboard, and mouse) has become the default model for human-computer interaction. Consequently, with the widespread adoption of desktop computing in commercial office environments concurrent with the growth of internet access, the web-based survey has emerged as an attractive research method for obtaining subjective feedback from building occupants due to its low cost to administer, scalability, and easy integration with database tools for data storage and analytics (Zagreus et al., 2004). However, for prolonged (e.g. multi-week) repeated measures study designs, GUI-based survey techniques have several limitations. First, GUI-based methods exclude building occupants who lack routine access to a computer. While this is unlikely to be a concern for evaluating commercial office environments, it could be a barrier to expanding POE to other building types and building user groups. Second, the GUI-based mechanisms available for prompting feedback from participants (e.g. repeated emails, pop-up windows) are notoriously distracting and can lead to low participation rates and reduced willingness to participate in future POE studies, a condition known as survey fatigue (Porter, Whitcomb, and Weitzer, 2004). And, where study participants are sampled from work environments where real work tasks are being performed, protocols that implement no prompt mechanism are likely to be forgotten, resulting in limited feedback.

3. Approach

The approach taken was to implement principles borrowed from the field of Tangible User-Interface design (TUI). A TUI is a user interface in which a person interacts with digital information through the physical environment rather than with generic remote controllers (e.g. mice and keyboards) or a visual display terminal (Ishii, 2008).

The objective of this approach is to better-enable collection of repeated measures human factors data in real work environments by:

- Detaching the data collection mechanism from the GUI
- Enabling multiple modes of user interaction (modes discussed in **Section 3.3**)
- Making interaction intuitive, convenient, ergonomic, and fast

- Using a small, portable form to enable sampling at the spatial resolution of individual workspaces
- Providing a continually accessible interface to record feedback simultaneously with changing perceptions of environmental conditions
- Encouraging recruitment, retention and engagement of study participants by making the process of participation fun

3.1 Design concept

The design concept of a small figure-like desktop object (**Fig. 1**) was informed by field observations of work environments were many occupants were found to supplement their desktops with non-work-related objects (e.g. small animal figures, globes, artwork, souvenirs etc.). Located within easy reach, these objects serve to personalize the workspace and potentially enable short distractions from work tasks. The decision to develop the polling station as an addition to this desktop menagerie follows the ubiquitous computing model defined as “machines that fit the human environment instead of forcing humans to enter theirs” (York and Pendharkar, 2004). The polling station device was also informed from previously developed mounted polling devices used in field evaluation of the potential effects of Demand Response (DR) precooling on occupant comfort (Xu et al., 2006, Lee et al., 2007). For example, Lee et al., (2007) used a project enclosure with a single five-point thermal comfort subjective scale to survey visitors and staff at three small commercial bank buildings located in Southern California. Subjective response data paired with concurrent physical measures of the thermal environment were analyzed to investigate the potential effects on comfort of morning pre-cooling to reduce peak electricity demand during hot summer days. The device presented in this paper develops this approach by introducing additional modes of prompting occupants for feedback (**Section 3.3**), by enabling customizable and branching multi-question survey structures through an on-board microcontroller and LCD screen, and by adapting the device to a multi-week, repeated-measure study design intended for individual workspaces. The quasi-human appearance of the device was chosen to stimulate curiosity in prospective study participants as well as de-emphasis perception of the device as a measurement instrument. The latter decision was informed from preparatory field interviews where occupants expressed dissatisfaction with the long-term presence of scientific measurement equipment in their workspace.

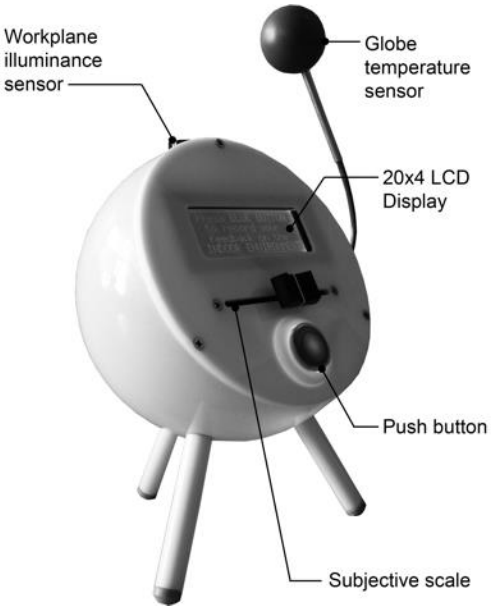

Figure 1. The desktop polling station.

In addition to an interface for subjective measures, the polling station serves as a platform for physical sensors. The first prototype includes a globe thermometer and global horizontal illuminance sensor. Globe temperature is measured using a globe thermometer attached to the side of the device. When in a state of equilibrium, a globe thermometer indicates the combined influence of radiative and convective heat exchange with a particular environment (e.g. a particular air temperature, air velocity, and temperatures of surrounding surfaces in an office) (Fountain, 1987). The sensor used in this study is an epoxy encapsulated precision thermistor[1] suspended inside a spherical shell[2]. Global horizontal illuminance measures are made using a cosine-corrected photometric sensor[3].

3.2 User interface design

The process for data input is simple and intuitive enough so that no device instructions or tutorials are required. The "plug-and-play" nature of the device is a necessity for large field studies of buildings in use, where not all participants are likely to be present when devices are distributed and complex instructions are likely to be unheeded or forgotten. The interface (**Fig. 2**) is composed of familiar physical controls and a 4-line, 80-character, white-on-blue liquid crystal display (LCD). A horizontal (60 mm) slide potentiometer is used to physically register subjective responses along a 7-point, bipolar psychometric scale (after Likert, 1932). This subjective scale was chosen because it is equivalent to the scale used by the U.C. Berkeley Center for the Built Environment's web-based occupant Indoor Environmental Quality (IEQ) survey (Huizenga et al., 2002). For questions assessing a preference (e.g. thermal preference), the slider was remapped to a 3-point scale: "Prefer to be cooler," "Neutral," and "Prefer to be warmer."

Figure 2. Example subjective response sequence. The participant is recording an assessment of "slightly satisfied" along the 7-point scale: "Very dissatisfied," "Moderately dissatisfied," "Slightly dissatisfied," "Neutral," "Slightly Satisfied," "Moderately Satisfied," and "Very Satisfied."

Subjective data are input by responding to a short survey. The survey consists of multiple short questions that query occupant satisfaction level or preference at the point in time the

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[1] Brand = Measurement Specialties, type = 44016RC precision thermistor, resistance = 10,000 Ohms at 25 degrees C. Prior to assembly, thermistors were calibrated in a thermal bath to within +/- 0.1 deg. C.

[2] The shell is a ping pong ball spray painted 50% matt grey.

[3] Brand = Licor, type = LI-210, nominal accuracy = 3%.

survey is initiated. During prototype evaluation, a seven-question survey was completed by most participants in less than two minutes. The survey can be initiated through multiple modes of interaction, which are discussed in the following section.

3.3 User interaction design

The desktop polling station is designed with three modes of collecting occupant feedback: *Push*, *Pull*, and *Ambient* (**Fig. 3**). *Push*, in this context, refers to the capability of the device to receive input at an arbitrary point in time, with interaction initiated by the study participant. *Push* interaction is needed for situations where the environmental stimulus may only be present for a brief period of time (e.g. glare, direct sun, disturbing noise), but may strongly influence overall perceptions of comfort or environmental quality. In addition, *push* interaction enables participants to have a greater level of perceived control and participation in the POE process. However, the *push* mode relies entirely on a proactive user, leading to feedback that is subject to an irregular sample rate. *Pull* interaction is needed when occupant feedback is desired at specific points in time, or synchronously among multiple participants. For example, to evaluate the thermal comfort implications of a morning pre-cooling strategy for demand response, the researcher may want to query all participants at 9:00 AM and again at 3:00 PM to evaluate comfort at two thermal extremes. To prompt the user for feedback in the *pull* mode, the device utilizes customizable visible (self-luminous) and audible signals to direct the user's attention to the device.

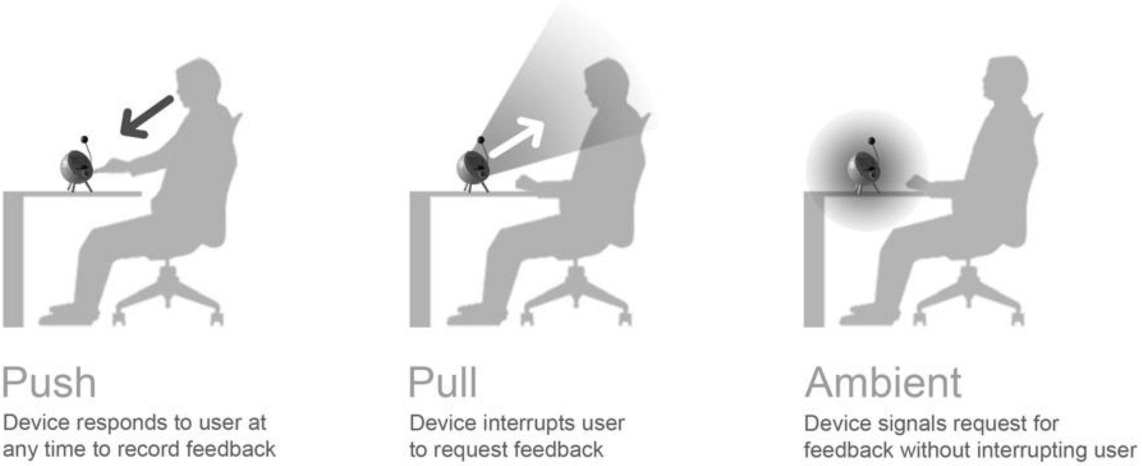

Figure 3. The three modes of user interaction.

While *push* interactions are initiated voluntarily by the participant and are thus unlikely to be considered irritating, *pull* interactions are disruptive because they interrupt the participant from his/her work task. To minimize the potential for irritation from an excessive number of *pull* interactions, a third mode, *ambient* interaction, was developed. *Ambient* interaction relies on the human ability to acquire and process information from the environment without foreground consciousness. For example, building occupants with a window view are aware of the outdoor weather conditions continuously while their attention may be focused on other cognitive tasks. The polling station initiates *ambient* interaction by gradually changing the color of an internal LED and the LCD screen luminance to present a non-disruptive signal to the user for feedback. In the event that the user perceives either the *ambient* or *pull* interaction to become irritating, the device is designed with a "sleep" function that can be easily activated by moving the horizontal slider.

4. Applications and sample results

The desktop polling station is a diagnostic device aimed at equipping building managers, engineers, green building rating agents, commissioning agents, researchers and architects with an inexpensive and flexible platform for implementing detailed IEQ performance monitoring in the field. Data collected using the polling stations have immediate relevance to researchers and professionals to improve the design, certification and operation of commercial buildings. Within the scope of individual projects, designers can conduct short-term post-occupancy field monitoring to identify the frequency and magnitude of discomfort conditions to determine "what's working" and "what's not" for environmental design strategies. Further, designers can utilize the temporal and spatial granularity of the data to identify "when" and "where" performance does not meet design expectations. Moreover, commissioning agents can compare occupant subjective assessments to simultaneous physical measurements to help inform appropriate control criteria for responsive mechanical and lighting systems. Regarding green building certification, periodic IEQ audits can ensure that projects seeking green building ratings achieve designated compliance criteria for IEQ in operation. In addition, the polling stations present a platform to enable green building rating organization technical advisory groups to include occupant feedback as a resource to validate and refine compliance criteria for IEQ. Finally, polling stations can be used to continuously improve the performance of existing buildings by serving as a platform for more detailed investigation of issues identified from web-based surveys or informal complaints. Moreover, energy consumption data can be examined in context with user feedback to ensure that the energy consumed by mechanical systems consistently results in a service to occupants. Beyond the scope of individual projects, data acquired systematically across a range of building types, locations, and climates can be aggregated to serve as a resource for both researchers and industry to investigate trends in the performance of environmental control strategies and building technologies.

The following section presents data from a field study of a high-performance office building demonstrating the applicability of a number of devices (N=15) to quantify the magnitude and intensity of a set of IEQ conditions, investigate occupant subjective responses in relation to indoor and outdoor climate, and enable the generation of field-based discomfort models.

4.1 Field study of a high-performance office building, San Francisco, California

Fifteen polling stations were fabricated and used to evaluate the IEQ performance of multiple floors of a high-performance office building located in San Francisco, California. "High performance" in this context refers to the implementation of passive environmental systems (i.e. daylighting, natural ventilation, exposed thermal mass) to reduce energy consumption and enhance IEQ. The monitoring approach was designed around multi-week (e.g. 2-3 week) monitoring phases, strategically distributed across the year to allow inferences from short-term monitoring to inform an understanding of annual performance. Subjective data were collected from 44 participants (38% male, 62% female). Due to the limited number of polling stations fabricated, data was collected from groups of participants (N <= 15) defined based on location on the floor plate (NW facade, SE facade, and Core). Survey responses to questions of thermal comfort, thermal preference, daylight sufficiency, daylight preference, impact of shades on view, visual discomfort, and need for electrical lighting were paired with simultaneous measurements of global horizontal illuminance, globe temperature, and vertical luminance (acquired using HDR imaging) as well as simultaneous measures of exterior solar and thermal conditions. Analysis of frequency-of-use for one multi-week monitoring interval showed that, on average, participants interacted with the devices three-to-four times each day, with a greater frequency of responses during the first week and a more regular frequency the following weeks (**Fig. 4**). The frequency of each specific interaction mode (push, pull, ambient) will be investigated in a future analysis of the pilot data set to examine the efficacy of each mode for eliciting a completed survey response. This analysis will be done by comparing the number of completed surveys for each mode to the number of instances when the survey was ignored via the sleep function. The data will also be explored to examine subjectivity trends in reporting between modes. For example, participants may be more likely to use the push mode of interaction to record assessments of discomfort (rather than comfort) due to the desire to register dissatisfaction motivated by uncomfortable environmental conditions. Finally, the data will be analyzed to look for fatigue effects, such as greater use of the sleep mode or fewer push interactions over the course of each day as well as over the course of the multi-week study.

Analysis by hour (**Fig. 5**) revealed that response frequencies peaked in the morning near 8:00 AM and in the afternoon near 1:00 PM. Responses recorded in the early AM (e.g. prior to 8:00 AM) were found to be the result of a decision by several participants to advance their daily work schedule to avoid traffic during typical commuting hours.

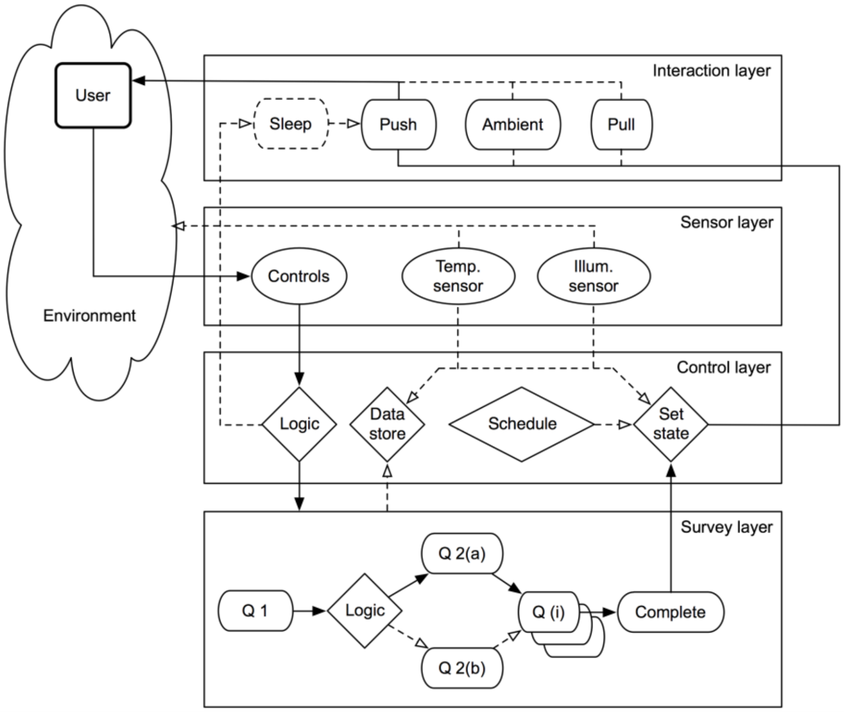

Figure 4. Frequency of responses in aggregate by day.

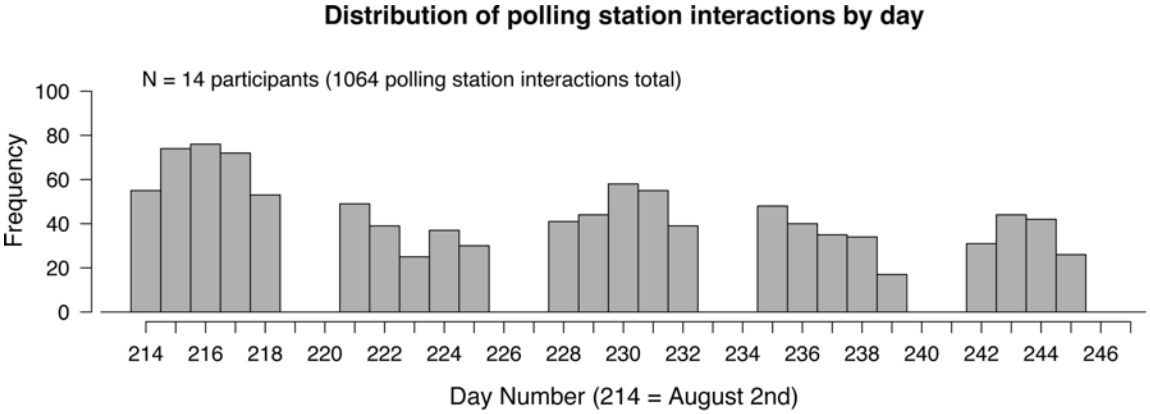

Figure 5. Frequency of responses in aggregate by hour (Daylight Savings Time).

4.2 Sample results

Fig. 6 presents a summary “dashboard” view of the feedback from one group of study participants (N = 14) acquired from August 2 to September 3, 2011. This group was located in the perimeter zone of the building adjacent to the south-east-facing facade window wall. Satisfaction levels are represented for each point on the scale as a percentage of total responses and are summarized into three bins: dissatisfied, neutral, and satisfied. For times when the occupant recorded dissatisfaction (e.g. with thermal comfort), the dashboard displays the results of the follow-up branching question recording their preference for change (e.g. “prefer to be cooler”). The dashboard can be used to quickly identify the frequency and magnitude of subjective assessments, as well as indicate the preferences of occupants for modifications to IEQ conditions (e.g. thermal preference). Based on performance issues identified and prioritized using the dashboard, the investigator can perform more detailed evaluation by examining spatial and temporal trends in the data and by examining subjective responses in relation to concurrent physical measurements.

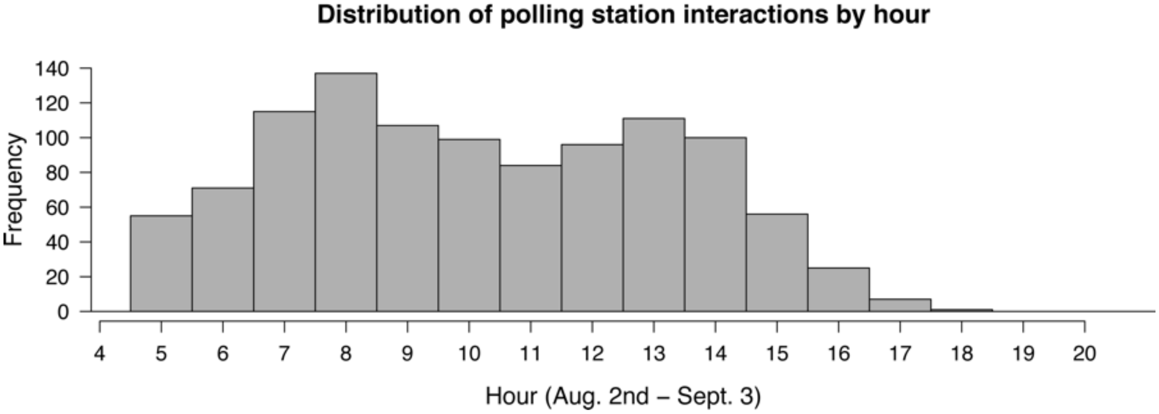

Figure 6. Sample reporting dashboard.

Fig. 7 displays the temporal distribution of thermal dissatisfaction and preference for change for the responses from the previous section (**Fig. 6**) in relation to indoor globe temperature measurements (grey lines) and outdoor dry bulb temperature (black dotted line) over two weeks of the monitoring interval. All dissatisfied responses are indicated with a triangle, where preference to be cooler points down and preference to be warmer points up. This figure illustrates how the temporal granularity of the polling station data can be investigated to quickly indentify trends in dissatisfaction in response to changes in outdoor weather conditions. For example, the first five days show that thermal dissatisfaction occurs predominantly in the AM, (following night-flush cooling), and the final four days indicate overheating in the afternoon in response to an increase in outdoor air temperature.

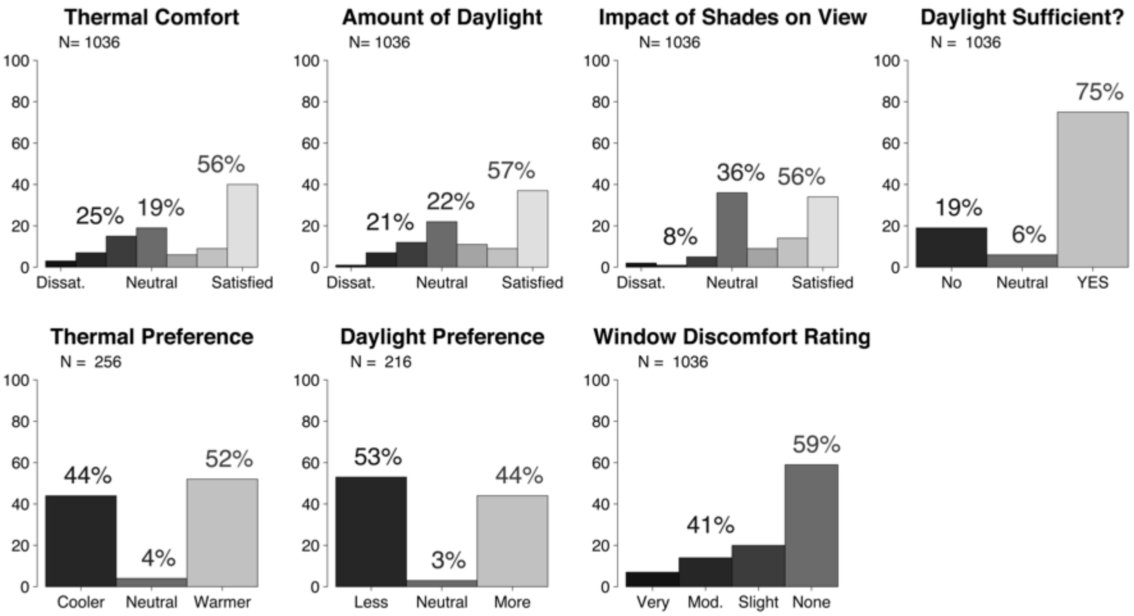

Figure 7. Distribution of thermal dissatisfaction and preference for change.

In addition to examining subjective assessments in relation to indoor and outdoor climate conditions, concurrent physical and subjective measurements acquired over time enable the indoor climate conditions acceptable to occupants to be modeled and compared to the indoor climate conditions provided by the building. To examine the probability of thermal dissatisfaction in response to indoor globe temperature, an approximation of operative temperature recommended for field measurements (ASHRAE PMP, 2010), single-variable logistic regression models were derived from the data collected from August 2 to September 3, 2010.

Because several days during the monitoring interval (days 235 – 237, referred hereafter as the “heat wave” condition) achieved significantly warmer and more variable outdoor temperatures (mean outdoor temp. = 64 deg. F, SD = 9.8 deg. F) than the days in August leading up to the heat wave condition (mean outdoor temp. = 57 deg. F, SD = 2.5 deg. F) referred hereafter as the “baseline condition,” observations from the heat wave condition were removed and modeled separately. For each model, thermal dissatisfaction is defined as any response of *very*, *moderately*, or *slightly* dissatisfied. Each model predicts the probability of dissatisfaction as a function of indoor globe temperature. The models can be interpreted to estimate the range in operative temperature (i.e. comfort zone) that must be maintained by the indoor climate to achieve less than 20% discomfort among occupants (horizontal line). **Fig. 8** shows the logistic models developed from the group of study participants in aggregate for the days in August leading up to the heat wave condition. Comparison of the models developed for baseline condition (**Fig. 8)** to the models for heat wave condition **Fig. 9** shows that the comfort zone shifted to warmer temperatures (from 72.6 – 75.5 to 74.2 – 77.5 deg. F), and the range of acceptable temperatures within the comfort zone increased (from 2.9 to 3.3 deg. F). The capability to measure and model the potential shift in occupant thermal preference in response to outdoor climate is important to validate and refine climate-based thermal comfort models (e.g. Brager and de Dear, 2000) with occupant data collected from buildings in use. Although this is a pilot data set and extremely limited in duration and survey population, the result supports adaptive theory that the thermal expectations of building occupants will depend on outdoor temperature and it demonstrates the applicability of polling stations for acquiring the data needed to investigate how preferred comfort conditions may vary over daily, weekly, or seasonal changes in outdoor climate conditions.

Field-based models of occupant thermal comfort can also be compared to the indoor climate conditions provided by the building to identify the times and extent to which the provision of indoor thermal conditions are unacceptable. For example, during the baseline condition in August, the indoor operative temperatures among all polling stations were below 72.6 deg. F or above 75.5 deg. F for 37% of nominally occupied hours (6:00 AM - 7:00 PM), with the measurements below 72.6 deg. F occurring in the morning and the measurements above 75.5 deg. F occurring in the afternoon (**Fig. 7**). During the heatwave condition, the percent of occupied hours where polling station operative temperature measurements were outside the modeled comfort range (74.2 – 77.5 deg. F) increased to 54%. Both outcomes, particularly the latter, indicate the need to tune available means of indoor thermal control as well as address the aspects of the building design (e.g. facade solar heat gain) that may be responsible for thermal overheating. In addition to thermal comfort, probabilistic models have been developed from polling station data to predict occupant perception of daylight sufficiency and visual discomfort. These models are presented and described in detail in (Konis, 2011).

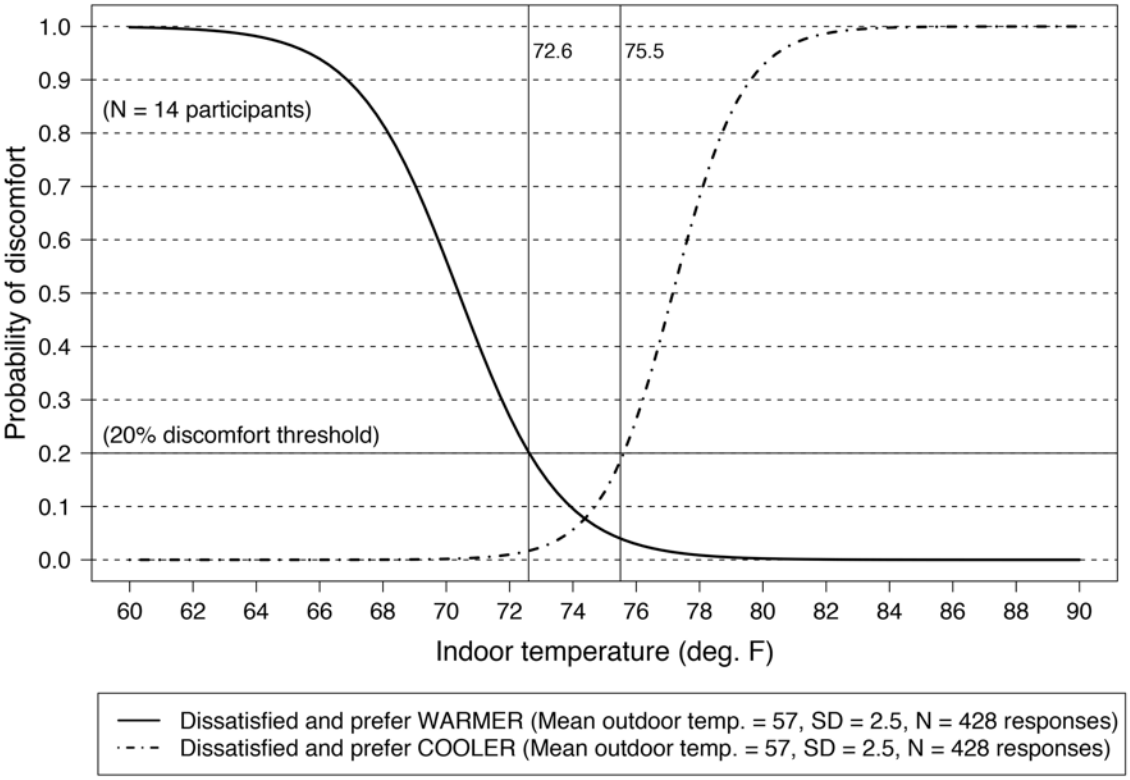

Figure 8. Logistic regression models of thermal dissatisfaction during baseline outdoor temperature conditions in August (days prior to heat wave condition).

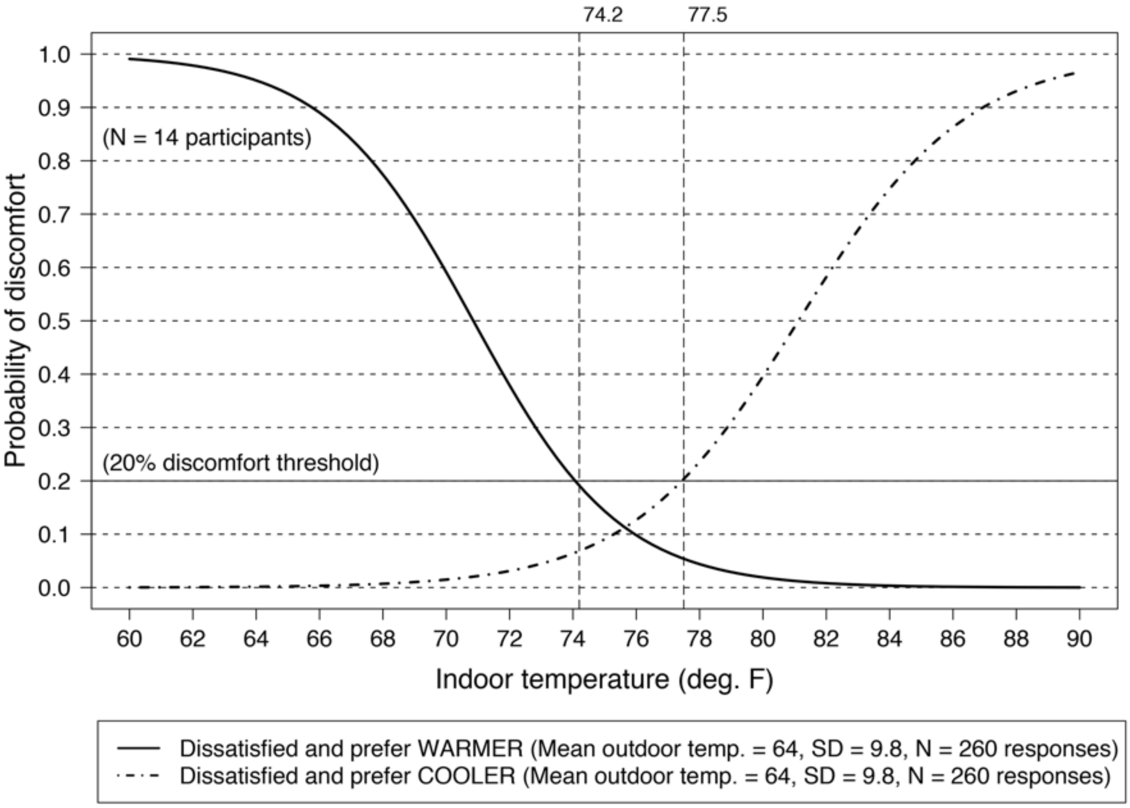

Figure 9. Logistic regression models of thermal dissatisfaction during August heat wave conditions.

5. Conclusions

The desktop polling station has the potential to serve as a useful diagnostic tool for detailed performance assessment of building IEQ to inform decision making for the design, certification, and operation of buildings. In the absence of reliable physical measures and field-validated performance criteria for many IEQ factors, methods are needed to acquire real-time subjective data directly from building occupants to effectively evaluate performance. Subjective data will increase in value towards informing building IEQ performance to the extent that they can be contextualized with supporting spatial, temporal, and environmental data. The polling station devices are designed to serve as a low-cost, scalable platform to acquire detailed IEQ performance data with the level of spatial and temporal granularity to identify “when” and “where” problems exist as well as to identify the magnitude of discomfort and occupant preference for modifications. To address the challenge of acquiring feedback data repeatedly from occupants over an extended period of time in a context where real work tasks are being performed, the principles of tangible user interface design and ubiquitous computing were used to develop an intuitive, “plug-and-play” user interface and less-disruptive modes of prompting user interaction. As a result, the devices and the monitoring process itself, (of delivering a desktop interface to register occupant feedback), have the potential to serve as a mechanism to acknowledge building occupants as a valuable source of information and to empower occupants to engage in contributing feedback to improve building IEQ.

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