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“I’d want to burn the data or at least nobble the numbers”: Towards data-mediated building management for comfort and energy use

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ABSTRACT
In this paper, we explore the role of pervasive environmental sensor data in workplace building management. Current interactions between management and workplace occupants are limited by the gap between experiences of (dis)comfort (i.e. individual preferences and perceptions) and the rigid objectivity of organisational policies and procedures such as static setpoint temperatures for indoor spaces. Our hypothesis is that pervasive sensor data that captures the indoor climate can provide an effective platform from which to more successfully communicate about comfort and energy use. Through a qualitative study with building managers and occupants, we show that while data does not necessarily resolve these tensions, it provides an engaging forum for a more inclusive building management process, and we outline directions for taking a more conversational approach in the design of comfort and energy-use interventions for the workplace.

Author Keywords
Comfort; Energy; Building management; Data; Intervention

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

INTRODUCTION

In workplaces in the UK and in many other parts of the world, we commonly outsource the provision and management of our comfort to automated heating and cooling systems and to professional management services. A consequence of this approach is that our involvement or interaction with these comfort processes and systems is limited or completely removed, and this is something that we have come to expect. This means that when discomfort is experienced that this approach affords little flexibility or scope for adaptation. The interaction that does take place is through the making of complaints—often following formal processes and procedures—when things go wrong or are not to our satisfaction. Another consequence is that the provision of comfort and the resources put forth in pursuit of this are disconnected from the actual experiences and preferences of occupants, and is hence inefficient.

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In this paper, we explore the potential of fine-grained indoor environmental data for enhancing interactions with and around comfort in the workplace. The environmental data (e.g. temperature measurements) available for control systems and building management is currently limited: usually one sensor per floor or building with access restricted to operators of Building Management Systems (BMS). Our investigation in this paper is not about the effectiveness of the pervasive sensor data as a platform in and of itself, but of the opportunities and limitations associated with it in advancing conversations (and hence processes and practices) around problematic comfort issues. To this end, we deployed a pervasive sensing infrastructure in three different workplaces with a history of comfort complaints. We captured three environmental factors that are common proxies for comfort (i.e. temperature, humidity, light) and investigated how visual representations of this data are perceived and understood by building occupants and managers. In doing so, we explore how the presence of this data does and does not influence discourses around comfort and energy use and the structure of the existing negotiations that take place.

CSCW can play important roles to address power imbalances in energy use negotiations, as Dillahunt et al. outline for domestic landlords and tenants [14]. In recent work, Clear et al. [10,11] highlight ‘social negotiation’ as an important element for sustainable thermal comfort. One of the strategies they suggest is to facilitate discourse “*so that people can work together to achieve comfort in environments exhibiting variation, and to ensure realistic and just treatment of occupants as resources put towards environmental conditioning are reduced.*” Drawing on participant accounts, we ask, how might existing negotiations about comfort change in scenarios where the workplace is instrumented with sensors measuring the indoor environment, and data from these is made available to management and occupants alike. We are concerned with

how the various stakeholders interact with, process, and make sense of localised indoor climate measurements in negotiations about comfort. Our interest is in understanding the purposes data serves in negotiations about infrastructure and work practices, and how compromises do or do not come about when agendas, practices and aspirations do not align. As Clear et al. highlight [10], a move towards less resource-intensive thermal environments will require ongoing renegotiation of expectations of comfort and resource use, and so our findings related to the utility of pervasive sensor data in bringing about shared understandings of indoor climates, experiences working in them, and accountability and responsibility in decision-making processes have direct implications for thinking about how sustainability might be better integrated into the workplace. In this way, we aim to grapple with the full complexity of organisational energy use, and consider interventions that fit with everyday practice [29].

RELATED WORK

Our research relates to a number of areas of CSCW and HCI including energy-use interventions, and negotiation in interaction design. It also relates to research on thermal comfort and facilities management outside these domains.

Interactive energy-use interventions

While our focus in this paper is on comfort and interactions with environmental data, a body of relevant related work investigated the potential role of smart meters and energy-use data feedback to engage workers in energy conservation [6,18,21,26]. For example, Milenkovic et al. implemented a personal office energy monitor that addresses individual and organisation energy management by providing end-user energy-use and environment data feedback, and a means to collect subjective measures of comfort to support building management decisions [22]. Besides energy data feedback, Foster et al. highlight the importance of employee engagement and empowerment, and of considering levels of responsibility for change in design [18]. Recent CSCW research has explored avenues for moving beyond individual behaviour change for energy conservation: Bedwell et al. [5] conducted workshops with occupant and management stakeholders in a workplace about energy consumption and management. They highlight the complexity of energy use in the workplace and a gap in understanding the role that policy plays in interventions, which we begin to bridge in this paper. CSCW research also investigated social framings of energy consumption in domestic communities [13], outlining the importance of user knowledge of contextual differences to explain variance between homes and to expose 'excess' energy use, which can be a powerful tool for residents to hold each other accountable for energy. In this paper, we concern ourselves with a gap in understanding of the design of digital interventions for comfort management in the workplace. In addressing this, we investigate how the availability of environmental data affects perceptions of comfort and energy use, and the ways that these are managed individually, socially, and at the level of the organisation.

Predicted and automated thermal comfort

Much work outside of CSCW and HCI focuses on infrastructures and control systems that automate, predict, and optimise energy-efficient mechanical provision of a thermally comfortable indoor environment (see Dounis and Caraiscos [15] for a review). These are designed for minimal or no human interaction, and are based on assumptions about occupants' thermal comfort, which are formalised as a PMV (Predictive Mean Vote) index. For example, Álvarez et al. present a model for optimising the control of HVAC in buildings that have renewable, and hence time-variant levels of, energy supply [1]. Available energy is distributed using a feedback loop that includes room occupancy and climate. Erickson and Cerpa propose ThermoVote, a more contextually sensitive approach to thermal comfort measurement than PMV [17]. Using an occupant voting system, they were able to demonstrate improved service and efficiency by algorithmically predicting setpoint adjustments. Tse and Chan demonstrated similar improvements using a distributed sensor network to carry out real-time PMV measurement and HVAC control [33]. Our focus here fits more with the adaptive approach to thermal comfort [12], which acknowledges that comfort preferences are non-uniform, are influenced by contextual factors and thermal history, and that thermal comfort can be achieved in less resource-intensive ways by reducing our reliance on mechanical systems. While we recognise a role for automation and mechanical provision of comfort, we do not consider it necessary, comfortable, nor energy efficient to fully design out human interactions and non-mechanical adaptations, and given the contextual influences and variation in comfort preferences, we see an important CSCW role for ongoing social negotiations of appropriate solutions as opposed to predefined, static ones.

Facilities Management

The Facilities Manager (FM) role is important in our research and recent work outside of CSCW and HCI presents understandings of its relevance to reducing workplace energy use. Parag and Janda treat FMs as middle-actors in organisational energy use and propose a 'middle-out' framework (as opposed to top-down or bottom-up) for understanding and supporting change [23]. They highlight agency and capacity as important factors in this, both of which come to the fore in our accounts. Goulden and Spence recently built on this work [19] by identifying the different rationales at play in FM decisions – energy as a cost, energy as a utility, and energy as an implicit right for occupants – and how these can often contradict each other. In this paper, we extend this, shedding light on the rationales that emerge in interpreting insights from environmental data from the perspective of those in FM.

Related work in CSCW for Healthcare

Our approach in this work has parallels with CSCW research that reconsiders the relationship between the patient and professional in the provision of healthcare. The contextual, conversational work involved in 'collaboratively articulating' a patient's situation is highlighted in CSCW and HCI research for rehabilitation [4,20], and other aspects of health [1,25]. This involves a mutual and negotiated sense-making of the patient's situation (e.g. hand injury and surgery [20]) and rehabilitation practices. Bagalkot et al. [3] draw attention to the notion of 'concordance' whereby the professional and patient partner in collaboratively negotiating rehabilitation programs so that they are suitable for the situated performance of carrying them out, which mostly takes place unsupervised outside of the clinic and in the context of the patient's everyday life. These approaches account for the embedded nature of practice [20], which is no less important for comfort [28] and energy use [26]. The workplace context adds some complexities, in that negotiations often include multiple occupants with conflicting demands, and negotiation already happens but is stinted by management's objective guides and policies. We are investigating how to enable better negotiations using sensor data as a subject of discourse. This idea relates more broadly to CSCW work on 'interoperability' [30] in that it involves reconciling different, incongruent perspectives on shared objects (i.e. the sensor data in our work) and 'boundary negotiating artifacts' [9].

METHODS AND PARTICIPANTS

We recruited FMs and occupants from 3 organisations via a Building Management project partner. At each site, we first carried out a deployment of BuildAX[1] environmental monitors to capture measurements of the indoor environment before conducting interviews and focus groups with participants. The sensor data collected consisted of temperature, light (LUX), passive infrared (PIR), and humidity. The BuildAX devices were factory calibrated to ensure outputs of individual sensors agreed with hardware specifications. The length of the data collection period varied from 2–4 weeks.

The authors generated summary statistics (e.g. min, mean, max) of the data and produced time-series and distribution graphs of these to prompt discussion during interviews and focus groups with the participants. Data was not provided to participants in real time. In thinking about design for building monitoring and management, real-time data might be more suitable. The purpose of the data in our study is to capture the indoor climate and understand how participants make sense of it in terms of their experiences and work/management practices. Hence, we provide insight into roles for and utilities of data, but further research would be required to design appropriate real-time interactions with and around it.

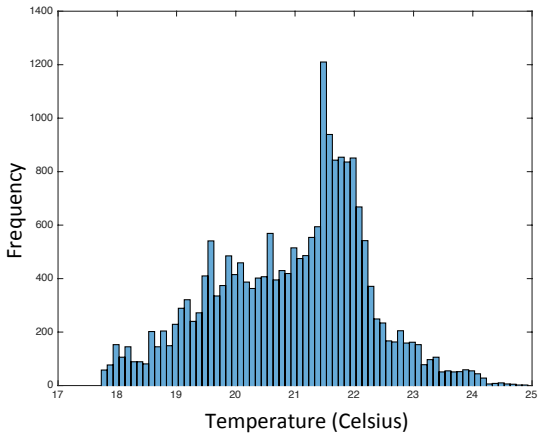

Figure 1: Example temperature distribution graph shown to participants in BIT.

Three types of graphs were produced for each sensor: a distribution of the temperatures recorded during the study period (e.g. Figure 1); average-of-median hourly temperatures for the 24-hour day, and raw daily traces featuring light, humidity, temperature and PIR overlaid on each other. The purpose of the graphs was to introduce the data to participants in a manageable way. The summary statistics provided representations of the whole study period, whereas the raw data provided a picture that did not mask detail. Numerical measurements illustrated the range of readings recorded, and temporal distributions provided a way to relate these to daily practices. The range of graphs we chose offer a number of perspectives on the data but the whole raw dataset was to-hand if more detail was requested (e.g. data at individual desks) during interviews and focus groups. It is possible that readings of some sensors were inconsistent with participants' expectations due to their placement (e.g. being placed under a vent). However, we believe this kind of misinterpretation was limited as we had a dense network of visible sensors in each study context (spaced approx. 6 meters apart) and participants used their understandings of the space and location of sensors to interpret readings, as well as comparing them to other sensors in the space if readings were unexpected.

We conducted 3 interviews with 6 management participants—2 group and 1 one-to-one interviews between 46-68 minutes in length (see next section for details)—because we wanted to investigate organisational processes and strategies from their perspective in depth. We conducted 3 2-hour focus groups (one at each organisation) with 10 occupants in total (see next section for details) and facilitated by 2 of the authors. Focus groups were chosen for occupants to enable discussion and negotiation among occupants about comfort-related issues and solutions. Interviews and focus groups were semi-structured and they were organised broadly to include questions that covered the following: work practices, experiences of (dis)comfort,

[1] BuildAX sensor documentation: http://buildax.co.uk/

comfort and energy use interactions, and perceptions of data. In both cases, we introduced the data by asking participants to help us understand what it represented in relation to comfort and complaints, and how it might be used. In the focus groups, we used a role-playing activity to elicit responses, where participants were tasked, based on their experiences and understandings, with scripting various conversations between management and occupant stakeholders (e.g. overheating complaints). Both groups were aware that data was being collected to better understand known discomforts and potential solutions to these, and were very curious to see what it showed. We included questions like, is that what you'd expect? Can you identify your discomfort in the graphs?, and discussed how data might change comfort interactions.

All interviews and focus groups were transcribed and open coded. 71 codes were consolidated into a coding framework that we applied in a second round of analysis to synthesise results. The findings presented are a synthesis of the most prominent themes that emerged. They include, for example, comparisons used in making sense of data, the limitations of data in expressing situations, and the politics of data. Some other themes that were less prominent and omitted for brevity are, for example, the ways that domestic life constrains the ability to adapt work schedules for comfort, 'thermal delight' associated with 'normal' indoor environments after long exposure to uncomfortable ones, and challenges for management in engaging time-constrained occupants in behaviour change. In the presentation of our findings, we use quotes to support emergent themes. We use pseudonyms for the three organisations and the participants throughout.

Summary of study environments and situations

BIT is part of an organisation with over 40 buildings in the UK managed in part by Mgt2_BIT and Mgt3_BIT. The building itself is a refurbished old school. BIT was chosen by the local FM (Mgt1_BIT) as it had a history of complaints about thermal comfort, glare, and noise levels. It is an open plan office with approximately 45 occupants on the top floor of a 2-story building, half of which houses a call center with fixed desks, and half of which hosts management teams with hot desks. It is L-shaped with mostly northeast, and some southeast, facing windows that could be opened, and they sometimes were for ventilation. The two sections of the office were not partitioned. The office has three HVAC units that were installed as part of the refurbishment. It has one entrance door that could be opened but this was often kept closed to avoid smells coming in from an adjacent kitchen area. We deployed 15 sensors on walls according to Mgt1's instructions (2 at approx. 2 meters from floor level) and on desks (13 at approx. 0.7 meters from floor level). 3 occupants took part in a focus group following an email circulated by Management to the IT management teams (not the call center) requesting volunteers. Their motivations for taking part were to be involved in decisions related to management of workplace comfort. Their experiences of thermal comfort varied with some considering the office too cold, while others found it too warm. Requests to change the HVAC settings had become a daily occurrence.

Min, Max, Median: **Temperature** (Celsius) 17.7, 25.2, 21.1; **Humidity** (%): 30.9, 51.9, 38.3

UoH is a 3-story building built in the 60's in a UK university with over 12K students and 2.5K employees. It was chosen by the Energy Manager (Mgt1_UoH) because many of the south-facing rooms had a history of overheating complaints. The university has a formal process for issuing and handling complaints. 19 sensors were deployed in administrative and academic staff offices, hallways, and stairwells over two floors in the vicinity of the complaints. Sensor placements were decided by Mgt1_UoH: 16 were placed on the top floor, where complaints had come from, in both north and south-facing rooms for comparison. 3 were placed on the floor below, again for comparison. All sensors were placed on walls at approx. 2 meters from the floor. 3 administrative staff took part in a focus group: two from a 3-person south-facing office with 2 sensors (invited by Mgt1_UoH due to a history of complaints), and 1 from a north-facing office across the hall (who was invited to take part by the other participants during the focus group). All agreed that the south-facing office was unbearably warm and exhausting to work in. A hatch was open during fixed student visit hours; otherwise it was kept closed to avoid interruption. The door was kept closed to adhere to a confidentiality policy. The room contained two radiators that were on a district heating system, but their thermostatic valves (TRV) were rarely switched on. The windows could be opened but, in practice, occupants felt they had to keep them closed to avoid strong breezes blowing their paperwork and to prevent bees from entering. The occupants used window blinds but felt this had little impact on their thermal comfort. Occupants noted reporting their discomfort to FM "*a lot, every year*" for about 3 years and their motivations for taking part in the focus group were to relate their perspectives and bring about improvements to their comfort.

Min, Max, Median: **Temperature** (Celsius) 20.5, 29.9, 23.7; **Humidity** (%): 25.9, 52.3, 38

CU is an office in a UK university with over 20K students and over 5K employees. It has a formal process for issuing and handling complaints. 19 sensors were deployed at approx. 2 meters from floor level in similar offices facing northwest on two different floors (7^{th} and 8^{th}) of a 6-year-old building. Mgt1_CU is the Energy Manager for the university, and Mgt2_CU is the FM in charge of the workplace that our occupant participants inhabit. Both offices were open plan and were chosen by Mgt1_CU because one (7^{th} floor) had a history of thermal comfort complaints of both overheating and overcooling, and the other one did not. Our focus group participants were from the former office who had complained to FM about thermal

comfort since they moved in 3.5 years prior to the study. They were recruited using flyers distributed by the researchers when they deployed the sensors. 4 participants took part in the focus group; 2 from opposite ends of the office, which were reported to exhibit opposite extremes of thermal discomfort. The office contained approx. 30 occupants, and was heated and cooled using 4 HVAC units that were centrally controlled by occupants using a panel on the wall. Floor to ceiling windows run the length of one side of the office but these cannot be opened and have UV-filtering film, and 2 office doors were kept closed and card-operated for security. Again, motivations for taking part were to have their perspectives accounted for and to bring about improvements to their situation.

Min, Max, Median: **Temperature** (Celsius) 19, 27.2, 23.1; **Humidity** (%): 29.8, 66.9, 37.9

FINDINGS

In this section, we begin by describing our findings related to understanding and using data, before presenting some broader findings about how comfort gets negotiated in the workplace that emerged from our data-led discussions.

Going through the data with participants, we wanted to understand the interactions that take place in 'reading' and making sense of one's own indoor climate data. What is the inherent utility of the data, and how can we support unlocking it? In two of the study contexts, the value of data in comfort complaints had already been considered with some of the occupants having collected their own data prior to our study—reading temperatures from an HVAC control display (CU), and an off-the-shelf temperature sensor acquired by the occupants (UoH)—to support complaints. In both cases, the data failed to advance their arguments.

"I used to report the temperatures down to reception, nearly every day […] We bought our own thermometers in the end, and Estates wouldn't accept the temperatures we were giving them from that. And we were recording 25's and 26' and sometimes higher in that office" (Paula).

Here, we outline the mechanisms used for making sense of the data in the context of comfort complaints, and the opportunities and limitations that it brings with it for comfort and energy management. Thermal comfort was a common interest. Consequently, participants mainly focused their discussions on the temperature data. They did not ask questions about measurement (e.g. frequency of capture, accuracy, measurement units), and did not suggest any further measurements that could be made (e.g. CO_2). They did sometimes ask for clarifications about the values (e.g. mean, frequency) and time periods of the graphs.

Roles of data in expressing cases of discomfort

Participants used various comparative analytical tools on the data when trying to make sense of their own situations. Understanding these is important for design because they illustrate some of the mechanisms required to get value out of the data for building occupants. However, to better inform design it is critical that we also understand the context in which these were employed, and what use came of them towards resolving comfort issues, and we further unpack these in the following sections.

When we spoke to participants about discomfort complaints before introducing the data, rather than describing their situations in absolute terms (e.g. 'it's too hot in here'), they expressed and justified their own situations by making spatial (e.g. 'it's much hotter here than in X'), temporal (e.g. 'it used to be more comfortable here'), and social comparisons (e.g. 'X has also said it's freezing here'). When we introduced the data, comparisons were used to contextualise it, which was a necessary step in making it useful. In practice, this occurred as an exploration of the data directed by searches for specific periods of time, spaces, or situations of others. But, significantly, the presence of data about the participant's environment itself (not just the environments of others) led to questions being asked about physical perceptions of comfort. It was not sufficient to *feel* uncomfortable, discomfort had to be demonstrated. In this way, we see that the very presence of data, and digital tools that promote data-oriented management of comfort, can serve to make it more objective, changing the structure of negotiations as a result.

Temporal comparisons were one mechanism used to evaluate the significance and validity of the data. Participants compared the data collection period to other periods that were more and less extreme. The purpose of this was to determine to what extent the data represents or accounts for the situation that they are reporting on, and to what extent it comes up short: "*it's not been a very nice summer […so] I think you've tested it at the worst time for us… for our benefit […] if you'd have taken that last year, it'd have been a heck of a lot different*" *(Carla).*

The opinions of others were also recounted to reinforce points that participants were making about their own situation. Participants had ideas that their own accounts, opinions, and even their own perceptions might be viewed as dubious in isolation. In fact, some of them questioned their own perceptions, and whether they were just a warm or a cold person. However, they felt that acknowledgement of their situation by others not working in the same space legitimised their case: "*I think everybody down this corridor would tell you that it's ridiculously hot. They're just not here to say it*" *(Michelle).* In this way, participants used normative comparisons in order to understand where their own perceptions of comfort fitted with others. Because in all cases our participants inhabited shared spaces, they perceived the validity of their complaints to be relative to the consensus. It is worth noting that the perceptions of others that they drew upon were limited: either from a minority of occupants making a complaint, or gleaned from informal, infrequent chats with one or two colleagues, as opposed to the consensus of the whole office.

Spatial comparisons were also used to question the validity of the data. For example, Martha asked to view the data from a sensor at her colleague's desk because her colleague had reported similar experiences of discomfort ("*No, I'm curious because Jessica is freezing as well and that's where she sits.*"). Spatial comparisons were also used by occupants to calibrate a reference point from which interpret what they were seeing in the graphs in relation to their own perceptions ("*Well [it'd be good to look at] something at the other side [of the building] because obviously at this side you've got the windows on most of them*" *(Carla)*). Finally, comparisons were used to substantiate cases of discomfort: "*But that's a 3 degree difference between the top end of the room and the bottom there […] I think you should definitely show [FM] that one, to say 'look, this is not normal*'" *(Tim)*.

In trying to make sense of the data for discomfort complaints, comparisons, inspired by subjective experiences and opinions, enabled occupants to create meaningful frames within which to understand it. The objective data was only useful in the context of such subjective reference points. However, it also brought such physical perceptions into question. This represents a point of contention in thinking about the design of tools to manage energy use and comfort, where lower-energy comfort might best be achieved by moving away from objective comfort standards and measurement so that comfort and the energy put towards it are better aligned [11]. Hence, we must think carefully about what platforms for sense making we embed in intervention designs. In the next section, we will relate what follows when subjective and objective measurements do not agree.

Data doesn't always match expectations and perceptions

In some cases, the reading of the graphs introduced an uncomfortable incongruence between what was felt and what was measured (i.e. between the subjective experience and objective measurements of the environment). This brought into question the validity of a data-oriented platform as a tool for negotiating comfort and energy use, particularly between occupants and management. In UoH, participants reacted to this mismatch with phrases like '*ridiculous*', '*a shock*', and '*there's no way.*' This was in spite of their temperatures being some of the highest that we observed in the study (often over 25°C and reaching up to 30°C). In this case, the participants were expecting to see a much larger variation between their office and the office across their hallway—that they were "*massively hot*" in comparison—than the one illustrated in the graphs.

"*we can't understand how it's come up the same […] why it's come up like that into graphs and things […the difference is] not to the extent what we know it is" (Carla).*

In the above example, it seemed that it was the depiction of relative variation between 'discomfort' (i.e. the quantitative measures of the environment they experienced in their own office) and 'comfort' (i.e. the quantitative measures of others' offices that they had experienced as being quite different) that was inconsistent with expectations, rather than the absolute measurements. This is naturally linked to the representation of the data that they were presented with. One of our participants wanted to make sure that any data presented to FM was represented in a way that would best expose variation. After making some comparisons and reaching conclusions about discomfort that he believed were significant, Tim requested that we make the axes of the graphs in question consistent before showing to FM: "*I would say, if you're going to show them that one, could you adjust that so they both go from 21 to 27… so they can actually see the big change in that… that would be good."* Representations of the data that may at first not seem hugely influential can have significant political implications, biasing comfort negotiations in one way or another. For design, this highlights the importance to remain sensitive to how data is represented, and to what ends it might be utilised.

When situations of discomfort could not be explained through the data using, for example, spatial comparisons (i.e. when their expectations of temperature differences between offices were not evident in the data), sometimes participants further interrogated it through direct, physical interactions with the spaces in question ("*But I can tell now–I just went in there–that …you can feel the difference" (Carla))*. In such cases, the participants asked questions of the data by trying to index perceived truisms about the climate with their associated data. In order to be able to read the data, or to evaluate its validity, participants were trying to understand how known relative differences were represented, so that they could apply this understanding to the data as a whole. In the UoH example above, one of the participants left the office where the focus group was taking place and walked across the hallway to feel the difference in temperature:

Susan: (from across the hall) Yeah, it's beautiful! […]

Michelle: Yeah, you can feel it as soon as you walk out of here though, can't you?

Here, we can start so see problematic issues with current mechanisms for building management that might be exacerbated by fully handing over the management of comfort complaints to a pervasive sensing system. Although the reliance on data and objectivity might make for straightforward management procedures, we see that it can provide a limited representation of what is actually being raised from the occupants' perspective. Participants expressed their own concerns in this regard. In BIT, Jack, who reported frequently feeling too warm in his workplace, was surprised to find that the average temperature throughout the study period was 21°C. Given that some of his colleagues had made complaints about the cold, he was concerned that the data could be used to make a decision that would worsen his situation:

"*I would probably say I'd want to burn the information about the temperature because that would imply it's going to get turned up… or at the very least be open to potentially nobbling the numbers.*"

The participants in UoH had similar concerns about how the data might be interpreted by management. In their view, it did not represent the true extent of the discomfort that they all agreed they were feeling. They worried that the data would present an abstracted account of their situation that would make it too easy for management to make an unfair judgment about.

Carla: I was just really surprised at that because we know—even she says it herself, she knows that her office is nowhere near as hot as ours…

Michelle: Because that's kind of making out that we're complaining about it but Susan's in the same heat and she's not complaining about it. You only have to walk between the two and feel the difference!

When data is ineffective, arguments extend beyond it

When the data misrepresented their experiences, participants looked for ways to delegitimise its role in drawing conclusions. For design, this brings attention to some limits on potential roles for pervasive data in building management. In some cases, participants searched for further mismatches between physical experiences and representations of these in the data, which might point to a systematic error in sensor data. Susan in UoH asked to see data associated with an office that she considered to have a comparable climate to the one her uncomfortable colleagues occupied: "*So what about Gerard's office though, because Gerard's office is on the same side as yours. ...Have you got his office on there?"* In both UoH and CU, participants called for the need to feel and physically experience their situation in order to understand it and properly evaluate it. Although the data provided an objective measure of their climate, they stressed that it failed to encapsulate the full extent of their situation: *"But you see an easy result of that is for someone from Estates or the University to come here and work in this office for a week. A day even would probably be enough. No one's ever done that" (Paula).*

In such cases, the data did not represent the reality that occupants were trying to convey, and management (and objective data readings) were too removed from the situation to really understand what it was like to work in such conditions. While participants speculated that management might be able to use it so say "*the data is fine, all the temperatures are fine for that room,*" this would not be considered as a resolution, because statistics do not meaningfully account for the physical effects ("*I don't care what the data says; we know what we feel!*" (Paula)) of uncomfortable climates on work practices, i.e. that reflected the lethargy, discomfort, allergies, etc. of working 8-hour days in it with major constraints on their ability to adapt.

Carla: We can't move because it's the only treble office

Michelle: […] I don't think there's anything that we can do to change it because everything that's suggested, we've tried. You open the windows and your stuff blows all over the place so you can't do that. We're not allowed to keep the door open because of the confidentiality. We use fans and then your paperwork blows everywhere. There just….

Susan: ...you work with your blinds down.

This suggests two factors that are important if data is to add value to conversations between FM and occupants about energy and comfort. First, it should be possible to explore and manipulate data to highlight significant variations, but what these are may not be clear without subjective reference points. And second, analytic tools may be insufficient in making data useful; because there are other important factors that cannot be captured with pervasive sensing, and so data must be used in a way that includes and facilitates input from those occupying and experiencing environments. For design, this suggests that while sensor data is useful, it is limited in isolation. Hence, there are important directions for research in exploring how the subjective and objective can be brought together in useful ways. For example, we see a risk of drawing conclusions based on quantitative data alone, and so we might look to interactive tools to facilitate processes of validation and negotiation before definitive decisions are made.

Data represents a partial, biased view of reality

As we have seen, data does not account for work practices and constraints on adaptation that might be a part of these. But, the graphs that we showed participants were also limited by the length of our data collection period, the types of data we captured, and the summary statistics that we abstracted from it. In this sense, it is a partial view of reality, and participants discovered ways that these shortcomings provided a biased view of the world that could be detrimental or advantageous for them.

Participants sometimes focused on parts of the data rather than the data as a whole. Having looked at data from other parts of the office, Martha, who felt her desk was cooler than others, requested to see temperature distribution data from the sensor closest to her. She looked straight to the bottom end of the distribution and responded with a scream of surprise:

Martha: "See, it's freezing! […] But, that let's you see.

Researcher: Lets you see what?

Martha: Well, it's lower.

Mgt3_BIT: Well, it's 20 to 22. Lower, but still…

Martha: Lower.

In this case, Martha was basing her judgment on her own individual space within the office, but also on a small proportion of the temperature measurements recorded at it

(which were still within a range that standards would consider 'comfortable'). Jack felt that a useful role for a middleperson might be to objectively consolidate the data, providing statistics rather than raw data so that small sections of the data could not be used out of context to exaggerate a case.

"you would probably want someone to be, you know the likes of yourselves, taking an outside view of actually trying to collate the numbers and make them productive rather than say someone with an inherent reason to justify a number, you know, to skew the answers the way they want them, instead of simply giving them the raw data or the complete data or, you know, tidied up the data kind of thing. You know, without any bias to it."

A challenge here is that data is presented or interpreted as the absolute and full picture of the world. In reality, it is a partial view, and so it should be treated as such. Interestingly, management participants were also worried about data being interpreted differently to the way that they must in order to handle complaints—according to standards and policies—and that it might lead to unrealistic expectations. In the next section, we will demonstrate how occupants tried to make sense of data within broader contexts like these, before discussing the implications of this for management in the following one.

Frames of reference for ascribing meaning to data

Participants were generally unconvinced that the conclusions they were able to draw from reading the sensor data would be effective in conversations with management. Some participants looked to building management guidelines or policies for extra leverage, and so it is useful to consider how these might impact negotiations about comfort and energy use, and if they might be leveraged more explicitly in design. For example, in UoH Michelle wondered, "*24-ish, is that considered… acceptable to be working in? Is everybody else working in that kind of…*" Later on, Susan asked, "*So is 26 degrees hot for an office?*" In CU, Paula responded to the graphs by asking, "*I would say that's too hot a temperature to work in. I don't know what the guidelines are, do you?*" Here, participants were trying to interpret the graphs by relating them to what was considered normal or acceptable in their organisation or by the national health services. To make sense of the data was to find justifications for their complaints, and this was important to provide them with some leverage to negotiate an organisational change to improve their situation. These challenges suggest the need for some defined bounds, for absolute thresholds and guidelines, in order to make data useful. The risk with tight definitions, however, is that conversations about comfort necessarily turn to numbers rather than physical perceptions, which, for energy use, can reproduce expectations of energy-intensive comfort provision. In this case, when the researcher explained the guidelines normally used for mechanical heating in the organisation (and emphasised that these do not apply the same during Summer), Susan applied these to quantify comfort on the graphs enabling her to ascribe more meaning to the figures on it. She concluded, "*So you're over 'comfortable' aren't ya?*"

In CU, participants felt empowered having explored the sensor data. Although they initially inquired about policies in order to try and make a valid case for themselves, in the end they found a valuable role for the data in legitimising their case. Their office space contained four HVAC systems that were centrally controlled and they were able to see the setpoint on the thermostat display. And so instead of holding management accountable through policies and guidelines, they sought to bring into question the system and its operation. With the data they were able to show that a) it was not maintaining a uniform temperature, which it was designed and set up to do, and b) that it provided climates at two ends of the office space that were significantly different.

Tim: I think you should definitely show them that one [graph], to say, look, this is not normal; three degree difference in the room.

Paula: I think those three [graphs]… I think they substantiate what we've been saying…

Tim: Yea, if it's 24 at one end, it should be 24 at the other.

Paula: […] it should be stable and it should be across the whole office. That was the whole point as far as my understanding goes.

In contrast, participants in UoH did not have a setpoint to hold to account, which cut short their conversations with management: *"They just agreed with us – yes it was hot! It's over eighty most of the time – that was anyway when we monitored it […] The answer was, 'yes, it's hot'" (Carla).*

These examples illustrate that just having a system in place that has a designed functionality can make it accountable. And, that data can have limited utility unless the reader has a frame within which to interpret it and ask questions of it. And so it is not surprising, given the challenges associated with expressing discomfort that occupants try to make use of whatever frame of reference is available to them. However, as we have previously discussed, data only represents a limited view of reality, and management may not interpret the data in the same way. In the case of CU, management were satisfied that the data did not contain "extreme" temperatures. Without agreement on an appropriate frame of reference, which may be challenging to define, an effective negotiation will be difficult.

Subjective interpretations of data can complicate management processes

Our management participants had some concerns that occupant interactions with data collected in their workspace that showed "bad" or "extreme" temperatures might jeopardise management's position in handling complaints. They talked about how it could be "*dangerous… giving*

people too much data" (BIT), and about the "*need to be careful*" (UoH). This was in part related to how data might be interpreted and understood. Subjective readings of the data could emphasise or exaggerate certain features in it in order to match up with physical perceptions of the indoor climate. Management worried that this could be used as a means to stress a particular individual's case, for example about being too warm or cool.

Mgt1_BIT: ...Martha's looking for the low figures, and that backs up her thinking then […]

Mgt3_BIT: And, they weren't the predominant figures, which I think is what she was expecting…

For management, this would complicate existing processes for handling complaints by providing occupants with misleading leverage that would need to be rebutted, or that could lead to them drawing conclusions or prescribing solutions for their situations that were shortsighted or infeasible. In reality, strategies and solutions require extensive consideration and research, and must fit within policies and procedures: *"Even me, I'm staying stuff that probably can't happen. It needs an engineer to look at it" (Mgt1_CU)*. Existing formal structures (i.e. policies and procedures) provide management with control by allowing them the capacity to provide responses and outcomes that are well-considered and justifiable. Negotiations that fall outside of these could put management in more vulnerable positions or threaten their integrity as a department. Participants were concerned that discussions with occupants around data could put them situations that are more difficult to relate to policies, or where they are pressured to provide responses that are less considered and less conclusive. And so, for Mgt1 in UoH, it was important that any uses of data were part of a process that allowed them to maintain some measures of control in this.

"… they'd [the occupants] want to ask, 'why is it so hot?' We need to have that response ready. And […] what we're going to do about it. […] So I think I'm happy to share [the data] with them and get their views, but it's part of the process rather than the answer to what they hope to see" (Mgt1_UoH).

Policies also provide management with a means to screen complaints by evaluating and challenging their legitimacy. This was necessary because sometimes the complaints reported by occupants were not directly related to physical comfort, but could be an emotional response to a conflict in the workplace or personal issues, or requests might be unreasonable in the context of other potential solutions.

"*…actually it's maybe not as bad as they're telling us […] So, you've got to be careful to filter down the complaints to figure out what is actually the key issue here—is it some kind of HR issue actually? Or, is it actually the temperature?*" *(Mgt2_BIT).*

"Martha knows she's sitting under a vent but she's in that desk because she likes the seat. […] if she was thinking sensibly, she'd just move desk" (Mgt1_BIT).

Interestingly, in cases like this, Mgt1_BIT thought the individual sensor data might be useful to give them some leverage (*"Well there's the room temperature there in black and white.")* to encourage occupants to adapt their practices: "*Don't dress in some skimpy wee blouse you could spit peas through. You're not going for a night out, you're coming for your work. Dress for it."*

Some management concerns were linked to the limitations of the data we discussed previously. Mgt1 in UoH was concerned about the temporality of the data and how short-term data might provide occupants with a skewed picture of the situation that, in the context of policies that they relied on, might exaggerate climate effects and add weight to occupant complaints. The guidelines in question were based on annual statistics that abstracted seasonal differences and so interpretations outside this frame of reference might lead to irrational (from a management perspective) judgments and unrealistic conclusions.

"So, I would want to present the data in such a context because that does enable us to get away with, or handle, high internal temperatures for a short amount of time. That's part of the normal expectation. […]" (Mgt1_UoH).

Part of the reluctance to share data with occupants was the tensions between the time scales that occupants expect discomforts to be addressed, and the time scales that management makes decisions on. And so for management purposes, to prevent complaints from escalating, some factors in decision-making—like the assessment of some situations based on yearlong cycles—are often withheld from discussions with occupants. A worry for management was that data, and questions about the validity of it, might make it difficult to avoid discussions about these.

Mgt2_BIT: Every time we're going to do anything—right, when's the lease date? It's in a year. Why would we spend £11,000 on a new boiler if we're going to move out?

Mgt3_BIT: Whereas people in the office would be like, well I don't care, that's a whole year. […]

Some concerns were specifically about the granularity of the data, and that providing occupants with fine-grained measurements throughout the office space would allow them to compare their particular climate to the climate that other occupants were experiencing. It was felt that this comparison would enable occupants to make a discomfort case based on fairness. However, all the workplaces in our study were shared and so questions about comfort are collective rather than individual. Some management participants were concerned that individual workspace sensor data may not be interpreted in this context where a level of compromise is required and some discomfort, and adaptation to remedy it, is expected.

"I don't really want to send out all the data to all of the staff because I think they'll get hung up over it. I mean I'm fine sending out […] some averages or something like that, but I don't really want to start sending out individual sensor data at this point. I think we need to be careful" (Mgt2_BIT).

Workplace negotiations

As well as learning about management and occupant interactions with data, and their reflections on the processes of reconciling it with comfort complaints and responsibilities, our study also brought to light relevant insights about how comfort is negotiated in the workplace.

Individual and collective comfort: prevalence of conflict

All of the workplaces that we studied were shared offices. However, only in one of these (UoH) were participants in agreement about comfort complaints. In CU and BIT, participants expressed variation in their perceptions and preferences of comfort. This sometimes led to adaptation, like putting a jacket on. But, frequently, it resulted in swings in how the HVAC systems in these spaces were set as individuals made complaints to the facilities manager or adjusted the controls themselves.

Helen: so we're switching [the HVAC] and it's battles between who's switching it on, who's switching it off.

Paula: And as soon as anybody goes near the control, certain people will go, 'What are you doing? What's going on?' You know, because they know that's going to change the temperature for them.

Despite, or in spite of, the conflicts around mechanical system control, participants generally acknowledged that a static programming solution was not possible, and that "*You're not going to please all of the people all of the time" (Martha)*. Jack thought that even if extreme cases of comfort could be mitigated, conflict would switch to minor grievances about it: "*And if you had a middle ground, neither of us would be happy. Because I would still moan it's a wee bit too warm and she'd still moan it's a wee bit too cold.*" However, the importance of consideration to alleviate tensions when manipulating the shared environment was demonstrated by Tim:

Paula: You see it will cause some sort of animosity before long, if this continues, because of people changing the controls because…

Tim: That's why I do it [turn on 'cooling'] for set amount of times, so people know that—I'm quite conscientious about it—so they don't stress…

We should underline that our approach in this work was not a behaviour change intervention, and in providing data to occupants we were looking to explore how this might be useful in supporting them in making sense of their own situations and expressing these to others. However, we found that the data was processed and used in similar ways to how behaviour change interventions often frame resource use. Occupants developed cases for complaints in individual-centric ways, questioning their own situations independent of the shared environments or institution; and they looked to normative comparisons in order to meaningfully describe their own situations.

Participants found it difficult and sometimes impossible to rationalise the data, and comparisons that attempt to establish what could be considered 'normal' were an important step in trying to do this. This resonates with the main reported limitations of eco-feedback [31], and with Schwartz et al. [27] and Dillahunt & Mankoff's [13] findings about the utility of social comparisons in shaping and motivating 'normal' behaviour. But rather than limiting the scope for making change, we see here that occupants were also limited in being able to interpret and articulate their own discomforts in terms of a workplace or institutional complaint, or something beyond their own physical perceptions and expectations. This meant that expectations of comfort moved from physical perceptions and the immediate environment to external factors, and that decisions and management processes often disregarded comfort at large by pandering to the preferences of a small number of occupants, reinforcing notions of the provision of comfort as a service.

Accountability and anonymity

Interesting tensions arose between accountability and anonymity when we spoke to occupants and FM about more active and inclusive roles for occupants in building management. Occupants felt that an open forum for discussing issues could be problematic with fine-grained data because people could be singled-out by their colleagues. They also felt a forum where colleagues are encouraged to directly broach issues could exacerbate conflict with the added "*emotional investment*" involved. As such, there are cases where anonymity would be appreciated. Jack thought that this could be achieved by incorporating a degree of detachment: *"you would either take it to the appropriate people or try and contact the relevant teams as a kind of middleman. You know, so you're not having direct confrontation." (Jack)*. However, there was also a sense that occupants should be responsible, and held accountable for their complaints as a way to avoid illegitimate ones (that are perhaps more personal) getting through. In the case of negotiations among occupants, participants felt that this would be important to preserve fairness. In CU, one participant recounted a situation of dubious validity that provided an occupant with more power over personal comfort:

"One of the girls said to me that she won't touch it [the HVAC control] because she got this nasty email from this other girl who said, 'my line manager has told me that this mustn't be on this setting' […] So she had gone to switch it onto cold for our end [of the office] and then someone from the opposite end said that" (Henrietta).

Likewise, some management participants worried that their management processes would become more challenging and costly if occupants could put forward issues without being held accountable for them: *"I don't think it should be anonymous. I think you've gotta—people have got to be responsible for what they say. I think you lose that if it's anonymous" (Mgt2_BIT).*

This raises interesting questions about the role of occupants in building management and their relationship to management and to other occupants. Management in our studies had a strong desire for objective interpretation and decision-making to avoid bias and misuse and preserve the professionalism in conflict resolution can remain professional.

"They're emotional about it whereas the property and facilities team have to be technical about it" (Mgt3_BIT).

But purely objective data and decisions risk arriving at conclusions and decisions that are inappropriate or ignorant of the subjective experiences of occupants (e.g. office politics and control). We must carefully consider how the presence of data and of digitally mediated participation in management shapes this through design.

DISCUSSION: RESTRUCTURING NEGOTIATIONS

In this section, we draw on our findings to develop insights and implications for design to effectively restructure comfort negotiations through management processes that are mediated by the availability of environmental data.

Positioning data for sustainable practice

Our findings draw attention to two important points for HCI in positioning data for new forms of building management. First, the acknowledgement that comfort in shared spaces is a collective pursuit, and reducing it to an individual's situation (as you might do with fine-grained sensor data and eco-feedback) is likely to increase conflict rather than resolve it. We saw how the granularity of the data enabled occupants to make individual cases about comfort in a shared environment. Second, as a consequence of this, solutions will necessarily entail compromise and, in the absence of formal policies, consideration of others' situations. Shared spaces will always be contested and this was appreciated by participants and acknowledged in negotiations. Hence, a direction for intervention designers might be to support and promote this, rather than designing it out or deemphasising its importance through design (e.g. through tightly specified policies for comfort provision).

Acknowledging these tensions, how might HCI support a move away from individual framings (occupants interpreting in terms of 'my data' or 'my situation') and objective measures (by management in terms of institutional procedures) that reinforce comfort as a product of the environment [10], and open up new forms of localised and inclusive building management based on shared understandings among these different perspectives? As we have outlined, more appropriate interpretations might be in terms of data representing a collective picture, like the Imprint application strives to do for workplace printer use, for example [24]. Challenges for design here relate to how such a framing could mediate negotiations about comfort in such a way that avoid office politics while still enforcing a degree of accountability, which has been shown elsewhere to be a valuable mechanism in reducing energy use [13]. We might look to make tensions more explicit, creating narratives around variation, compromise, adaptive comfort, for example by incorporating elements of comfort voting and collective, subjective measurements. But, we also see how this, by itself, and without institutional context or authority, might be of limited use for considering change. We must acknowledge that reframing is not just a question of HCI design, but involves more broadly thinking about the design of facilities management in organisations. For an approach to comfort that better matches energy use to comfort requirements to be truly on the agenda, we require shifts in standards, procedures and polices for building management.

Negotiating the politics of comfort: towards collaborative facilities management

The presence of the data and the different perspectives on it that unfolded shed light on and sometimes emphasised the tensions that exist in building management, which have a direct impact on comfort and energy use. Research on behaviour change and sustainable HCI has drawn attention to the limitations of, and potential negative effects associated with eco-feedback (e.g. rebound effects [16]), normative feedback (e.g. boomerang effects [1]) and individual framings of behaviour and energy use [8]. Significantly, here, we see that even without presenting the data in the context of changing occupant behaviour, the challenges associated with rationalising it drove occupants to apply such framings to interpretation. This clearly reflected the objective framings that management apply in order to understand and handle comfort complaints. Their interest in the pervasive sensor data was to micro-manage in the sense of 'Resource Man' [32], i.e., investigating how temperature dynamics relate to system functionality, how occupant reports fit in with standards and policies, and exploring ways to automate the management of these spaces. As Goulden and Spence put it, this encourages "a very singular understanding of these buildings and the activities within them" [19]. Although we have outlined a number of challenges associated with the role of data in building management, we suggest that it might have a useful role to play here if it is carefully framed. First, in that it can act as a shared artifact that engages occupants in the management process, as we elaborate on in the next section. And, second, data offers both management and occupants something tangible to reflect on and critique. In this way, it is a means for 'open-ended engagement' rather than a prescription and evaluation of particular behaviours [24]. Its presentation in interactive tools might afford questioning of the data to reach better, shared understandings of work

practices, the environment, and the institutional context of these. However, we would stress that data is valuable but not conclusive, and it is important to recognise these limitations in the design of the management approach and any interactive system that supports it. Rather than normative framings of comfort and energy, we would move towards a collective framing where the legitimacy of and accountability for issues are evaluated on this level, and all of the constraints and compromises ('you can't please everyone') that go along with it are acknowledged. We might look to position the data that better reflects the relationship between the occupants and the institution, where both occupants and management hold responsibilities for comfort and energy use. The FM has an important role as a 'middle actor' [23] in prompting and guiding the rationalisation process, but our findings suggest that knowledge of occupant experiences can provide scope to better match energy use with comfort needs.

Engaging occupants in change

Finally, we want to emphasise the utility of data as a platform for engaging occupants in the building management process. As our findings have shown, inconsistencies between the data and their experiences of the work environment led to frustrations and concerns, and many of them had long since become jaded and disengaged with formal and methodical management processes.

In fact, our original methodology had included plans to undertake participatory design exercises around alternative ways of managing the workplace. These never materialised because following brief introductions at the focus groups, the researchers felt that it would be inappropriate to distract participants with visions for workplaces far off in the future when they just wanted to try to resolve their more immediate uncomfortable predicaments. Initially, in UoH and CU, participants positioned us in a similar role to management (even though we declared our neutrality) and showed frustration when we to tried to better understand their comfort situation instead of addressing their problem. They seemed to consider us inattentive and skeptical of their complaints. However, when we introduced the data and began using it to talk through their situations, they began to engage with the process and according to their own accounts left feeling energised and empowered.

To us, this demonstrated the potential afforded by data-mediated negotiations. This scenario might imply an importance of the neutral middleperson in such negotiations. But in the context of the rest of our findings, we suggest otherwise. Rather, what is required is a more interactive and cooperative relationship between management and occupants to work out how comfort and energy use fits with the experience of everyday work life.

One might consider that our data was flawed in that it was partial and often did not reflect our participants' expectations. However, we argue that there is significant merit in making the incompleteness of data a driver for change. Data in this sense becomes a mechanism for identifying gaps in understanding, and for 'filling in the holes' of organisational policy and individual expectations. In making evident the partial nature of the data, we saw that participants, managers and occupants alike, began to recognise the partiality of their own accounts and policies and began to account for the variations, comprises and adaptation required in the workplace. Thus, in positioning data for comfort and appropriate energy use, and establishing mechanisms for collaborative facilities management, we reiterate a role in the possibility to open up and to collectively engage in questioning data as a foundation for a more sustainable workplace. We conclude that there is value in data-mediation here, but that the shortcomings of this as a resource for intervention design must be acknowledged and embraced. A promising direction for design going forward is to consider how this might be incorporated into a more conversational approach to interventions for the workplace.

CONCLUSION

In this paper, we hypothesised that pervasive sensor data that captures the indoor climate can provide an effective platform to more successfully communicate about comfort and energy use. Through a qualitative study with building managers and occupants, we show that while data does not necessarily resolve tensions—between subjective occupant experiences of comfort and objective measures commonly used by management to cope with comfort variation and legalities—it provides an engaging forum for a more inclusive building management process, and we outline directions for taking a more conversational approach in the design of comfort and energy-use interventions for the workplace. For design, we see this as about facilitating a conversation to reach mutual understanding and action, and this involves design challenges of reconciling occupant and management perceptions—a conversation that will vary across different situations. Beyond workplace management, we see this approach being more broadly applicable (e.g. supporting data-mediated neighborhood politics) and hope it will inspire future research that explores other contexts.

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