ThermoKiosk: Investigating Roles for Digital Surveys of Thermal Experience in Workplace Comfort Management

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ABSTRACT
Thermal comfort in shared workplaces is often contested and impacts productivity, wellbeing, and energy use. Yet, subjective and situated comfort experiences are rarely captured and engaged with. In this paper, we explore roles for digital surveys in capturing and visualising subjective experiences of comfort *in situ* for comfort management. We present findings from a 3-week field trial of our prototype system called ThermoKiosk, which we deployed in an open plan, shared office with a history of thermal comfort complaints. In interviews with occupants and members of facilities management, we find that the data and interactions can play an important role in initiating dialogue to understand and handle tensions, and point to design considerations for more systematically integrating them into workplace comfort practices.

Author Keywords
Thermal comfort; workplace; survey; subjective experience; energy; office; qualitative methods.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

INTRODUCTION
The ways that digital technology and data can and do shape the politics of everyday life is an increasingly important subject for the HCI community. Relevant topics include civic technology [4], data publics[1], and citizen sensing [2]. In this paper, we are concerned with a more local and perhaps everyday form of political engagement than is normally addressed, namely the politics of shared comfort. This is an important topic for HCI since the design of the digital interfaces that support comfort practices have significant impacts on wellbeing, energy, and productivity.

[1] http://datapublics.net/

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In desk-based workplaces in many parts of the world, we have come to expect that a standard indoor climate will be provided by the building and its management team through automated mechanical heating and cooling systems. By design, occupants are often distanced from controlling their own comfort. Thermal discomfort is prevalent in offices and quantifiable effects of thermal discomfort on health and productivity have been demonstrated [31]. The usual course of action when discomfort arises is for occupants to report to a facilities manager who would ensure that the building infrastructure is working as it should. In this paper, we investigate an alternative design rationale, along the lines of Costanza et al's [13] Temperature Calendar, of using interactive systems and data to better include occupants in the everyday management of comfort and energy use in their workplace.

We designed and deployed a technology probe [21] consisting of tangible digital survey devices and displays (see Figure 1, right) in a shared office that exhibited long-term, unresolved discomfort issues. The design was motivated by practical utility to aid understandings of discomfort issues, as well as a means for understanding the use of subjective data as a design material for workplace comfort management. It is well known that comfort is subjective, but in making subjective experience explicit and visible, our probe serves as a locus for expressing thermal comfort and then as a site for occupants and managers to understand discomfort and negotiate the local challenges (including office politics) of collectively responding. Our findings are concerned with the individual and collective sensemaking of this data and how its presence affects issues related to the subjectivity of thermal comfort. This builds on prior work that found that the politics of measurement [28] around thermal comfort, particularly the absence of subjective experience data and a dominant reliance on objective measures of the indoor climate, can be problematic for occupants in expressing discomfort [9].

Our contributions are 3-fold: We present an account of the *in situ* building occupant interactions with our technology probe; we present findings from our qualitative studies with occupants and facilities managers exploring roles and the utility of subjective comfort data in management practices; and we illustrate how the interactions with digital surveys and sensor data changed how thermal comfort was experienced, understood, and done, and how these relate to interaction design for comfort.

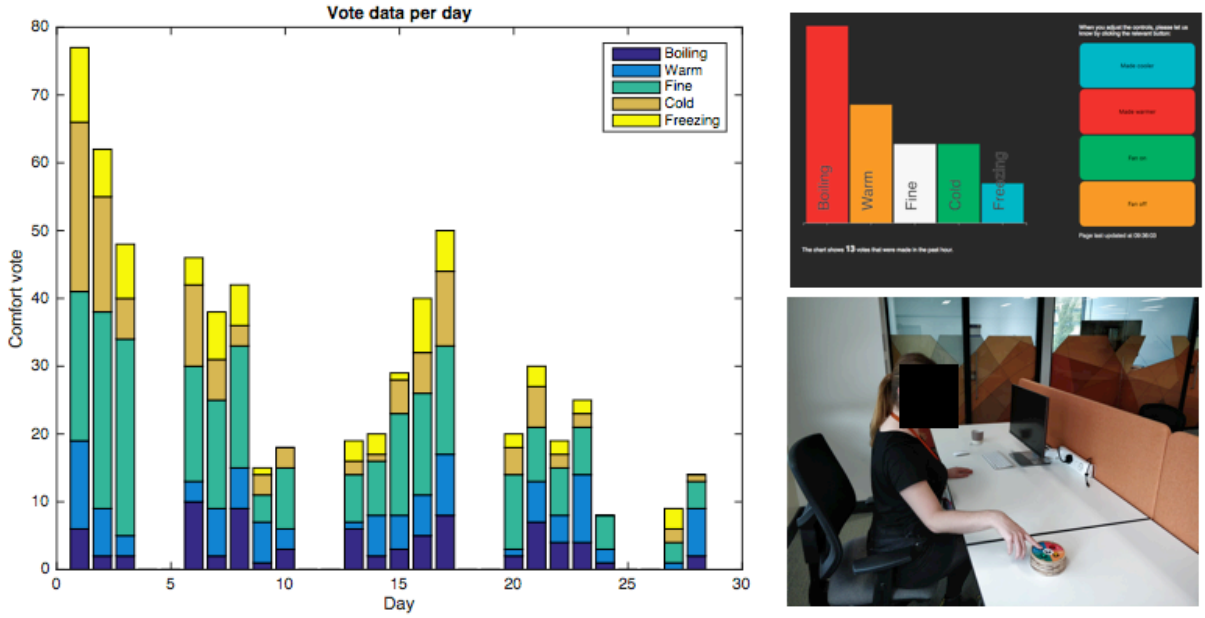

Figure 1: Left – Total sample count of each category cast on study days; Top right – The ThermoKiosk display interface (the chart on the left shows the 13 samples captured in the previous hour); Bottom right – a researcher demonstrating the use of the survey device in an office setting.

RELATED WORK

Non-domestic buildings in many parts of the world rely heavily on mechanical heating and cooling systems for thermal comfort. The dominant approach for thermal comfort involves fully automating climate control according to thermal comfort standards that specify a uniform, static temperature (usually 18–22 Celsius) at which most occupants will be comfortable, all year round. This approach gives prominence to the physiological factors that influence comfort and assumes that occupants are passive recipients of a conditioned climate [11].

The need to reduce greenhouse gas emissions or to address persistent chronic discomfort issues in practice [23], has led to a need for new notions of comfort [8] that acknowledge its complexities, in particular the important influences of psychological and social factors [6] which are culturally defined [7], and the variability across different contexts [23], which makes generalised behaviour profiling difficult to achieve [17]. Occupant satisfaction and experiences of comfort are influenced by, for example, the type of building (e.g., if it is air-conditioned or naturally ventilated [36]), the occupant behaviour and metabolic rate [1] (treated as constant in standards), and the means available to occupants for alleviating their own discomfort [32,36]. Comfort is also negatively influenced by poor perceived control, which in turn is negatively influenced by increasing numbers of people sharing a space [Schweiker and Wagner in [16]].

The adaptive model of thermal comfort [26] embraces these factors in advocating a loosening of mechanical control of the indoor climate and a more active role for occupants in the ongoing achievement of comfort. Clear et al. [10] explored how Ubicomp might play a role in supporting this more interactive approach in conventionally heated buildings and highlight the socially negotiated nature of comfort and the importance of supporting effective communication among co-occupants for this. In recontextualising the notion of comfort, Cole et al. [11] highlight the need to support comfort as a participatory process that "*considers the relationships between inhabitants, and between inhabitants and building systems as interactive and multidirectional.*" In this paper, we explore the use of subjective experience data (which are often not voiced and incorporated into negotiations in practice [9]) in bringing these relationships into consideration and stimulating participation in the collective understanding and management of comfort.

Research within sustainable HCI has examined how office occupants might more explicitly be persuaded to enact more sustainable behaviours [19,38]. Brynjarsdóttir et al. [5] argue that such reductionist approaches limit the framing of sustainability to individual action, and suggest a more promising framing in terms of social practices. In this vein, Bedwell et al. [3] highlight a gap in understanding the role that policy plays in energy use. In our work, we explore the utility of interactions with subjective comfort measurement in provoking such questions for occupants. Importantly, we also include facilities managers who are critical for designing for change given their scope for addressing this from the middle out, i.e., effecting change both in top-level policies, and bottom-level occupant practices [27]. Building managers, though, face challenges in the tensions between cost, comfort, and sustainability [20].

Our investigation draws on pervasive sensing of the indoor environment and digital comfort measurement, both of which have been proposed in previous work [30]. Related work has explored the use of digital voting devices to capture subjective opinions about workplace topics and events [35], and specifically about thermal comfort [18,34]. Vlachokyriakos et al. [35] demonstrated how a digital voting platform improved social inclusion in the workplace. Erickson and Cerpa [18] present ThermoVote, which allows building occupants to vote on thermal comfort using similar categories to those we use in this paper. However, in contrast to our approach, votes are captured using a smartphone application or website, and feed directly into the control of the HVAC (Heating, Ventilation, and Air Conditioning) system. While these latter works aim to capture subjective preference, they mask the variation in experience and preference by averaging them out (as with Predicted Mean Voting [26]). Our focus in this paper is on thermal comfort as a sociotechnical issue and, as such, the social interactions and perceptions of thermal comfort are as relevant and inextricably linked to the technological infrastructure and interfaces that support it.

Existing HCI work has considered the design of digital material artefacts for mediating social interaction in the workplace. For example, Pousman et al. [29] introduced Imprint for drawing awareness to printer use in the workplace. In domestic settings, interventions have sought to make private resource consumption [24] and waste [12] publicly available to provoke community discussions and changes in behaviour. Perhaps closer to our work in this paper is Costanza et al.'s [13] Temperature Calendar that visualises deviations of workplace temperatures from organisational policies for control.

THERMOKIOSK DESIGN & IMPLEMENTATION

The ThermoKiosk system comprises of survey devices (Figure 1 – bottom right), digital displays (Figure 1 – top right), and temperature sensors. The survey devices consist of a Raspberry Pi enclosed in a laser-cut case, containing five buttons that correspond to thermal comfort experience, which are labelled on the top of the case (e.g. 'I'm a bit cold'). They are networked for remote logging and to send real-time data to the displays. On deployment, the devices are plugged into mains sockets and connect to a pre-configured WiFi network. Each button press is recorded as a sample, timestamped, and logged in a remote SQL database. The ThermoKiosk displays consisted of Android tablets displaying a dynamic webpage in 'kiosk mode'. The data presented consisted of total samples recorded in the previous hour and their categories, refreshed every 10 seconds. Our design was influenced by the following considerations and requirements.

Ease of use and convenience: we decided to capture experience using physical buttons to minimise the interaction effort required and, hence, encourage participation in data capture. We wanted the survey device to be simple and to draw attention to itself without being obtrusive.

Fit with workplace rhythms and social life: we wanted to externalise occupant experiences and assumptions about thermal comfort. This was intended both as an intervention, but also as a means to elicit accounts of these in our qualitative studies. To achieve this, we chose to make comfort survey input a public interaction, in the same way that opening a window or operating a radiator might be. We designed shared devices for surveying and we decided to preserve 'quantitative anonymity' by not associating participant identifiers with samples. We introduced the study to occupants as one of understanding comfort as opposed to an intervention to change behaviour.

Preserve comfort context: We chose to link samples to the time and location (survey device) where they were input. Our rationale for this was to encourage interactions related to immediate thermal comfort experience e.g., discouraging retrospective interactions. We opted for a loosely structured interaction (i.e., experiences could be input any time as opposed to at set times) to allow interactions to emerge organically as comfort is experienced and negotiated.

Quantifiable: We represent comfort numerically to allow comparison with the environmental data. We chose five categories to mirror a subset of the 7-point ASHRAE thermal sensation scale (+3/hot, +2/warm, +1/slightly warm, 0/neutral, -1/slightly cool, -2/cool, -3/cold).

Subjective: We phrased the labels on the buttons subjectively (e.g. "I'm cold") to elicit accounts of experience as opposed to ambient temperature.

Feedback: To encourage thermal comfort interactions that were collaborative and inclusive, we placed a digital display at each HVAC controller that visualised the opinions provided by all occupants in the previous hour.

METHODS AND PARTICIPANTS

We conducted our study in an 8-floor, 6-year-old building in a UK university that was designed for low-energy use. The 7th-floor office that we studied is an open plan administration office containing 26 occupants. It had a history of complaints of both overheating and overcooling. The office was heated and cooled using four fan coil units (a HVAC system consisting of a heat exchanger for heating and cooling, and a fan for circulating air) that were controlled by occupants using two panels on the wall, one at either end of the office. The control of the HVAC had only recently moved from fully automated to manual control following unresolved discomfort complaints. Importantly, this scenario presented us with a research context where practices were moving away from automated tight control of a static temperature so we could study the role of subjective data in this. Few other adaptive opportunities existed: the office has two outer walls containing large windows that cannot be opened. It has two doors that are card-operated for security. Participants had

been complaining about discomfort for over a year and multiple investigations and actions were taken in response (including adding the second control panel so that both ends of the office could be controlled separately). Nevertheless, P8 sums up the current situation:

…if they're warm they'll come and turn the heating down—put the cold on—and then we'll get even colder. So then we'll turn it up and put the heating on and then they'll end up getting hotter […] people are getting up and changing [the HVAC mode] fairly regularly. […] it's very rare that you would find everybody happy at the same time. (P8)

We recruited two participants from facilities management, the Sustainability Manager (SM), and the Maintenance Officer (MO) responsible for the study building. Having exhausted possibilities for improving comfort for the office participants (they had multiple engineer call-outs to ensure the fan coils were functioning correctly, changed the control from 'automated' to 'occupant controlled', and added a second HVAC controller to the room) they were keen to explore alternative approaches.

We deployed ThermoKiosk for 3 weeks. We deployed 4 survey devices on desks and side tables so that each occupant's desk was within a few meters of a device, and so that input could be observed by colleagues in the vicinity. Each device is uniquely identified in the sample logs, allowing us to spatially map samples. We positioned ThermoKiosk displays above the two HVAC controllers in the office to encourage reflection on the data during interactions with these. This positioning also drew attention to HVAC controllers as a shared interface. We wall-mounted 8 temperature sensors in the office, positioned, again, to best maximise coverage. The sensors logged timestamped readings at 7-second intervals to a remote database. In presenting the data to participants in interviews we cross-referenced the survey and temperature data traces. We initially showed them the data from the sensor closest to the center of the office, and explored data from other sensors on request (e.g., if they asked to see the data closest to their desk, or at the other end of the office).

We explained the devices and motivations of the study to occupants during setup. We also placed an information sheet on all workstations, which included an invitation to take part in a 20-30 minute semi-structured interview. We interviewed 14 office-occupant respondents individually about their thermal comfort experiences, practices, and their perceptions of ThermoKiosk. Participants did not receive financial incentives. During interviews, we showed them daily graphs of the temperature traces with timestamped comfort survey samples overlaid. We asked questions like, 'what is thermal comfort like in your office?', 'can you describe what ThermoKiosk is and what it is for?' and 'has your thermal comfort changed during the study period?' Interviews lasted 21-40 minutes. Having interviewed the office occupants, we interviewed SM (63 mins) and MO (48 mins), separately. We presented the survey and

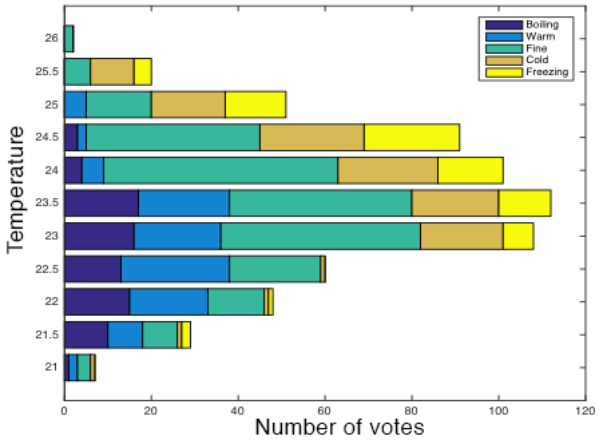

Figure 2: Distribution of samples input and their categories for recorded room temperatures.

temperature data to them (e.g., Figure 2) and summarised accounts from occupant interviews.

All interviews were audio recorded and transcribed with consent of the participants. We present the data here in anonymised form. We analysed the data using open-coding and thematic analysis, and the findings that we present are synthesised from these themes. The themes that emerged include, interactions with the devices, new social interactions and negotiation, politics of interaction and control, and intervention/change. Although we collected a large amount of quantitative data, our concern in this paper is on occupant and management perceptions and accounts of this data in practice, as opposed to any statistically significant changes in comfort and the indoor climate.

FINDINGS

In total, 629 samples were input during the study. Figure 1 (left) shows how levels of interaction changed throughout the study period. While the quantity of samples decreased as the study went on (perhaps due to a novelty effect), the patterns of input remained similar throughout. Participants generally felt that most people in the office participated in survey input, but it was likely that those suffering more extreme discomforts interacted more frequently. The ways that these devices were appropriated gives us some insight into how this opportunity was rationalised and incorporated (or not) into existing thermal comfort practices. To advance our understandings of the sociotechnical design space of HCI for workplace thermal comfort, we highlight perceptions of the data by management and occupants, and impacts of our technology probe on thermal comfort experience and practices.

Improving awareness and local negotiations of comfort

The presence of the ThermoKiosk, and the interactions that took place with and around it, led to new negotiations and a greater awareness of thermal comfort for the office occupants. This was described as a positive outcome by participants as it improved how they and their colleagues rationalised and acted on experiences of discomfort. It

unearthed social and physical characteristics of the office environment that enabled participants to better explain their own situations. For example, by observing patterns of survey input in the office, participants discovered that some colleagues experienced comfort in a similar way to themselves, whereas others' experiences were at odds with them. For P14, knowing how others are feeling in a shared office is important in making sense of one's own situation:

…it is useful to see if someone else interacted that they're hot, and you're hot, then that way you know that you're not the only one—without having to ask everybody else 'are you hot?' […] you go over and press [a button on the survey device] then you can see on the [ThermoKiosk display] that someone else said they're hot. (P14)

This awareness sometimes alleviated frustrations about discomfort by revealing that the underlying cause was not someone else's negligence or lack of consideration (e.g. leaving the HVAC in 'cool' mode and forgetting about it). As one participant alludes to in the following, the nature of thermal comfort as collective and conflicted became more apparent through experiences with ThermoKiosk:

I think they're realising everybody has a different micro-climate, depending on where they are, and that's not them just complaining, it's actually the building design. (P5)

And, these better understandings, in turn, led to more informed (i.e., inclusive) interactions with the HVAC: *"I think since the study [began…] people are a little bit more conscious about what the temperature is and actually asking people's opinions as well before changing it—saying, 'is anybody hot, will you mind if I change it?' […] so there's a much better sense of awareness now of actually what we're using the controls for." (P4)*

The survey data that we presented on the ThermoKiosk displays played a minor part in this increased awareness but, for the most part, it came about through social interactions that were stimulated by the presence of the survey devices and people's interactions with them. The act of pressing survey buttons sparked conversations where colleagues would acknowledge or question the experience expressed by the person interacting, and participants felt this was important in negotiating configurations that were sensitive to everyone's comfort.

… it's bringing it up in conversation […] if you can see people are pressing the buttons, they're like, 'oh are you feeling a bit hot, or…?'. Questions are being asked now as opposed to people just being quiet before. (P11)

The scope that ThermoKiosk afforded for expressing individual experiences improved participants' perceived control over their own thermal comfort. In one sense, this simply related to the ability to put forward one's opinion and have it heard.

I suppose it's just being able to control it, if I feel too hot then I'll say I'm too hot, and people are generally quite polite and they'll say, 'ok, well put the cool air on for a bit', but then if it gets a bit cold and somebody wants to turn it up for a bit we'll say, 'ok, well turn it up for a bit'. (P8)

In another way, the consensus that the survey data provided, or at least some metric of agreement, was useful for an individual wanting to adjust the HVAC setting in that it allowed them to justify their action as fair and inclusive.

You can see on the monitor that someone else said they're hot and then you kind of, you don't have to start a whole conversation about who's hot and who's cold. […] because I don't think they would want to touch the Air-con if they're the only one who might be either way. (P14)

In summary, the presence of ThermoKiosk, and more importantly the interactions with it, led to greater awareness of comfort as a collective experience. This new comfort literacy came about through the data and through conversations that interactions sparked, such as questions about why a colleague pressed a button and what they were experiencing at their desk. It provided a new sense of control in expressing comfort and changing the HVAC.

Survey input practices

Our participants recounted inputting survey data in three different types of circumstance. First, when they were feeling uncomfortably warm or cool, they would provide input at the closest survey device or do so as they were getting up to adjust the HVAC. Second, if the subject of comfort was brought to their attention by someone else interacting with a survey device, or through conversation.

…if someone else mentioned that they were feeling uncomfortable then I would go over and record if I was fine at that point or if I was hot or cold. (P14)

Finally, experiences were input when participants walked past a survey device and their attention was drawn to it. The visibility and physical nature of the devices was important in this, as well as the low levels of effort required for interaction. Consistent with our design considerations, button pressing was easy and convenient, the devices attracted attention without being disruptive, and they did so at times when people were more accepting of interruption (i.e., between work tasks).

The visibility I think then prompted you to go 'oh yea'. You just did it as you were passing by, so it was a lot more of a passive thing. Whereas, if you maybe had something online you'd have to remember to go in … (P5)

This meant that as well as capturing negative sentiments about discomfort or conflicts, the devices also captured some random sampling of comfortable experiences. When we queried participants about waning levels of interaction over time, they associated this with the ThermoKiosk system becoming less interesting "*part[s] of the furniture.*" In general, however, participants felt that although they would expect levels of engagement with ThermoKiosk to

decrease, that it would have a useful role over the longer term as the office environment changed.

It'd be interesting to see it again in Winter to see what the differences might be then […] I think […] the amount of votes would drop […] people would get used to it almost. I still think they'd vote if they felt like they needed to make changes […] I just don't think it'd be as much. (P4)

The conversations that survey input brought up were not always perceived as positive. P5 felt they were sometimes a way for dominant personalities to assert their own preferences, and this sometimes had the effect of inhibiting interaction by other occupants in the office. In a sense, the control that was previously asserted over the HVAC control by these occupants moved to control over digital surveys.

… whenever anyone went to press it, other people in the office would be like, 'oh, are you cold?'; 'are you hot?' I think then what developed is maybe people had a reluctance then to go and press a button […] for fear of being commented upon. (P5)

Nevertheless, in P5's case, such interrogations prompted her to use ThermoKiosk as a political tool to express "*Yeah actually, I am cold. My temperature is real, just as yours is.*" Significantly, ThermoKiosk provided her with a mechanism to do this in a way that was perceived as acceptable and non-confrontational. This is an important insight for interaction design since in the absence of ThermoKiosk, thermal comfort was perceived as contentious in the office and there was social stigma associated with expressing one's discomfort. In contrast, ThermoKiosk was perceived as being inclusive of opinion, and contested opinions were acceptable.

People who wouldn't have been more vocal are using them […] I think it's not as contentious because people have a mechanism by which their opinions are being captured […] before I think it was more frustration because there was no vacuum for them to get their opinions out. (P5)

This was particularly evident for P14 who had only recently joined the office, and so had not had time to develop a suitable rapport for negotiating thermal comfort with colleagues in the shared space.

Maybe I would have thought I should just grin and bear it a little bit… whereas having the boxes did mean that it was a way of showing that you were hot or cold. (P14)

While management and social hierarchies existed in the office, and likely affected survey input practices, we received no other accounts of this from participants. Generally, ThermoKiosk was recognised in the office as being an acceptable way to express individual opinion and so served to mitigate the effect of social hierarchies and politics on the expression of comfort experiences.

…[the survey devices] made [people] aware that they could actually say they were freezing cold, that their opinion was valid and that it would be captured in some way. (P5)

However, there were also ways in which interacting with ThermoKiosk could be perceived by others as contentious. Some participants reported that acceptable frequencies of survey input became normalised over the study period. This is an interesting finding as we designed the ThermoKiosk interaction to be open and convenient but, as a result, the design made possible individual 'button bashing'. However, as the devices were deployed in shared spaces, interactions were visible to others and, as a result, were not anonymous. This meant that the frequency of an individual's input could to some extent be socially controlled.

I think people perhaps voted less than if they had their own box. […] I think some people are watering down their feelings because they don't want to seem like they're the one that's always complaining or fine, and everyone else is just being whingy. (P14)

ThermoKiosk became integrated into thermal comfort practices in the office through a process of questioning and understanding interactions, and reflecting on what these said about collective comfort. Importantly, previous stigmas had little effect on survey input and, over time, socially acceptable ways of participating through surveys and controlling the HVAC were negotiated. These emergent interaction norms, and the establishment of what data is useful to input, can to some extent be seen in the drop-off on input in Figure 1 (see page 2, left).

Meanings of survey data & thermal comfort

Perhaps unsurprisingly, our study did not challenge entrenched ideas about the roles and responsibilities of occupants and management in workplace thermal comfort. Participants were motivated to 'do their bit' in the data-collection, but the actioning of the data for improved comfort was primarily seen as Management's responsibility:

Hopefully the data will be useful in helping us to make changes to the way that the Air-con is programmed—is probably my reason for [providing survey input…] Something does need to be done, and [ThermoKiosk is] a good way of potentially tracking how everyone across the office is feeling, and how that relates to what people are doing with the Air-con. (P14)

This is in part a manifestation of existing expectations of thermal comfort and responsibilities of building managers in providing this for them, but is also a consequence of how we introduced the system. Although we did this informally—we did not give specific instructions about when and where to input an opinion—we did tell them that we would explore the data with Management. This agenda was a strong motivation for interacting with the system and so we should caution that we might not have otherwise

achieved the same level of engagement, and resultant increase in awareness and comfort among occupants.

It also led to some anxieties for occupants about the validity of the data that was being captured, i.e., that it would provide a representative picture of their situation. Some participants were concerned with the granularity and accuracy of the spatial mapping of survey samples, which they felt was important for Management to be able to grasp the different experiences of comfort that they knew to exist:

The difficulty is that wherever the [ThermoKiosk] box is placed it can be, even the distance between where I was sitting, [which was cold, and] where the [ThermoKiosk] box or whatever [was], would be really hot. (P5)

Other participants were concerned about whether they were providing survey input 'correctly'. Part of this related to questions of whether the co-location of samples and experience was significant: *"if it's capturing data for a micro-climate zone, and somebody walks on and presses another [ThermoKiosk] box, it's capturing the data in the wrong area (P5).* Participants also noted the shortcomings of the system in capturing a balanced account of experience, particularly in neglecting times of day and 'non-extreme' perceptions of comfort.

I find that if I'm fine I don't think about pressing it. You know, it's only if I'm too hot or too cold that I tend to press it, really. […] You're getting on with your work and you're fine, and you don't think 'Oh I better go and press a button because I'm fine'. (P3)

Finally, some participants were concerned that the accounts provided by each participant were not consistent across the office (i.e., people were providing input in different ways) and that this might affect the conclusions that Management drew from the data.

I've seen other people do different things, so they've just been interpreting [when/where to provide input] differently. (P11)

These findings suggest features that could be incorporated into a redesign of ThermoKiosk with a more defined purpose, and we discuss this approach in the next section.

ThermoKiosk data for professional management

While MO and SM's management practices were data-led in many ways—using sensors and Building Management Systems (BMS) for monitoring and to investigate reported issues—the use of subjective data was new to them, apart from, for example, infrequent conversations with a building occupant regarding a complaint. In analysing the data, they were curious to see any spatial variation in samples, and how survey input correlated with recorded temperatures in the room. *"[I'd like to see] temperatures compared to what [button] they're actually pressing." (MO).* However, the survey data was only useful to them if it corresponded to temperatures that fell outside the bounds that they sought to maintain as part of their heating policy and standards. Hence, it initially seemed like subjective data might not add any value to the data they already used because they assumed that the subjective data would always sensibly correlate with the indoor temperature measurements that they assessed thermal comfort with.

[The ThermoKiosk data is] important because that's essentially what we're trying to do—we're trying to make sure employees and students have comfortable conditions to work in. But then […] if I see the temperatures on the BMS and they're around what we would expect, you're not going to get lots of votes telling us they're either very cold or they're very warm. In which case, you're never going to get a disparity between the data. (SM)

In reality, the subjective data did not align with the quantitative temperature measurements (see Figure 2). For example, perhaps counter to intuition, most of the samples for 'Freezing' were cast at the highest temperatures.

It brings up some interesting questions. I'm surprised that people are voting that they're freezing—25 votes for freezing when it's between 24 and 24.5 degrees? (SM)

A closer look at the survey samples in comparison to daily temperature data enabled the management participants to relate the discrepancy to the way that the HVAC functioned and was being controlled. By aligning the survey data with the change in temperature over time, they concluded that occupants were uncomfortably cold as soon as the HVAC was put in 'cool', regardless of the temperature. This meant that occupants found it extremely challenging to curb rising temperatures throughout the day.

It is strange you get a vote for 'cold' that just precedes the peak [daily temperatures]. (SM)

It's saying to me that it's getting too hot, and that's when they're putting it [in cooling] and that's when they're complaining [of cold]. (MO)

However, these discrepancies did little to further the process of resolving discomfort because they did not allude to possible courses of action that had not already been tried. Essentially, the space of potential solutions was constrained by existing management practices. First, in that their main focus was on the operation and maintenance of the building and in this case, on numerous occasions the fan coil units were tested and deemed to be functioning correctly. Second, their heating policy was based on acceptable office temperatures, which were defined in terms of numerical bounds (19–21 Celsius). Although the temperatures recorded in our study mostly did not fall into this range, they were judged to not be 'extreme'. Finally, they did not consider changing the operation of the HVAC because they had previously handed full control of this over to occupants, so there was nothing else that Management could or should do to change the situation.

Because, really, they should be comfortable. You should just be getting buttons pressed, 'yeah comfortable' because

they can choose what they want. They can just decide what they want so at no point should they ever be or feel uncomfortable. (MO)

This example highlights an important disconnect between Management and the office occupants. It demonstrates the importance of subjective experience data in this multi-stakeholder sociotechnical system, but also highlights the limitations of this outside of broader ways to challenge Management's assumptions and existing processes. In the end, rather than providing conclusions or solutions to the discomfort issues, the discussions of the survey data brought to the fore the constraints under which Management were working. Occupants and Management still negotiated thermal comfort independently and on their own terms. Wider change in policies and practices is needed to bring about collaboration, but subjective experience data could play valuable roles in supporting this.

Reconsidering how comfort is managed

The survey data played a promising role in highlighting to Management fundamental questions about how comfort is approached in organisations. In particular, it highlighted to SM that the way they were framing comfort and energy use, and the metrics that they used, were perhaps somewhat ineffective. The correlations between subjective experiences and indoor temperatures seemed at odds with the heating policy. Hence, while the policy might be a useful tool for setting occupant expectations of comfort, perhaps, in practice, it should be applied more loosely.

It brought up more questions than it answers, which is quite good, because it's made me think, is the way that we approach heating and cooling correct? Have we got our setpoints at the right level? Where we've typed them on our policies and on our website, the average that they're comfortable at is between 19 and 21. From looking at that data, that's telling me, no it's not. (SM)

However, this exercise also highlighted the constraints that Management faced in responding to issues that the subjective data made apparent. One of these was the need to characterise issues as technical ('*there's an actual fault*') or systemic. Facilities management processes frame comfort at a much coarser level than the individual:

We're obligated to not to change it in response to one person commenting. So if one person said 'Oh, I'm too cold because I'm sat under one of the vents' or something […] we'd just say it might be better if you all just put an extra layer of clothing on or something. (SM)

This meant that it would be difficult for them to respond to cases where issues were with individual situations or where reported experience was diverse, since the infrastructure is designed for a uniform climate in shared spaces. Although ThermoKiosk provided an account of subjective experiences of comfort in the space, existing processes and infrastructures did not afford ways to negotiate alternatives based on this. An important step towards this was the development of benchmarks that would point to meaningful ways to interpret the data.

[Subjective data is] not a route that we've used before in assessing what the conditions are like. There's no standard or benchmarking that we can use […] for example, if we were to look at the voting within an hour's timeframe—what would we say if 70% of the votes cast during the time were cast for 'boiling'? Would we say that's the benchmark or that's the level at which we would then think that's when something would need to be changed? But we don't have any standards or instructions with regards to that. (SM)

If such benchmarks were in place, however, the survey data could provide Management with another metric for reviewing energy use and for prioritising their activities to reduce energy use.

It would be used to target where our next projects are going to be […] we've got [BMS data] by building and by significant energy user […] we could [include 'heating voting' where] for an A-rating you would say less than 25% votes cast over this certain amount of time for 'boiling' or 'warm'. And then for your 'D[-rating]' you would be getting over 75% of the votes for 'boiling' or 'warm' or 'too cold', either way–it would take a lot of discussion into finding a systematic way of incorporating that data. (SM)

In the absence of benchmarks and standards, MO suggested there might be ways that adaptation strategies could extend to changing daily working practices in order to fit better with the way that the HVAC system functioned. This required occupants to coordinate change for themselves to fit with the existing infrastructure. For example, occupants could organise trials of various configurations of the HVAC controls and use ThermoKiosk as a means of reaching consensus on what the most suitable configuration was for the office. Or, as the following quote describes, they could coordinate their daily activities:

If they've breaks, put the cooling on when they go out, go and make a cup of tea, and then turn it back off. They can do that because they've got control. […] Or everyone's out of the office for their dinner […] Put it in 'cooling', when you come back, turn it off. Your room's back down to 21, might be a bit chilly to start with but it's going to slowly creep up and by that time, the day's finished. (MO)

While this fitting change to the existing infrastructure might be a compelling avenue to explore, it is important to note that the abilities and scope for negotiating shared control and work practices did not readily exist for the office occupants. In fact, this would require a sociotechnical system for negotiation and coordination not only with facilities management but with other divisions of organisational management also.

DISCUSSION AND IMPLICATIONS FOR DESIGN

In originally 'designing' comfort as a collective pursuit for occupants, by adapting the HVAC settings for manual

control, Management made assumptions about how shared control of the HVAC would be fairly and rationally distributed. It became evident in participant accounts that people often did not know how to participate in shared control practices and achieving collective comfort was challenging. This was to some extent a question of navigating the infrastructure and thermal dynamics of the room, but also a question of understanding the experiences of others and the politics of comfort and control. The meaning of participation in these daily office practices varied between occupants and this led to variation in input to how the climate was controlled. The ThermoKiosk system and our research study brought this onto a more even keel by providing a platform for legitimately expressing (through conversations and button presses) one's experience and, as a consequence, for developing understandings of thermal comfort as a collective issue, and strategies for negotiating it. Whilst subjective measurement of comfort is not new, our findings contribute new understandings of how it is appropriated and put to use by occupants and management when it is incorporated into an interactive system for public capture and display. Its presence highlighted a literacy gap and our findings reveal the mechanism and processes by which new literacy comes about, which we might aim to support through design.

Formalised measurement and comfort literacy

Ultimately, shared thermal comfort is contested, particularly if it is framed around mechanical conditioning of a static climate to suit everyone. In this context, the extent to which any grievances are voiced can be limited [37]. However, in the context of more participatory notions of comfort, 'social comfort', which Cole et al. [11] describe as "*collective understandings of experienced comfort and the co-development of agency for achieving comfort*", can have a strong influence on individual experiences and understandings of comfort [11]. In our findings, the public nature of survey input and the collective feedback were hugely valuable in helping to raise awareness of others' situations. The better understandings that it led to, that there was not a straightforward 'fix' for thermal comfort, were important to calibrate perceptions of control and to find ways to deal with it. In this way, by accommodating greater participation in shared comfort, ThermoKiosk provided a technological and political context to help develop this important social dimension, which is almost non-existent by design in fully automated climate control systems.

However, while the subjective data was useful in better understanding thermal comfort issues, it was unsuccessful in finding a management resolution. This was largely due to limitations of the office environment (e.g., no operational windows) and the scope for intervention, i.e., discomfort resulted from limitations of the infrastructure and the building, as well as variation in comfort experiences, as opposed to a faulty system. Indeed, these are well-known factors that influence occupant satisfaction (e.g., [32,36]). However, illustrating that discomfort is not caused by an underlying fault – which was not apparent before our study – is important in arriving at approaches and strategies for dealing with it. Hence, we see this as an important role for design interventions: to develop understandings of thermal comfort and its constraints, and to uncover naïve assumptions made about comfort experience.

Of course, that is not to say that occupants or management would consider ThermoKiosk to be a successful 'solution'. While ThermoKiosk played a very valuable role for our participants in developing comfort literacy, as an overall approach to thermal comfort it is somewhat at odds with normal expectations that comfort is something that is resolvable and stable. We framed ThermoKiosk as a mechanism for better understanding the solution space. However, such a framing comes with the expectation that there is in fact a solution. Participants had existing expectations of comfort and the perception that something was broken in delivering it: which could be fixed, as opposed to a space that was poorly designed for this purpose. These comfort expectations were important to occupants and it's unlikely that ThermoKiosk would have been as well received if we had alternatively framed it as a mechanism for enhancing social comfort to cope with (as opposed to solve) daily discomfort dilemmas.

This leads us to question what appropriate models for negotiating thermal comfort might be. Existing expectations of occupants fit more closely with consensus models as these are traditionally applied in comfort standards and interventions (e.g., [18]). These reduce comfort to an average measure and assume that universal comfort can be reached. And, indoor air temperature is a straightforward dimension to average. In contrast to this, ThermoKiosk employs a model that engages with differences in experience. This is more along the lines of agonistic pluralism [14,25] where negotiation is a process of continuous questioning. In this way, ThermoKiosk affords statements of the form, "this is how I feel", and the negotiation that takes place is a social one of understanding what this implies in terms of adaptive measures for the collective. Our findings demonstrate that this negotiation is complex and the outcome is not deterministic and involves trade-offs and compromise, and we would caution that such properties can be lost in more structured approaches like post-occupancy evaluations (POE) [11].

Hence, in thinking about fundamental changes to how thermal comfort is framed and approached in control systems and interface design, for example with adaptive thermal comfort [26], the implementation of an agonistic model would require a parallel program of engagement by the institution. Our study demonstrates that, for example, mandating subjective data collection could have positive, indirect impacts on comfort for occupants and management, independently. But this in itself is insufficient to bring about a more dynamic and participatory approach [11] to thermal comfort. Engagement with alternative approaches

to thermal comfort might require contractual intervention (Zemtseff (2007) in [11] reports on lease stipulations for tenants of net-zero buildings); more focused development of knowledge and competences (e.g. of how the infrastructure works and the thermal dynamics of the office) which computational systems can help model and visualise; and the kinds of support for collaboration and navigating the politics of participation that ThermoKiosk enabled.

Designing for collective comfort as a matter of concern

In our study, thermal comfort practices took on a more collective nature, and ThermoKiosk provided a medium to coordinate participation in them–participants provided input after observing colleagues interacting with ThermoKiosk, and used the ThermoKiosk displays to justify changes to the HVAC. This occupant involvement is in contrast to the service provision model of automated HVAC control where occupants are passive recipients of an indoor climate. We might draw parallels to DiSalvo's concept of *Adversarial Design* where ThermoKiosk played a role in embracing conflict and provoking and engaging the political [15] (i.e., that thermal comfort is shared and contested). In practice, our study, and the presence of ThermoKiosk, the visual data, and interactions with it, 'occasioned' the accounting for subjective experiences and (mainly, in this case, anomalies in) sensor and survey data [33]. But we could draw closer links with Latour's ideas of *Dingpolitik* in which "*objects become things when matters of fact give way to their complicated entanglements and become matters of concern*" [22]. ThermoKiosk, and the 'articulation work' [33] that it provoked, helped to reveal these complicated entanglements, which were previously misunderstood or taken for granted (e.g., that a setpoint to suit all was possible). ThermoKiosk provided a platform around which the development of understandings and awareness were stimulated. Developing thermal comfort literacy in this way ultimately led to new representations of thermal comfort from the provision of a service to something that occupants play an active role in achieving. The subjective data itself also provided a crude account for third parties of how the sensor data was experienced *in situ*, mitigating some of the misrepresentations that can be drawn from sensor data in isolation [9,33]. ThermoKiosk and our study moved thermal comfort from something that was not considered a matter of concern for occupants to "*an object of concern to the eyes and ears of those who have been assembled around it*" [22].

We think that this highlights an important area for HCI and interaction design to explore further. Adversarial design and Dingpolitik might be more commonly associated with grander matters of politics, but there are important mundane questions about everyday life, service provision, and resource use that might not normally be considered political, but which we might valuably frame as political, and expose their political nature in design. The establishment of thermal comfort as a 'matter of concern', i.e., as something to be interrogated, came about as an artefact of our research as opposed to an effect that was orchestrated through design. But what might control systems and interfaces look like in buildings that were designed for an indoor environment in which prevalent disagreements about a shared indoor temperature are acknowledged? Such a design might acknowledge the inadequacies of buildings and their infrastructures, or simply not require a uniform indoor temperature– as in the adaptive thermal comfort standard [26]. What might we want to sense, what data might we want to share, and what interaction might be most appropriate? What agency should we afford the mechanical system in response to human input, given that its operation affects a shared space? We could extend this further to consider how values other than perceived comfort, for example, energy efficiency (e.g. via a Sustainability Manager), might be at stake.

One promising avenue brought up by Management is the integration of subjective data into their "energy review". While the uses of this data in benchmarking building performance may not directly lend themselves to more fundamental changes for sustainability, the presence of this data, and analytical tools to explore it might facilitate managers coming to similar conclusions themselves about the validity of heating policies and standards, as they did in our study. For example, in the first instance it might expose cases of overheating and cooling where subjective experience is at odds with assumptions about comfortable temperatures, signifying low hanging fruit for intervention.

CONCLUSIONS

In this paper, we presented a study of ThermoKiosk to understand the utility of subjective thermal comfort data in workplace comfort management. Through a qualitative study with building managers and occupants, we uncover much about digital comfort surveys as a new facet in participatory comfort management. We see valuable roles for interaction design in supporting the everyday expression of subjective comfort experience, and in providing a medium for negotiating and developing the knowledge, competences, meanings, and politics required for effective collective comfort practices. For Management, the data brings into question how comfort is approached in institutional policies and management practices, but further work is required to find ways to more systemically integrate it in ways that challenge these. In establishing thermal comfort as an 'object of concern', these findings point to interesting potential for sustainability applications: first in engaging occupants and management with alternative approaches to thermal comfort where the energy required is more closely linked to comfort experience; and secondly, in providing a platform for the establishment of new, sustainable practices.

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