Building and Environment 185 (2020) 107266

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

Field investigations of a smiley-face polling station for recording occupant satisfaction with indoor climate

Niels Lassen [a,b,*], Francesco Goia [a], Stefano Schiavon [c], Jovan Pantelic [c]

[a] Department of Architecture and Technology, Norwegian University of Science and Technology, NTNU, Trondheim, Norway
[b] Skanska Norge AS, Oslo, Norway
[c] Centre for the Built Environment, University of California Berkeley, California, USA

ARTICLE INFO

Keywords:
Occupant satisfaction
Polling station
Subjective feedback
Thermal comfort

ABSTRACT

The use of smiley-face polling stations has had a rapid growth as a means of automatically and efficiently collecting user satisfaction verdicts in airports, restrooms, museums, and retail. Their advantages are that they are low cost, efficient for both respondents and analysts, in addition to having higher response rates than other survey types. Their main disadvantage is the lack of control with who is voting, meaning both repeat voters and non-voters may lead to biased results. The aim of this study is to assess the representativeness and functioning of such publicly located satisfaction polling stations (SPSs) in an indoor climate setting, and to evaluate their potential for real-time evaluation of occupant's satisfaction with the indoor climate. We carried out continuous field tests in two office buildings for more than two months where the results of SPSs were compared with 473 survey results collected in 10 rounds during the tests. To assess how sensitive the instrument was to changing conditions, we deliberately changed temperature setpoints on selected days in one of the buildings. We found that the SPSs had a high and variable non-response bias which could result in a low accuracy for benchmarking of building indoor climate satisfaction. Results also showed a high correlation between SPS complaints and complaints recorded in the surveys for the thermal comfort aspect of indoor climate, including thermal comfort induced by temperature interventions. SPSs can provide valuable continuous recordings of the occupant's satisfaction with the indoor climate.

1. Introduction

The use of smiley-face polling stations, or single-button response kiosks, has had a rapid growth as a means of automatically and efficiently collecting user satisfaction feedback in airports, restrooms, and retail. Such polling stations often display one single question like "*How satisfied are you with …. ?*" followed by four to five large smiley-face response buttons which users can use to respond quickly as they pass by. Because of their user-friendliness and ability to engage the users in providing feedback on their experience, these satisfaction polling stations (SPS) could also be considered as a tool for collecting information on people's satisfaction with the indoor climate (IC) of the built environment.

The aim of this study is to assess the representativeness and functioning of a satisfaction polling station in an indoor climate setting and evaluate its potential relative to four main use-cases: indoor climate (IC) *benchmarking* among spaces, IC *tuning* and commissioning, IC *control*, and continuous *learning* related to occupant preferences. This is performed by comparing polling station results with results from survey responses collected by approaching each individual occupant in field tests in two office buildings in California. The research questions are as follows: (1) How representative is the polling station feedback compared to a thorough survey (considered as "ground truth")? We evaluate this by comparing daily mean vote, share of dissatisfied votes as well as by investigating the measured and self-reported non-response bias specifically. (2) How sensitive is the polling station feedback to environmental changes? We evaluate this by performing temperature interventions in one building and investigating correlations between the shares of thermally dissatisfied voters in the survey and from the SPSs, and the predicted thermal sensation of occupants according to Cheung et al. (2019). (3) Is there a difference in voting habits (votes and voting frequency) among occupant types and over time? We investigate this by studying self-reported voting frequencies categorized by voter age and sex. We also study the total SPS usage frequency over time.

* Corresponding author. Department of Architecture and Technology, Norwegian University of Science and Technology, NTNU, Trondheim, Norway.
E-mail address: niels.lassen@skanska.no (N. Lassen).

https://doi.org/10.1016/j.buildenv.2020.107266
Received 29 April 2020; Received in revised form 30 August 2020; Accepted 3 September 2020
Available online 5 September 2020
0360-1323/

2. Background

An analysis of occupant surveys of more than 90,000 respondents from ~900 buildings showed that people are most satisfied with the spaces' ease of interaction (75% satisfied), amount of light (74%) and cleanliness (71%), and most dissatisfied with sound privacy (54% dissatisfied), temperature (39%) and noise level (34%) [1]. In building design, the optimization of IC parameters is normally based on theoretical and deterministic models as well as guidelines for predicting the comfort and satisfaction of a generic group of occupants. In practical operation, the design set-points are, together with the experience of facility managers, used as a starting point before specific changes are made according to occupant feedback in order to accommodate zonal differences, occupant group, and individual differences. The feedback from occupants is used for immediate changes of IC, but seldomly as a systematic tool for long-term improvements [2]. When the occupants have to submit their complaints via systems with several hidden layers (for example facility management call centres), or when it is unclear how to submit the complaint, we imagine that occupants may find it difficult to provide feedback and lose interest in doing so. Tight design set-points and limited user-feedback can have large effects on energy use, user satisfaction, and investment costs [3]. In the case of thermal comfort, studies of facility management practices have shown that in practice the setpoint bandwidths in buildings are as small as 1–2 °C. Such tight bandwidths are probably adopted to prevent complaints from occupants [2,4,5]. These demands and practices lead to a need for equipment with large heating and cooling capacities, high power peaks, and high energy use [6]. At the same time, several field studies have found that narrow temperature bands do not necessarily lead to higher occupant satisfaction with the thermal environment [7,8].

Studies showed that a high number of factors influence the subjective and psychological state of satisfaction [9–11]. Some of the factors (such as occupant expectations or satisfaction with the amount of space) are difficult to measure in practice, and accurately predicting occupant's satisfaction may therefore be extremely challenging. Hence, enabling occupants to efficiently provide continuous feedback regarding IC satisfaction and preference may be an important contribution towards improving occupant satisfaction, environmental impact, and continuous learning regarding indoor climate in buildings. There are, however, no established practices today that allow for continuous and direct measurement and documentation of the satisfaction level of building occupants. The only known and established tool to capture the subjective opinions of occupants are Post Occupancy Evaluations (POE). However, POE surveys are done at maximum once or twice per year, and while they may be used for benchmarking, documentation, and fault indications, they are not suited for continuous indoor climate control or tuning. Continuous and real-time data of the occupant satisfaction level regarding indoor climate would have potential to be used for indoor climate benchmarking of buildings; tuning, fault finding, and commissioning; or for direct control of the indoor environment such as temperature or air quality control.

Several recent research approaches related to smart buildings [12, 13] have investigated continuous subjective data collection, such as participatory sensing mobile applications (apps) where occupants voluntarily provide feedback through a smartphone app [14–16], internet enabled thermostats, or wearable and static devices where control behavior is tracked and logged [17–19]. Although relevant, these solutions focus on non-intrusive data collection from occupant *preferences* or *perceptions*, which may be substantially different from occupant *satisfaction* evaluations. Moreover, they focus on a specific dimension of IC. Satisfaction refers to whether our expectations to a certain object, service, or experience are fulfilled. It contains components of both judgement (cognition) and affect (emotion) [10]. Indoor climate s*atisfaction* may be compared to customer satisfaction and results at the end of the consumers processing activities, and not necessarily when the product or service outcomes are observed [20,21]. Occupants who are satisfied with the overall environmental quality of their workspace are assumed to be more productive [22,23]. In the context of this study, where the length and number of questions we can ask at the polling station is constrained, we prioritize asking the occupant for their satisfaction level as it is the "summary state" of subjective evaluation. If the occupant reports to be satisfied with the indoor climate, there is no need for further investigations.

Although the use of smiley-face polling stations has had a rapid growth for certain applications, we only found one study assessing the accuracy of polling station results. The available study [24] was conducted in a security checkpoint implementation and it concluded that the results were highly correlated with results of a traditional usability survey, but that the dispersion of kiosk responses was significantly larger than that of the survey. Passing through a security checkpoint is a one-time event for the user, while experiencing the indoor climate of an office is a continuous or re-occurring event. Due to this difference, it is assumed that the results of this study may not necessarily apply to an indoor climate application. Most surveys are based on voluntary responses but assume high response rates for statistical representativeness, thus neglecting the likelihood of the sample being biased. There is a general trend of falling response rates in sample surveys throughout the richer countries of the world [25], making this problem increasingly crucial. The non-response bias (also known as *participation bias*) is a phenomenon in which the results of a survey become non-representative because the respondents differ in meaningful ways from non-respondents [26]. It is often tested by comparing responses from two separate samples, where one of the samples is treated as the "reliable" sample. For comparison, POE studies are normally distributed by email and the response rate can be estimated between 10% and 60%.

There are three known instances where polling stations have been tested for continuous assessment of satisfaction with indoor climate in buildings [27–29]. One of the studies investigated personal polling stations, while the other two investigated a public satisfaction polling station (SPS) with smiley face ratings. No studies have assessed the accuracy of SPSs with the feedback from other survey types. To the best of our knowledge, this analysis has not been done with POE surveys either, and the magnitude of non-response bias in these types of surveys is also unknown.

3. Methodology

3.1. Overview

The research questions focus on determining the representativeness of the satisfaction polling station (SPS). This is done by asking occupants to use one or more SPSs placed in the office environment as they wished over a period of several weeks. Simultaneously the room temperature was measured, and the researchers assessed comparable occupant opinions by approaching each occupant on given days and asking them to fill out a separate 2-min survey. By personally surveying each occupant, high response rates of 70–100% were achieved and the risk of non-response biases in this sample was reduced to a minimum. The personal survey contained identical questions to what was shown on the SPS, as well as a modified version of the UC Berkeley Center for the Built Environment (CBE) Occupant Survey that only focused on questions about thermal sensation and acceptability. The survey also included other questions regarding the use of the SPS and metadata about the respondent (sex, age, workplace location).

In order to investigate the sensitivity of the SPS responses to changes in the indoor climate, temperature interventions were performed on four individual days in one of the buildings, during which the temperature set-point for the entire space was either lowered or raised compared to the regular set-point. Temperature interventions were chosen as an example of IC changes that could happen in a space because they are the easiest type of environmental change to carry out in practice. Other examples could have been noise masking, different lighting and daylighting strategies, different air filtration levels, or outdoor air flow rates.

The occupants were not aware in detail of the ultimate goal of the study (i.e. to study the use of the SPS and to compare the SPS's feedback with the survey's feedback), but they were informed on the study being focused on assessing indoor climate. In this way, the tests became partially blind, and the occupants can be said to be un-biased and representative of real-life occupants introduced to new equipment.

3.2. Case buildings

Field experiments were performed in two separate office buildings during the spring and summer of 2019. Building 1 is an office building located in Berkeley, CA. The entire 3rd floor was selected for the study, with a total area of approximately 2950 m^2. The floor had approximately 200 available workspaces, which are mainly cubicles in an open office environment. It is estimated that about 95 employees work on this floor on an average day, mainly doing administrative tasks related to human resources and accounting. The office demographics are made up of 22% male and 78% female occupants. The building is an old industrial building that has been retrofitted for office purposes. It is located nearby an industry plant emitting airborne pollutants that produce odour, and close to train tracks producing noise pollution. According to the assessment of the researchers who conducted the surveys, the mechanical HVAC system is rather noisy and produces draft in some places. Interior shading devices are present on all sun exposed facades. Some interior materials, such as carpets and blinds, exude a noticeable odour. 60% of the occupants report to have acquired personal heaters or fans which they use on a regular basis. The building does not have operable windows and apart from personal heaters, fans, and blinds, the occupants have no control over the indoor climate.

Building 2 is a high-rise office building located in downtown San Francisco. The entire 14th floor was selected for the study, with a total area of approximately 1550 m^2. The floor has 50 available workspaces, all of which are desks in an open office landscape. It is estimated that the average number of occupants per day is 25 people, performing tasks related to civil engineering and construction. The demographics are made up of 66% male and 44% female occupants. The building was built in the 1970s, but the floor has been retrofitted in recent years. The central HVAC system is supplemented with additional local HVAC units. The indoor climate is in general good and the occupants are mostly satisfied, except for some who complain about being cold. None of the occupants have acquired personal comfort devices. The building does not have operable windows and, apart from blinds, the occupants have no control over the indoor climate. Direct solar irradiation in the office space is limited due to shading from surrounding buildings.

3.3. Experiment procedures

The experiment in Building 1 was carried out for 75 days, while the experiment in Building 2 lasted 70 days. Five survey rounds during which the researchers asked occupants to answer questions were performed in each building at 1–3 weeks intervals. These days are referred to as "survey days". During the 2nd and 4th survey day, signs were put up with the message "*Please vote today!*" to try to increase the number of SPS votes on that day.

Temperature interventions were performed on four individual days in Building 1, where the temperature set-point for the entire space was either lowered or raised compared to the regular set-point. Two of the four interventions were done on survey days.

Before the SPS was introduced, occupants of each building received information about the experiment stating that the SPS and temperature sensors were part of a research project about using new digital solutions to better understand the indoor climate in buildings. Occupants were asked to "*use the kiosks as much as possible, but only as it feels convenient to you*". In Building 1, this information was conveyed as part of a newsletter from the management team. In Building 2 it was sent as an email to each occupant (Table 1).

3.4. Measurements of physical environment – continuous monitoring

Internet of Things (IoT) sensors were used to continuously monitor the environment. 18 × 18 mm button sensors of type Disruptive Technologies Wireless Temperature Sensor Model EU100118 (Disruptive technologies, Volda, Norway) were used to measure dry bulb air temperature in the space with a declared absolute accuracy of 0.4 °C. 34 IoT sensors were distributed in Building 1 resulting in a sensing density of 86 m^2 per sensor (Fig. 1 A). In Building 2, we distributed 20 IoT sensors with a sensing density of 76 m^2 per sensor (Fig. 1 B). Air temperature sensing density was above the required by IoT sensing standard RESET [30] in both buildings, which suggest one sensing point per 540 m^2, and the WELL v2 standard [31] that requires one sensing point per 350 m^2. The sensors were placed on the cubicle walls or work desk dividing screens in the open office environment. CO_2 was continuously measured at 5s sampling intervals by IoT sensors of type Telaire, T6713 CO_2 module (Mouser Electronics, Mansfield, TX, USA) to give a general impression of the CO_2 levels at one point in each building. These sensor have a relative measuring accuracy of 3% for readings below 1000 ppm. Three temperature sensors placed along the west facade in Building 1 were excluded from the dataset as they found to be affected by direct sunlight.

3.5. Satisfaction polling station (SPS)

A Satisfaction Polling Station (SPS) was developed in the form of a webpage displayed on a tablet computer mounted on a stand. Several studies have shown how crucial the aspects of usability and adequate interfaces are to collect high frequency occupant data [32,33]. No usability studies were however performed for the interface used in these field tests, and the occupants' opinion about the interface were not investigated in this study. Different results may have been obtained with a different interface. SPSs were installed at strategic locations close to exits in both buildings throughout the test period. The SPS displayed a front page showing the question *"How satisfied are you with the indoor climate at your workspace today?"*. Five smiley-face buttons were displayed below the question. The question wording was selected after asking a few randomly selected people to describe their understanding of several similar questions, and it was found that this question conveyed the intended meaning to most people. Questions with other terms, such as "indoor environmental quality", were by several interpreted to relate to nature and the exterior environment. There is, however, no guarantee that all respondents had a full or correct understanding of the question. As occupants pressed buttons on the touchscreen, the response was saved in a database as integers between −2 and 2 where −2 is "Angry", 0 is "Neutral" and 2 is "Happy". If one of the three right buttons (0–2) were pressed, a *"Thank you for voting!"*

Table 1
Experiment sequence.

Task	Building 1	Building 2
Experiment notification	May 13, 2019	May 01, 2019
START	May 06, 2019	May 01, 2019
Survey 1	May 22, 2019	May 23, 2019
Survey 2	June 04, 2019 *	June 03, 2019 *
Survey 3	June 21, 2019	June 20, 2019
Survey 4	June 27, 2019 *	June 28, 2019 *
Survey 5	July 11, 2019	July 10, 2019
Intervention 1 (- 4 °F/2.2 °C)	June 27, 2019	NA
Intervention 2 (+4 °F/2.2 °C)	July 11, 2019	NA
Intervention 3 (- 2 °F/1.1 °C)	July 16, 2019	NA
Downtime 1	July 18, 2019	NA
END	July 21, 2019	July 10, 2019

*Days with extra SPS visibility

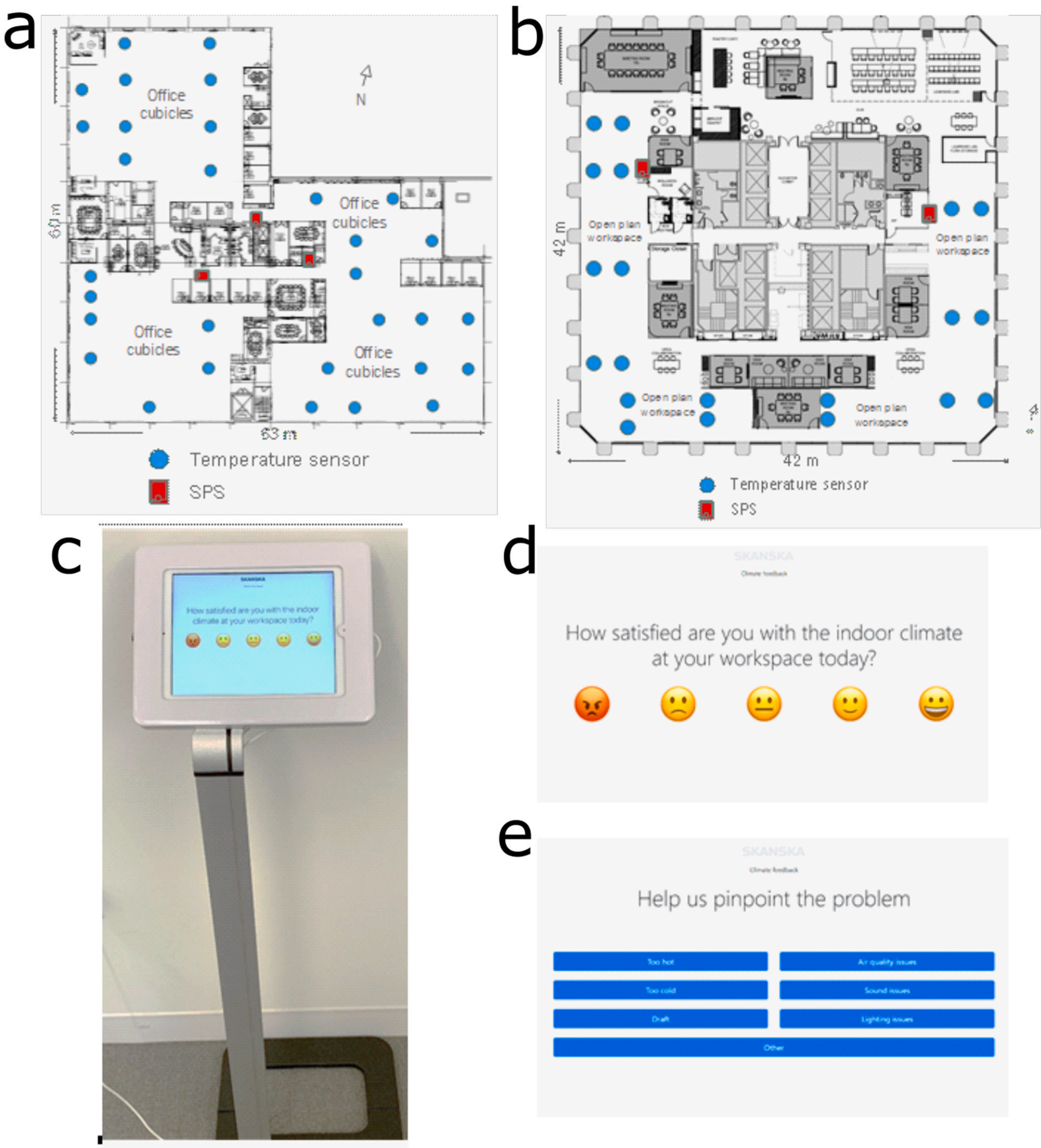

Fig. 1. a) Floor plan of Building 1 with temperature sensors (blue) and SPSs (red) plotted. b) Floor plan of Building 2 with temperature sensors (blue) and SPSs (red) plotted. d) Satisfaction Polling Station (SPS). d) SPS Page 1. e) SPS page 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

screen appeared before the screen returned to the front page. If one of the two left buttons were pressed (−2 or −1), a second screen appeared with the text *"Please help us pinpoint the problem"* followed by seven buttons with the following statements: *"Too hot"*, *"Too cold"*, *"Draft"*, *"Air quality issues"*, *"Sound issues"*, *"Lighting issues"* and *"Other"*. Only one of the statements could be selected, and all responses were stored in a database. The available response buttons were selected based on the researchers' experience with known common occupant complaints. It was desirable to have two response alternatives for the thermal complaints to be able to study the sensitivity to environmental changes. After selecting an issue, the *"Thank you"* screen appeared.

SPS locations are shown in Fig. 1 A and B, while Fig. 1 C-E show the SPS and screenshots of SPS page 1 and 2. Three SPS's were used in Building 1, each one by the entrance to the elevators. One of these was also located close to the kitchen area. Fire staircase exits were not covered. Two SPS's were used in Building 2, located in a busy corridor and covering two exits. The exit in the reception area was not covered, as this area was often used by building visitors and conferences and it was not desirable to receive responses from people who had not stayed in the building for longer periods of time.

3.6. Occupant survey

A digital survey questionnaire with 13 questions was prepared, focusing on four main topics: (1) Occupant metadata – Age, sex, workplace type etc. (2) SPS questions – Identical questions to those on the

SPS. (3) POE questions – Similar questions to those relevant in the CBE Occupant Survey tool. (4) SPS usage habits – How the respondent uses the SPS. Relevant survey questions are summarized in Appendix A.

3.7. Performance evaluation

3.7.1. General comments

The SPS results have been grouped by days. This was found to be the most suitable time resolution in order to have a representative number of responses per time-step, although the climate conditions may vary throughout a single day (see Fig. 4 A and B). However, it is important to note that the questions in the SPS required the user to express the feedback on the indoor environment "*today*" (not "now", or "in the past hour(s)"). The temperature measurements are rendered with a time resolution of 15 min. The samples of the SPS and survey are considered equivalent, as all people in the building had the access and the possibility to vote at the SPS. Additionally, we assume that voters do not change opinions between the time of entering the SPS vote and the time of answering the survey. There is however no reference to back up this assumption.

3.7.2. Representativeness of polling station

Non-response bias – Error of daily mean SPS vote. The non-response and multiple response bias (bias of respondents voting multiple times) is assumed to be the main source of error in the SPS, as there are few other likely errors. The SPS data and survey data are compared for identical questions, eliminating question interpretation as a possible source of error. Three methods were used to investigate non-response bias. First, the daily mean score of the two samples (SPS and survey) were compared for each survey day. The error indicates the bias. The total mean score from the SPS and Q7 in the survey were also compared. Second, the number of received votes per person for each response alternative from the SPSs and the survey were compared (Q7). The result indicates whether voters with certain opinions are inclined to have different voting habits. Third, the self-reported SPS voting habits are compared with smiley scores in the survey. The results also show whether or not those with certain opinions report to have different voting habits.

Accuracy and response rates. The error between the cumulative mean and the final daily mean of the SPSs for each one of the 5 survey days for each building is plotted and assessed visually to determine how the number of SPS votes compared to the error. Although the indoor climate and general opinion may have shifted throughout the day, the figures give an impression of how many votes were needed to achieve a valid daily mean.

3.7.3. Sensitivity to environmental changes

Four temperature interventions, expected to influence the number of thermally dissatisfied occupants, were made in order to study the sensitivity of the SPS to environmental changes. The share of SPS voters reporting to be dissatisfied with thermal issues was compared to the predicted sensation based on the measured physical environment and survey responses. As the air temperature was the only measured variable used to calculate the comfort of occupants, standard comfort equations such as the comfort equation given in ISO 7730:2005 (PMV-PPD model) could not be used without making assumptions about other variables that had not been measured. The predicting accuracy of the PMV-PPD model has been criticized previously, most recently by Cheung et al. (2019) [34]. Cheung et al. suggest a simple temperature scale instead of the more complicated comfort equation, and demonstrate that it has higher predicting accuracy than the PMV-PPD model for their dataset. We, therefore, used this model as a representation of the physical environment for comparing SPS and survey responses to the measured temperature. The model scale is shown in Table 2. Interpolation was used because most temperatures were within the "Neutral" zone.

The calculated predicted thermal sensation was compared to the Thermal Sensation Vote (TSV) recorded in Q12 of the survey. The SPS percentage of thermally dissatisfied votes was compared to the percentage of thermally dissatisfied in the survey Q10. The criteria for counting dissatisfied responses at the SPS was a score of

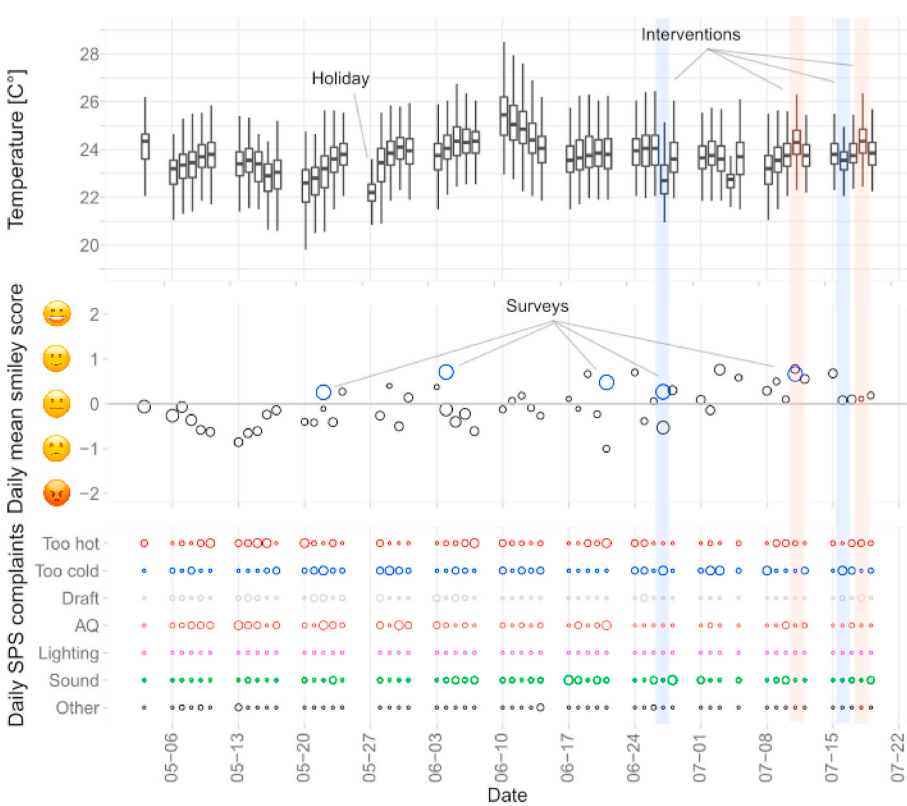

Fig. 2. General presentation of collected data in Building 1, shown as time series. The top boxplot shows indoor temperature distribution and mean per day for all sensors during working hours. The middle plot shows the daily mean of the SPS (grey) and equivalent smiley score in survey (blue). Dot sizes render the number of votes on that day. The bottom plot shows the daily share of complaints by dot size. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

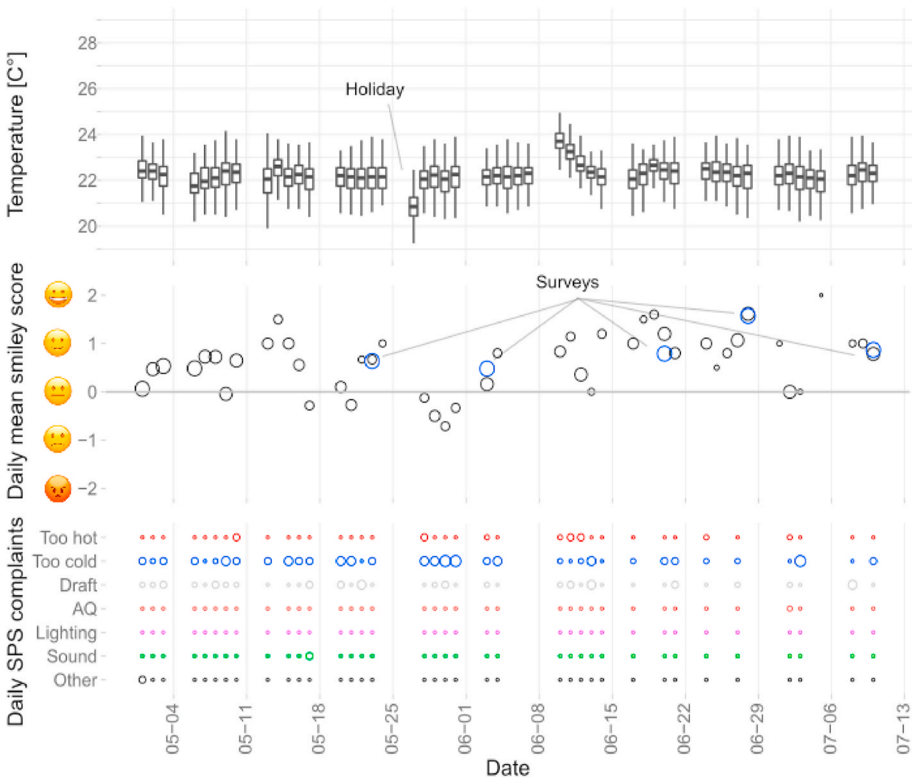

Fig. 3. General presentation of collected data in Building 2 shown as time series. The top boxplot shows temperature distribution and mean per day for all sensors during working hours. The middle plot shows the daily mean of the SPS (grey), and equivalent smiley score in survey (blue). Dot sizes render the number of votes on that day. The bottom plot shows the daily share of complaints by dot size. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

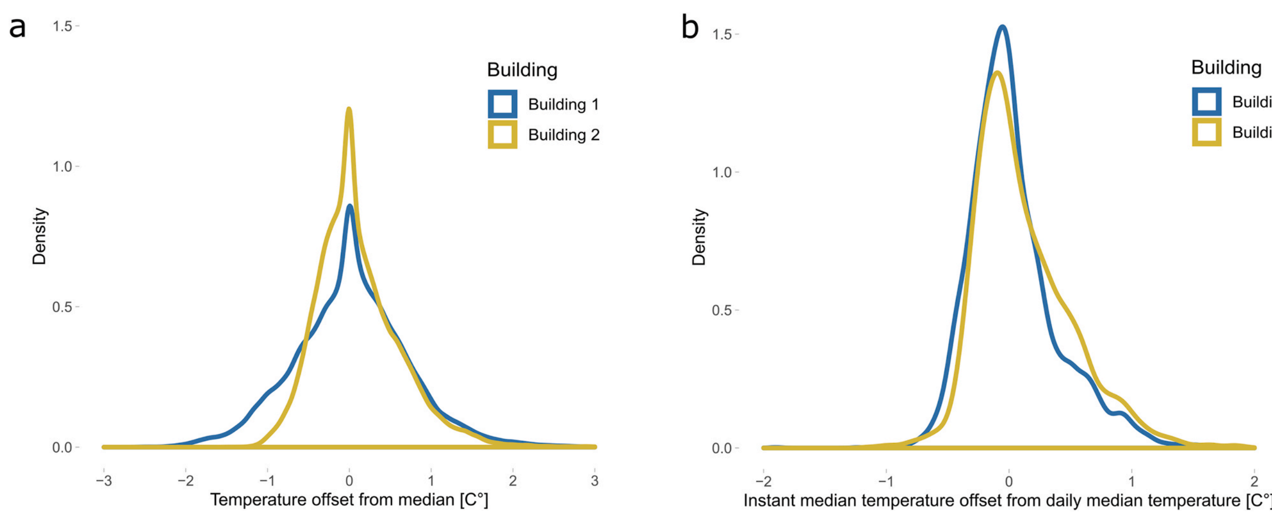

Fig. 4. A and B display the temporal and spatial distribution of temperature registrations in each of the buildings during the experiment period. The spatial temperature distribution in Building 1 was approximately 3–4 °C, while the daily temporal distribution during work hours was approximately 1.5 °C. In Building 2 the spatial difference was approximately 2–3 °C and the temporal difference was 1.5 °C.
Fig. 4 A) Spatial temperature distribution, shown by temperature sensor offset from median instant temperature.
Fig. 4 B) Distribution of temporal error between median temperature and daily median temperature.

Table 2
Predicted thermal sensation scale from Cheung et al. (2019).

Predicted sensation	Measured air temperature
Cold	<15 °C
Cool	15–18 °C
Slightly cool	18–20 °C
Neutral	20–25 °C
Slightly warm	25–27 °C
Warm	27–30 °C
Hot	>30 °C

<0 ("Unhappy"/"Angry"), accompanied by a thermal complaint ("Too cool"/"Too hot") on page 2. The criteria for counting dissatisfied votes on Q10 in the survey was a score of <0 ("Somewhat dissatisfied"/"Dissatisfied"/"Very dissatisfied"). Only data from work hours (between 7 a.m. and 8 p.m.) on weekdays was included.

3.7.4. Voting habits

Demographics. The mean reported voting frequencies (daily votes per person) from survey (Q13), classified by sex and age class.

Response rate development over time. The number of votes received per day divided by the assumed building population of each building (daily votes per person).

4. Results and discussion

4.1. Overview

The field experiment in Building 1 collected 1303 SPS smiley votes with 519 complaint messages, and 413 survey responses on 5 separate survey days (assessed to be ~70% of building population on the given days). During the survey days, 233 SPS votes were collected (18% of total SPS votes, equalling 49% of building population).

In Building 2, the field experiment collected 534 SPS smiley votes with 137 complaint messages, and 60 survey responses on 5 separate survey days. During the survey-days, 73 SPS votes were collected (14% of total SPS votes, equalling 58% of assumed building population). The average response rate on surveys was approximately 80–90% of the building user population on the survey days.

Figs. 2 and 3 show a generalized view of the collected data for Building 1 and 2, respectively. They also serve as examples of how data from both the physical environment and the SPS can be visualized. For example in Fig. 2, a temperature intervention during which the temperature was reduced was done on June 27th in Building 1. The effects can be seen in all three plots: as a mean temperature reduction of 1.5 °C in the temperature plot, a reduced mean SPS satisfaction in the satisfaction plot, and a shift towards more "Too cold" complaints and fewer "Too hot" complaints in the complaint plot. For Building 1 the complaints are distributed between several indoor climate issues, while for Building 2 they are concentrated toward low temperature. The area where the buildings are located experienced a high outdoor temperature event between the 6th and 16th of June, which also led to higher indoor temperatures in both buildings. The increased indoor temperature in this period is, however, not reflected in the number of "Too hot" complaints, indicating that occupants may have adapted to higher temperatures by, for example, reducing their clothing level.

4.2. Representativeness of polling station

4.2.1. Non-response bias – error of daily mean SPS vote

The error of the daily mean was calculated for each day and for each building. The errors are visualized in Fig. 4 A. The results show that SPS votes in Building 1 were on average 0.59 scale units below the equivalent survey responses (Q7). For Building 2 the error was smaller, 0.04 scale units on the positive side. There is no indication that SPS daily mean error was directly correlated with the number of SPS responses on the given day (rendered in Fig. 4 by size of dot).

4.2.2. Distribution of votes

In order to further understand the reasons for the error in mean daily votes, two separate approaches were used to investigate the voting habits of occupants. In Fig. 4 B, the frequency of each voting alternative in SPS votes are compared with survey smiley votes (Q7) for Building 1. The figure shows that the share of negative votes was much higher than for the equivalent alternatives in the survey. This indicates that people who were dissatisfied were more inclined to vote, or vote more often, at the SPS than those who were indifferent. Very satisfied voters have similar voting frequencies in both SPSs and surveys. Fig. 4 D shows the smiley vote collected in the survey categorized by the self-declared SPS voting frequency from the same survey. The figure shows that the individuals who reported to vote more often, also had a lower mean vote. The more often they reported to vote, the lower was the mean vote.

A similar trend can be seen in Fig. 4C for Building 2, although the effect is smaller and appears more arbitrary. Those least and most satisfied (−2 and 2) both appear to have voted more on the SPS than in the survey. In Fig. 4 E there is, as for Building 1, a falling trend of mean vote for respondents who vote more often. But the group who voted twice a day (3 persons) had a higher than average mean vote.

The results in all the above figures confirm a significant non-response and multiple-response bias in Building 1, while this effect was significantly smaller in Building 2. The reasons for this difference are unknown. Possible causes could be related to the occupants and their work culture, indoor climate quality, heterogeneity of indoor climate conditions (as dissatisfied voters with a poor local climate may affect the bias), or how the SPS had been presented to the occupants.

4.2.3. Accuracy and response rates

SPS response rates varied significantly from day to day. The standard deviation was also large, meaning that there was a large difference in the score from vote to vote. Fig. 4 F and G show the development of the error between cumulative daily mean and final daily mean on the SPS for the 5 survey days in each of the buildings. Although the indoor climate and general opinion may have shifted throughout the day, the figures give an impression of how many votes were needed to achieve a representative mean.

The results in both buildings show how the daily mean naturally converged toward the final mean as more votes were added. Large errors occurred when less than 5–10 votes were entered. With more than 5–10 votes, an error of 0.3–0.5 scale units remained. Daily means based on few votes should therefore not be considered. Further, the figure indicates how the daily mean can drift throughout the day, possibly due to environmental changes or voting habits.

4.3. Sensitivity to environmental changes

A visual comparison between the predicted thermal sensation, calculated according to Cheung et al. (2019), the SPS thermal complaint responses, and the survey responses for Q12 (Mean vote, MV/Thermal Sensation Vote TSV) and Q10 (Persons Dissatisfied, PD) is shown in time series format in Fig. 5A and B.

The upper plots show how occupants in both buildings reported to be colder than what was predicted by the deterministic model from Cheung et al. During Intervention 1 in Building 1, there was a decrease in the mean temperature in the space from approximately 24 °C–22.5 °C. Most models for thermal comfort assessment would not predict occupant discomfort at these temperatures, provided that all the other variables remained unchanged (as we expected to happen during this temperature intervention). Both the SPS and the survey did however register a significant increase in thermal discomfort among the occupants on this day. The facility managers in Building 1 also reported having received several complaints on the same day. The other temperature interventions were smaller and did not lead to the same magnitude of dissatisfaction, at least as far as this could be detected through the responses via the SPS.

The Pearson correlation between SPS thermal complaints and survey thermal complaints (Q10) was calculated, and results are summarized in Table 3.

The percent of thermally dissatisfied occupants recorded by the SPS is significantly correlated with the percentage of dissatisfied recorded in Q10 of the survey in Building 1. The results indicate that the SPS can be useful in recording occupant dissatisfaction, which might not be predicted by the deterministic comfort models.

4.4. Voting habits

4.4.1. Demographics

Fig. 6 A shows the mean self-reported voting frequencies reported in survey (Q13), classified by age class and sex (survey Q2 and Q3).

Younger people in Building 2 voted more often than older people, but this effect was not present in Building 1.

4.4.2. Voting frequency in time

Fig. 6 B displays a smoothed graph of the number of votes received per day divided by the assumed building user population of each

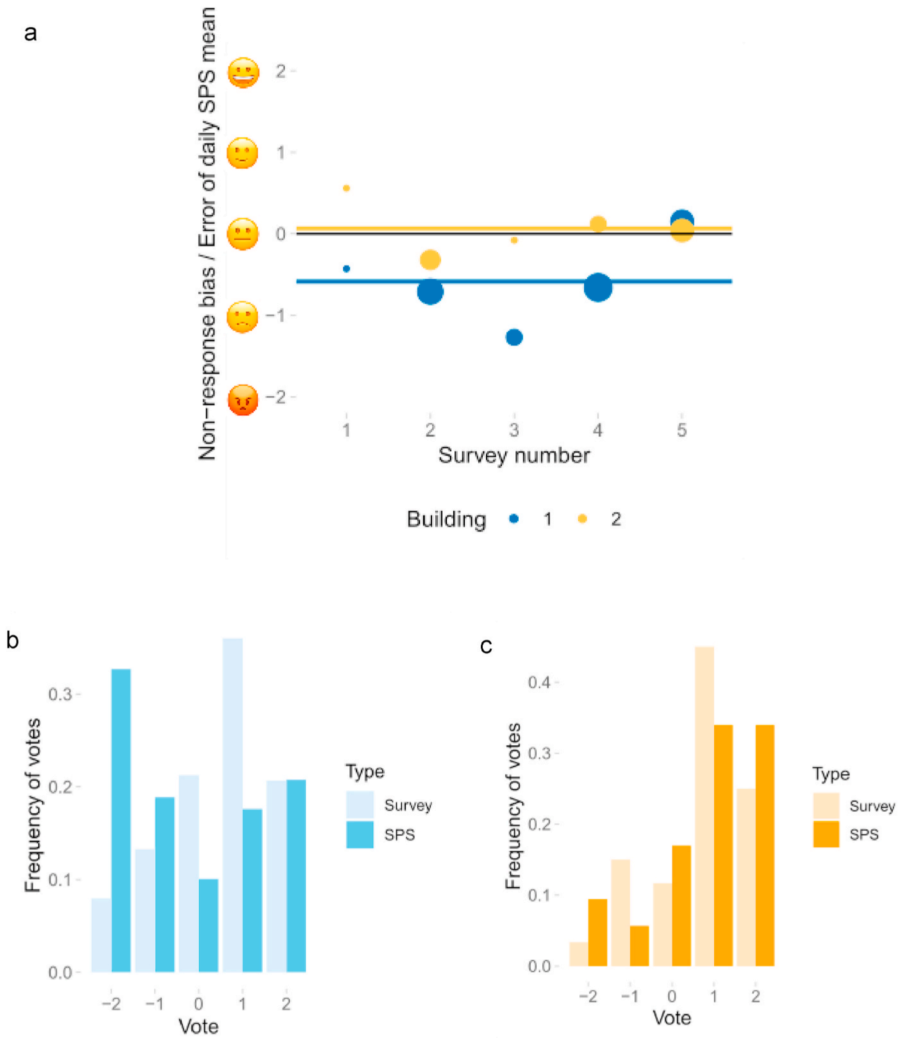

Fig. 5. A) Non-response bias of daily mean smiley score of surveys (Q7) and SPS on interview days. Dot size relative to number of SPS responses. Lines represent total mean error of all surveys for each. B) Voting frequencies for each response alternative in SPS and survey (Q7) for Building 1. C) As B for Building 2. D) Mean smiley vote in survey (Q7) classified by self-reported voting frequency (Q13) in Building 1. Width of the columns is proportional to the share of respondents. E) As D for Building 2. F) Error between SPS cumulative mean and total daily mean for the 5 survey days in Building 1. G) As F for Building 2.

building. The transparent areas represent the 5% and 95% confidence intervals.

The results show that both buildings experienced a decline in voting frequency during the first 20 days. After this, the voting frequency stabilized at around each occupant voting once every 3–4 days and did not decline further. It should be noted that "*Please vote today!*" signs were posted in both buildings on two separate days in order to investigate the effect of such measures. Both buildings experienced relatively large day to day variances in voting frequency.

Fig. 7C displays the distribution of SPS votes in the two buildings by hour of the day. The results show that votes were distributed relatively evenly throughout the day and were not only entered at specific times during the morning and afternoon when occupants entered and left the office.

4.5. Limitations and recommendations for future studies

Only one response alternative could be chosen for complaints at the second page of the SPS, and in the survey. This was chosen for research design reasons (i.e. to keep the structure of the feedback as simple as possible), and we were unsure whether or not the study could be affected by the possibility of multiple sources of complaint. During survey rounds, we got the impression that several occupants wished to make more than one complaint, meaning that some thermally dissatisfied voters may not have entered a thermal complaint if it was not their most important source of dissatisfaction. A multiple response solution should be used in future studies to capture all complaints.

The occupants of Building 2 seemed to become more committed to the study than occupants in Building 1. This may have been because the study was introduced in different ways to the two occupant groups. It could also be that the occupants in Building 2 were more inclined to be interested in the phenomenon of indoor climate (as they were employed in a design-construction company), or that they had a slightly stronger organizational connection to the researchers conducting the surveys. These factors may have affected the results but are however considered to lie within what one could expect of such disturbing factors in a real-life application of SPS data collection in buildings.

The votes collected through the SPS were compared directly to survey responses from occupants, under the assumption that the presence of the researchers did not affect their responses. As occupants filled out the survey, the researchers would take a step back and never interfere. There is, however, a chance that the presence of a researcher may have affected some of the responses.

The indoor climate conditions variability throughout the day, and the time of the day for the completion of the survey may have a significant effect on the results, as survey responses were compared to SPS votes collected throughout the whole day. All surveys were conducted in the afternoon, in order to be as representative as possible for the total daily mean. Survey time of the day may however have impacted the overall results. According to Fig. 6C, SPS votes were entered at a steady

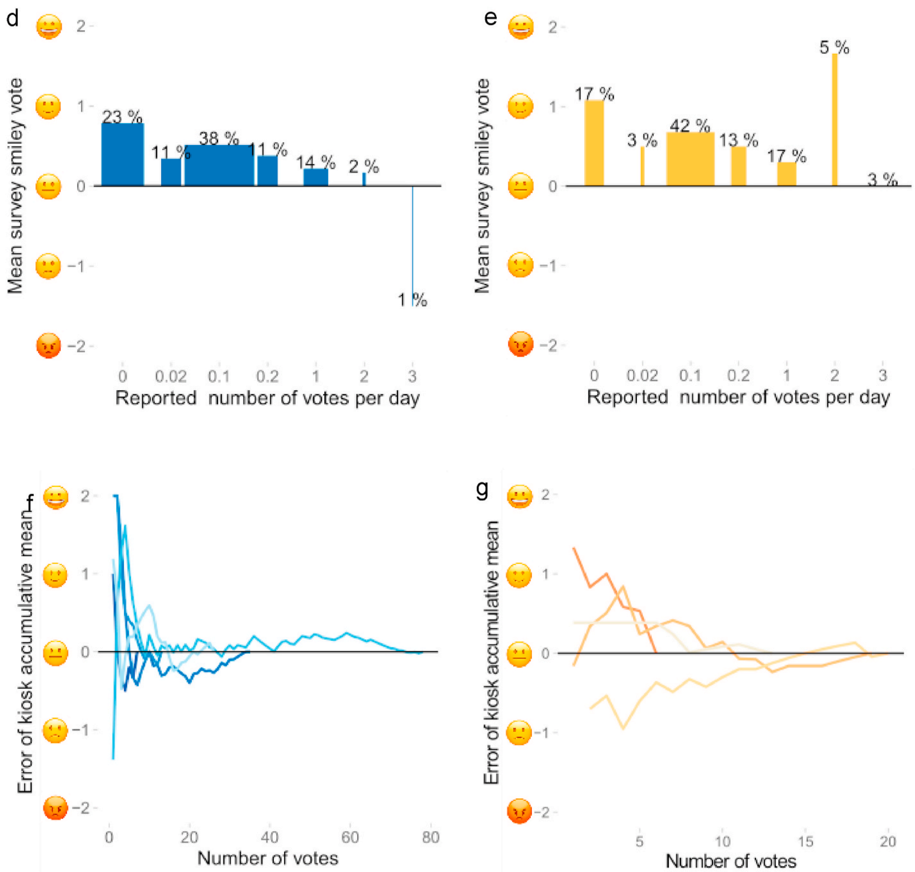

Fig. 5. (*continued*).

Table 3
Correlation coefficients between percent dissatisfied occupants measured in SPS and survey Q10. Corresponding to $P > 0.05$ – ns (non-significant), $0.01 < p < 0.05$ *, $0.01 < p < 0.001$ **, $p < 0.0001$ ***.

	Building 1	Building 2
SPS thermal dissatisfied vs. Survey Thermal dissatisfied (PD)	$\rho = 0.910$*	$\rho = 0.416$ (ns)

pace throughout the day. Votes entered in the morning may have been more likely to not be comparable to survey responses made in the afternoon, but we could not filter out these votes as they may still be valid.

Several studies, such as [35], have found that interactions between different environmental conditions may have a large effect on the verdicts for one isolated condition. In a field study, there are several climate conditions we do not have control over. Occupant responses to thermal conditions reported in section 4.3 may have been affected by other climate conditions such as light, sound, odour etc. without this being recorded in the current study. A large number of studies, and established practice in the field, have demonstrated the impact of other ambient variables than air temperature for thermal comfort. In this study we only measured air temperature, and could not use established models such as [36] for predicting thermal comfort. Instead we predicted occupant thermal comfort based solely on air temperature according to findings in a recent study [34]. This should be taken into consideration when interpreting the results. However, measurement of all relevant variables for thermal comfort is impractical in real-life buildings. Thermal comfort control is then done with air temperature as the only variable, leading to the same potential errors as may exist in this study.

Further studies should be done to clarify the potential link between SPS complaints and actual dissatisfied respondents in a survey. SPSs may also have a potential use for direct control of the indoor climate. However, this application would require further studies to investigate implications of fairness among occupants and quality control in order to avoid unwanted incidents or use. The choice of asking occupants for daily ratings may also affect the benchmarking capability. Further investigations are needed to assess the use of SPSs for benchmarking.

5. Conclusions

We found that the use of a satisfaction polling station (SPS) for assessing satisfaction with the indoor climate is subject to several error sources, among which the non-response bias is the most important. Nonetheless, the studies showed that the polling station (SPS) had a high sensitivity to environmental changes and could record changes in occupant opinions over time. The studies also showed that the polling station was taken into consistent use by the occupants of both buildings, although they were not informed that this was an aim of the study.

When it comes to polling station accuracy, the error for the mean daily score was found to be between 2 %and 32% of the scale range when compared to survey results on 10 different survey days in the two buildings. The total mean error in the two buildings was 12% and 1%. This was found to be caused by the non-response bias effect, where occupants who have no strong feelings about the indoor climate fail to vote, while occupants who are dissatisfied (and in some cases satisfied) tend to vote more often and even multiple times per day. This effect was shown to be different in the two buildings and we do not know the reason(s). Due to the high and variable bias identified in the study, the polling station results cannot at this point be recommended for *benchmarking* of buildings. The same problem could happen in POE surveys if a minimum response rate is not achieved. POE studies are widely used for benchmarking of buildings, but our knowledge, no investigations of possible biases and response rates have been performed for this benchmarking technique.

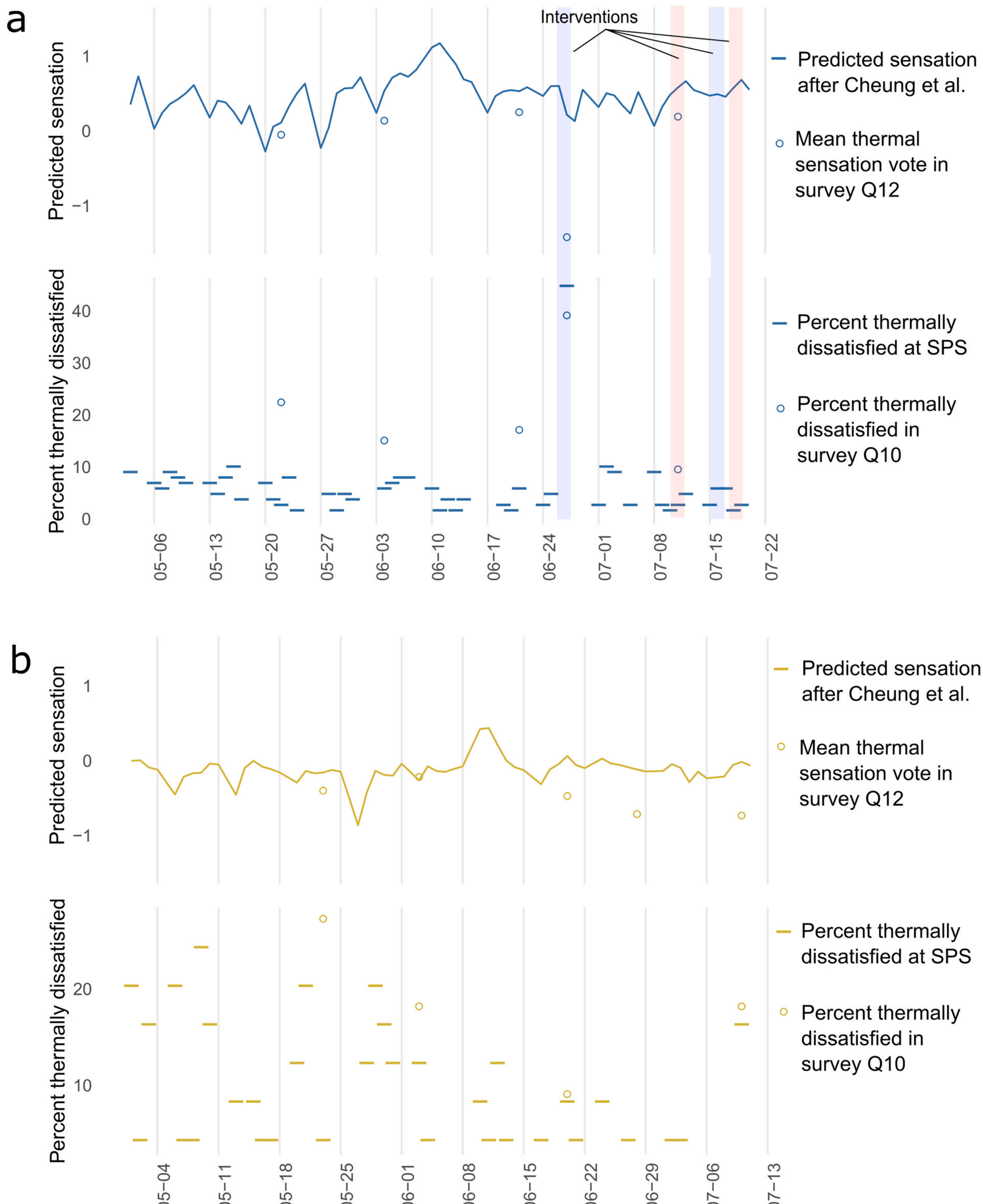

Fig. 6. A) Building 1. Upper plot: Visual comparison of calculated Predicted Sensation (line) after simplified thermal comfort model by Cheung. et al. (2019) and measured TSV from surveys (dots). Lower plot: Comparison of percent of building population dissatisfied at SPS (vote < -1, bars), and measured percent of respondents dissatisfied in survey (dots). B) Building 2. Upper plot: Visual comparison of calculated Predicted Sensation (line) after simplified thermal comfort model by Cheung. et al. (2019) and measured TSV from surveys (dots). Lower plot: Comparison of percent of building population dissatisfied at SPS (vote < -1, bars), and measured percent of respondents dissatisfied in survey (dots).

Although the satisfaction polling station ratings were not always representative of the "ground truth" (which was, in this study, assumed to be equal to the response collected though the surveys), sensitivity studies showed that the rate of thermal complaints entered into the polling station served as a good marker of occupant thermal dissatisfaction. The thermal complaints recorded by the SPS were significantly correlated in time with the thermal complaints made in the survey for Building 1. The polling station was able to capture an increase in thermal dissatisfaction among the occupants in cases where a deterministic model could likely not identify a source for the dissatisfaction.

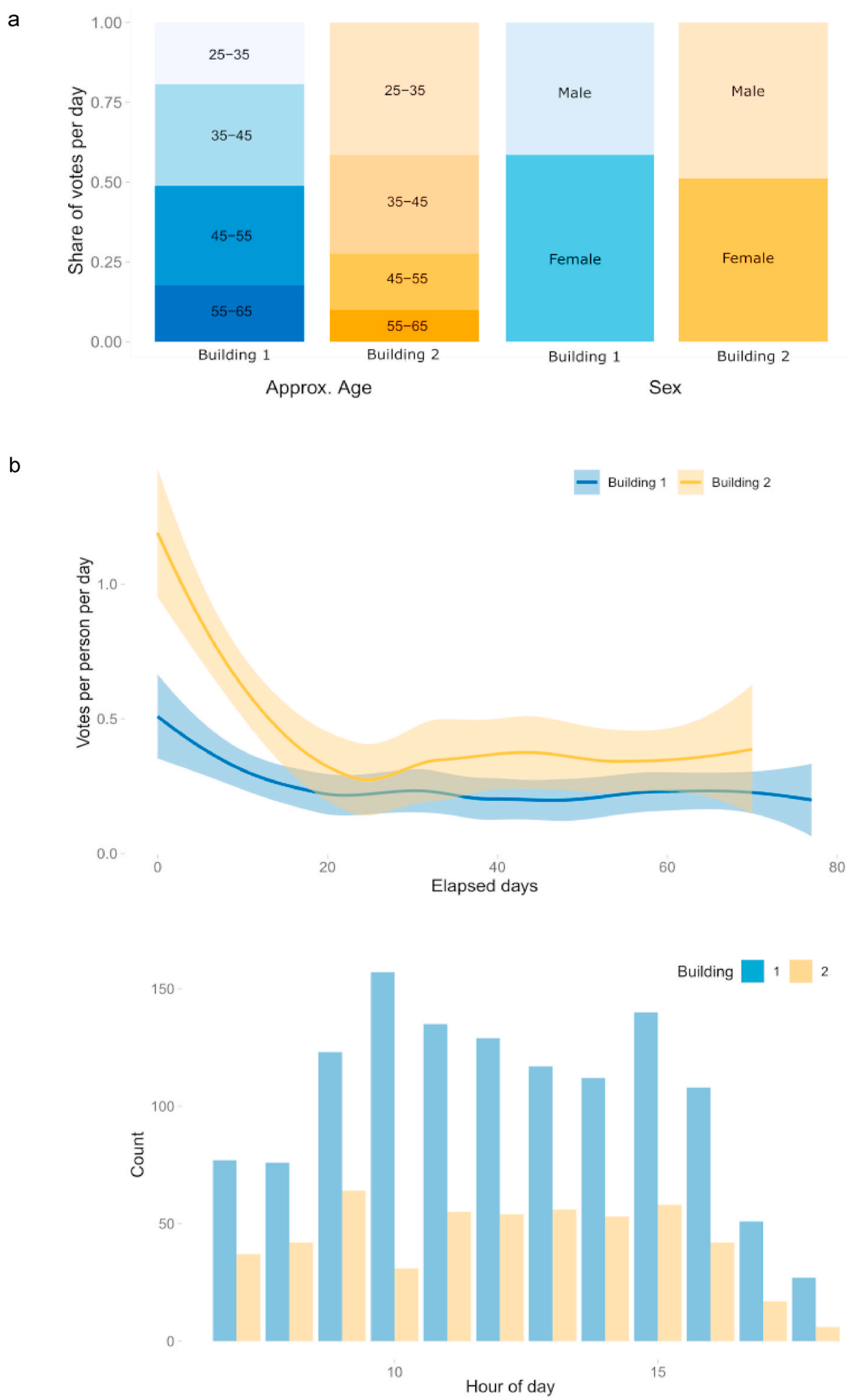

Fig. 7. A) Mean reported voting frequency classified by age and sex in both buildings. B) Total voting frequency (votes per occupant) over time for both buildings. The shaded areas represent the 95% confidence intervals. C) Distribution of votes by time of day for Building 1 and 2.

This may also indicate that measuring dissatisfaction is a more reliable measure than the daily average satisfaction score, as the non-response bias effect (where indifferent or satisfied voters voted less frequently than those dissatisfied) is eliminated. The study of polling station sensitivity has demonstrated that the polling station had a high sensitivity to environmental changes and may potentially be used for indoor climate *tuning*, *commissioning*, and continuous *learning*.

When it comes to occupant voting habits, no important differences were identified in voting habits between occupant of different sex and age. General voting frequencies showed a decline during the first 20 days of usage, before remaining stable for the last 40–60 days of the experiment. After stabilization, approximately 25% of the building population in Building 1 voted on an average day, while 33% of occupants in Building 2 voted. This demonstrates that SPSs remain relevant for capturing votes from occupants for longer periods of time, although it is not known how occupant interest in voting would develop over durations longer than 70 days.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study has been performed with the financial support of the Research Council of Norway, within the project "Methods for real-time user involvement of indoor climate in smart buildings" (project number: 277048). The support provided by the Research Council of Norway, Skanska Norway, The Center for the Built Environment at UC Berkeley, Skanska US and NTNU is gratefully acknowledged. The authors would also like to thank Ellika Taveres-Cachat for contributing to the readability of this research.

Appendix A

Topic	Question	Response alternatives
Metadata (inserted by researcher)	Q1 - Workplace ID	[Text]
	Q2- Approximate age	[Years, binned]
	Q3 - Sex	[Male/Female]
	Q4 – Workplace type	[Open plan, cubicle, single office, Team office]
	Q5 – Workplace comments	[Text]
	Q6 – Other comments	[Text]
SPS questions	Q7 – How satisfied are you with the indoor climate at your workplace today?	[5 smiley face buttons]
	Q8 – Help us pinpoint the problem (if dissatisfied)	[Too hot/Too cold/Draft/Air quality issues/Sound issues/Lighting issues/Other
	Q9 – Please specify the problem(s) (if chosen Other)	[Text]
POE questions	Q10 – How satisfied are you with the temperature of your workspace today?	[Very satisfied/Satisfied/Somewhat satisfied/Neither satisfied nor dissatisfied/Somewhat dissatisfied/Dissatisfied/Very dissatisfied]
	Q11 – How satisfied are you with the air quality of your workspace today?	[Very satisfied/Satisfied/Somewhat satisfied/Neither satisfied nor dissatisfied/Somewhat dissatisfied/Dissatisfied/Very dissatisfied]
	Q12 – How do you feel about the temperature of your workspace?	[Hot/Warm/Slightly warm/Neither/Slightly cool/Cool/Cold]
SPS voting habits	Q13 – How often do you vote at the smiley kiosk?	[Never/Once since it was introduced/A few times sporadically/Regularly each week/ Regularly once per day/regularly several times per day]

References

[1] L.T. Graham, T. Parkinson, S. Schiavon, Where Do We Go Now? Lessons Learned from 20 Years of CBE's Occupant Survey, 2020.
[2] N. Lassen, A study of running set-points and user IEQ satisfaction perspectives in the Norwegian commercial building stock. 39th AIVC Conf. Smart Vent, Build., 2018, pp. 180–189. www.rehva.eu.
[3] H. Zhang, E. Arens, W. Pasut, Air temperature thresholds for indoor comfort and perceived air quality, Build. Res. Inf. 39 (2011) 134–144, https://doi.org/10.1080/09613218.2011.552703.
[4] M. Fountain, G. Brager, R. De Dear, Expectations of indoor climate control, Energy Build. 24 (1996) 179–182, https://doi.org/10.1016/S0378-7788(96)00988-7.
[5] M. Mendell, Indoor thermal factors and symptoms in office Workers : findings from the U.S. EPA BASE study. Indoor Air, 2009, pp. 1–26. https://escholarship.org/uc/item/7dx9w6x9.
[6] T. Hoyt, E. Arens, H. Zhang, Extending air temperature setpoints: simulated energy savings and design considerations for new and retrofit buildings, Build. Environ. 88 (2014) 89–96, https://doi.org/10.1016/j.buildenv.2014.09.010.
[7] E. Arens, M.A. Humphreys, R. de Dear, H. Zhang, Are "class A" temperature requirements realistic or desirable? Build. Environ. 45 (2010) 4–10, https://doi.org/10.1016/j.buildenv.2009.03.014.
[8] P. Li, T. Parkinson, G. Brager, S. Schiavon, T.C.T. Cheung, T. Froese, A data-driven approach to defining acceptable temperature ranges in buildings, Build. Environ. 153 (2019) 302–312, https://doi.org/10.1016/j.buildenv.2019.02.020.
[9] R.L. Ollver, A cognitive model of the sntecedents and aonsequences of satisfaction cecisions, J. Market. Res. 17 (1980) 460–469.
[10] R.L. Oliver, Cognitive, affective, and attribute aases of the satisfaction response, J. Consum. Res. 20 (2002) 418–430, https://doi.org/10.1086/209358.
[11] M. Schweiker, R. Rissetto, A. Wagner, Thermal expectation: bnfluencing factors and its effect on thermal perception, Energy Build. 210 (2020), https://doi.org/10.1016/j.enbuild.2019.109729.
[12] B. Balaji, A. Bhattacharya, G. Fierro, J. Gao, J. Gluck, D. Hong, A. Johansen, J. Koh, J. Ploennigs, Y. Agarwal, M. Bergés, D. Culler, R.K. Gupta, M.B. Kjærgaard, M. Srivastava, K. Whitehouse, Brick: metadata schema for portable smart building applications, Appl. Energy 226 (2018) 1273–1292, https://doi.org/10.1016/j.apenergy.2018.02.091.
[13] R. Jia, B. Jin, M. Jin, Y. Zhou, I.C. Konstantakopoulos, Z. Han, J. Kim, et al., Design automation for smart building systems, Proc. IEEE 106 (2018) 1680–1699.
[14] F. Jazizadeh, A. Ghahramani, B. Becerik-Gerber, T. Kichkaylo, M. Orosz, User-led decentralized thermal comfort driven HVAC operations for improved efficiency in office buildings, Energy Build. 70 (2014) 398–410, https://doi.org/10.1016/j.enbuild.2013.11.066.
[15] A. Hang-yat, D. Wang, Carrying my environment with Me : a participatory-sensing approach to mnhance thermal comfort, in: BuildSys '13, 2013, https://doi.org/10.1145/2528282.2528286.
[16] K. Konis, M. Annavaram, The Occupant Mobile Gateway: a participatory sensing and machine-learning approach for occupant-aware energy management, Build. Environ. 118 (2017) 1–13, https://doi.org/10.1016/j.buildenv.2017.03.025.
[17] J. Kim, F. Bauman, P. Raftery, E. Arens, H. Zhang, G. Fierro, M. Andersen, D. Culler, Occupant comfort and behavior: high-resolution data from a 6-month field study of personal comfort systems with 37 real office workers, Build. Environ. 148 (2019) 348–360, https://doi.org/10.1016/j.buildenv.2018.11.012.
[18] S.K. Gupta, S. Atkinson, I. O'Boyle, J. Drogo, K. Kar, S. Mishra, J.T. Wen, BEES: real-time occupant feedback and environmental learning framework for collaborative thermal management in multi-zone, multi-occupant buildings, Energy Build. 125 (2016) 1–13, https://doi.org/10.1016/j.enbuild.2016.04.084.
[19] S. Liu, S. Schiavon, H.P. Das, M. Jin, C.J. Spanos, Personal thermal comfort models with wearable sensors, Build. Environ. 162 (2019), https://doi.org/10.1016/j.buildenv.2019.106281.
[20] J. Kim, R. de Dear, Nonlinear relationships between individual IEQ factors and overall workspace satisfaction, Build. Environ. (2012) 33–40, https://doi.org/10.1016/j.buildenv.2011.09.022.
[21] R.L. Oliver, Satisfaction: A Behavioral Perspective on the Consumer, Routledge, 2014.
[22] A. Leaman, B. Bordass, Are users more tolerant of "green" buildings? Build. Res. Inf. 35 (2007) 662–673, https://doi.org/10.1080/09613210701529518.
[23] O.A. Seppänen, W. Fisk, Some quantitative relations between indoor environmental quality and work performance or health, HVAC R Res. 12 (2006) 957–973, https://doi.org/10.1080/10789669.2006.10391446.
[24] L.R. Rabbitt, J.A. Hasselgren, C. Cook, Y.B. Sirotin, Measuring satisfaction with standard survey instruments and single-button responses on kiosks, Proc. Hum. Factors Ergon. Soc. Annu. Meet. 62 (1) (2018) 1429–1433, https://doi.org/10.1177/1541931218621325.
[25] R.M. Groves, E. Peytcheva, The impact of nonresponse rates on nonresponse bias: a meta-analysis, Public Opin. Q. 72 (2008) 167–189, https://doi.org/10.1093/poq/nfn011.
[26] Fowler Jr., J. Floyd, Survey Research Methods, fourth ed. fourth ed., SAGE Research Methods, 2009.
[27] K.S. Konis, Leveraging ubiquitous computing as a platform for collecting real-time occupant feedback in buildings, Intell. Build. Int. 5 (2013) 150–161, https://doi.org/10.1080/17508975.2013.781499.

[28] J. Berquist, M. Ouf, W. O'Brien, A method to conduct longitudinal studies on indoor environmental quality and perceived occupant comfort, Build. Environ. 150 (2019) 88–98, https://doi.org/10.1016/j.buildenv.2018.12.064.
[29] N. Lassen, T. Josefsen, Experimental setup and testing of an in-field system for real-time occupant feedback, Publ. Opin. Q. 609 (2019) 1–6, https://doi.org/10.1088/1757-899X/609/4/042045.
[30] Reset Healthy Buildings, 2.2 RESET Air Standard for Commercial Interiors v2.0, 2018.
[31] WELL.v. Well, 2 T06 Thermal Comfort Monitoring, WELL v.2 Stand, 2018. https://v2.wellcertified.com/v/en/thermal comfort/feature/6. (Accessed 1 April 2020).
[32] S. Karjalainen, O. Koistinen, User problems with individual temperature control in offices, Build. Environ. 42 (2007) 2880–2887, https://doi.org/10.1016/j.buildenv.2006.10.031.
[33] T. Peffer, M. Pritoni, A. Meier, C. Aragon, D. Perry, How people use thermostats in homes: a review, Build. Environ. 46 (2011) 2529–2541, https://doi.org/10.1016/j.buildenv.2011.06.002.
[34] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE global thermal comfort database II, Build. Environ. 153 (2019) 205–217, https://doi.org/10.1016/j.buildenv.2019.01.055.
[35] A. Jamrozik, C. Ramos, J. Zhao, J. Bernau, N. Clements, T. Vetting Wolf, B. Bauer, A novel methodology to realistically monitor office occupant reactions and environmental conditions using a living lab, Build. Environ. 130 (2018) 190–199, https://doi.org/10.1016/j.buildenv.2017.12.024.
[36] E.A. Arens, F.S. Bauman, J.R. Breckenridge, R.E. Chase, P.O. Fanger, R. R. Gonzalez, D. Int-hout, J. Klassen, E.A. Mccullough, L.W. Nelson, B.W. Olesen, G. Reeves, M.K. Anderson, L.W. Burgett, M.E. Dillon, D.L. Geistert, ANSI/ASHRAE Standard 55–2017, 1995, p. 1995.