Understanding Adaptive Thermal Comfort: New Directions for Ubicomp

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ABSTRACT
In many parts of the world, mechanical heating and cooling is used to regulate indoor climates, with the aim of maintaining a uniform temperature. Achieving this is energy-intensive, since large indoor spaces must be constantly heated or cooled, and the difference to the outdoor temperature is large. This paper starts from the premise that comfort is not delivered to us by the indoor environment, but is instead something that is pursued as a normal part of daily life, through a variety of means. Based on a detailed study of four university students over several months, we explore how Ubicomp technologies can help create a more sustainable reality where people are more active in pursuing and maintaining their thermal comfort, and environments are less tightly controlled and less energy-intensive, and we outline areas for future research in this domain.

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Sustainability; Thermal comfort; Heating; Cooling

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation: Miscellaneous

INTRODUCTION
Heating and cooling of indoor environments is resource-intensive and accounts for a large proportion of energy demand (estimated at 24% in the UK, and 18% in the US). This energy is put to work creating indoor conditions which aim to provide "thermal comfort." This concept has been largely articulated by building engineering research and is framed in terms of the design and operation of building infrastructures, such as air conditioning or central heating [21, 23]. There has been a global trend of convergence and tighter specification of indoor environmental control [4]. Indeed, standards and policies in many countries are predicated on the desirability of a universal room temperature, typically in the range 19–22°C. And yet, it is clearly possible for people to live and work in environments with temperatures outside such standards and subject to more variation: for example, temperatures of 16°C were common in British homes as recently as the 1970's; in Pakistan a large proportion of office workers were able to achieve comfort in the range of 20–30°C [21]; and during Japan's Cool Biz campaign, air conditioners in government-administered buildings were set to 28°C.

With increasing priorities for minimal-energy and free-running buildings, there have been recent proposals to allow indoor conditions to vary more, and to be explicit about the active role that people ("occupants") take in achieving their own comfort, for example through personal adjustments such as clothing, or local adjustments such as windows [2]. This approach is known as the adaptive model of thermal comfort (here, we use *adaptive thermal comfort*), and is of growing interest in Built Environment research [20]. Nicol and Humphreys [21] argue that current standards imply that superior buildings are ones that are more tightly controlled. As an alternative, they suggest that perhaps superior buildings should be those that use the least amount of energy, while promoting conditions in which people are able to make themselves comfortable. Tied into this is a departure from the view that a comfortable environment can and should be provided as a service (comfort-as-product), rather moving to the view that environmental conditions are but one factor in a process of dynamic adaptation where personal comfort is pursued (comfort-as-goal) [19, 21].

In this paper, we explore how existing thermal comfort practices can be reshaped towards this adaptive approach through supporting Ubicomp technology. We first develop a detailed snapshot of thermal comfort in practice through an in-depth formative study of the thermal comfort–related experiences and actions of four students living in on-campus, university accommodation. The study illustrates how indoor conditions can be highly variable and far from universal; that a range of adaptive comfort strategies are employed as part of everyday life; and that there is value in and potential for increasing awareness and reflection on thermal comfort variation and adaptive measures. We use our findings to explore how Nicol and Humphreys' proposed adaptive comfort standard [21] might be brought about with and supported by Ubicomp technology. Our contribution is a comprehensive account of strategies for realising adaptive thermal comfort through Ubicomp technology, and an outline of open research questions in this under-explored but very important area.

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RELATED WORK

Heating and thermal comfort has not to our knowledge been widely studied in the Ubicomp and HCI communities. However, the inefficiencies of domestic heating control and the resulting energy use and waste has been highlighted as a popular site for interventions. Mozer et al.'s neurothermostat aims to replace householders' programming of the thermostat with a predictive model based on sensed occupancy data with the aim of minimising 'misery' (cost associated with wasted energy) while maximising comfort [18]. Here, comfort is defined as achieving a desired setpoint temperature ostensibly set by the householder. In more recent work, Gupta et al. describes a GPS-controlled thermostat that factors in the journey time to home for the occupant and triggers the heating system at an appropriate juncture [12]. Scott et al.'s approach similarly augments the thermostat based on a machine learning algorithm that uses historical traces to predict future home occupancy [22]. Lu et al. augment the home with simple sensors to automatically sense occupancy and sleep patterns, and show how these patterns can be used to optimise the HVAC system in 8 households [16]. While it is true that this work could lead to energy savings given the current context of thermostats and central heating and ventilation systems, it is worth calling into question the fundamental assumption: that the goal is to optimise around a desirable setpoint temperature, and that this is the implicit key to achieving thermal comfort.

Understanding behaviour is essential to unpacking where and how Ubicomp interventions might intercede to help create more sustainable futures. The role of behaviour and its relationship to energy use has been extensively studied in other domains. In a study of variation in energy use of similar families living in physically similar, co-located homes, Sonderegger finds that differences due to occupant behaviour dominate those due to structural variations [25]. Andersen et al. analyse large scale surveys of Danish homes to explain variability by defining standard behaviour patterns using statistical methods to unpick the effects of multiple control mechanisms (window open/closed, heating on/off, lighting on/off and solar shading in/not in use) and its correlation to factors including house ownership, outdoor temperature and stove ownership [1]. In contrast, and more inline with our combined quantitative and qualitative approach, Gram-Hanssen accounts for variation in heating demand of up to three times between identical houses by applying a socio-technical practice-theory based analysis to understand the technologies, habits, knowledge and meanings that make up the variations in practices between the households [11].

Thermal comfort itself has also been widely studied in other domains, where the notion of a uniform setpoint temperature has been called into question. Fountain et al. reviews the limitations of comfort standards and examines how thermal sensation is influenced by culture and climate [8], highlighting the importance not purely of physiology, but also of perception and expectation—and exhorting relaxation of culturally-induced clothing norms and occupant expectations of rigidly controlled environments. In contrast to static assumptions underlying current standards, de Dear and Brager call for an adaptive thermal comfort standard in which air-conditioned buildings are controlled by an adaptive algorithm more closely resembling that of naturally ventilated 'free running' buildings [6]. Nicol and Humphreys go further, highlighting that comfort is not a product provided for building occupants, but rather a goal they achieve [23, 24]. They propose an adaptive approach in which occupants adjust their environment to suit their requirements, and buildings must allow them to achieve comfort goals [21]. They then propose a model based on occupant control and dynamic indoor temperatures, drifting to suit indoor and outdoor conditions. Strengers draws our attention to how peak electricity demand in Australia is shaping and being shaped by what are considered 'normal' expectations of comfort (particularly in regard to air conditioning), and calls for more research to assess the impact of demand-management techniques on escalating comfort expectations [26]. Cole et al. considers how comfort can be re-contextualised to enable a lower carbon society—moving from the automated, uniform and predictable, to a broader dynamic notion, integrative of participatory aspects [5].

In partnership with thermal control, clothing both underwrites our thermal expectations of environments, and provides us with a means of adapting to them. Baker and Standeven use observation to highlight the importance of adaptation of activity (metabolic rate) and clothing in adjusting to local thermal conditions in office environments [3]. Morgan and de Dear study clothing in two indoor settings with a particular focus on the insulation (clo) values. They observe that adaptive comfort standards hold the potential to conserve energy, but to work effectively it is essential that occupants are free to adapt themselves, and more specifically their clothing [17]. Gauthier employs an automated diary based on SenseCam to understand the interactions between householders and their heating systems, and particularly their activity and clothing responses to thermal discomfort [10].

Following on from this work, we aimed to understand how adaptive thermal comfort might be supported by new Ubicomp systems. To do so, we conducted a small, focused but longitudinal study observing a number of students and their perceptions and expectations of, and strategies for achieving, thermal comfort across a seasonal change.

METHODS AND PARTICIPANTS

The study took place between February and June 2012, in a student hall of residence on Lancaster University campus. The four-storey building housed approximately 250 undergraduates, and consisted of conjoining sections, each containing four flats of 3–4 bedrooms sharing a kitchen. The site was specifically selected because of the comparable structural design, heating system, and maintenance regime of the rooms. Each bedroom was single-occupant and had exactly the same basic features: a radiator with a thermostatic radiator valve (TRV), an externally facing window, and an adjoining en-suite bathroom with shower, toilet and sink. All TRVs were functional, but the radiator operation corresponding to the intermediate TRV settings did not always match participants'

	Lent term (up through 22 Mar)		Easter break (23 Mar - 22 Apr)		Summer term (From 23 Apr)	
	Temperature in degrees Celsius: Min-Max (Median)					
	Night	Day	Night	Day	Night	Day
Zoe	22.8 - 27.5 (25.4)	23.7 - 27.7 (25.6)	24.9 - 29.8 (26.5)	24.4 - 31.5 (26.3)	19 - 26.8 (23.9)	20 - 27.5 (24.6)
Nadia	22.3 - 25.4 (23.9)	21.4 - 25 (23.5)	-	-	-	-
Emily	19.1 - 24.6 (23.1)	20.1 - 24.1 (23.1)	22.1 - 24.6 (22.6)	21.6 - 24.6 (22.6)	19.4 - 25.4 (22.6)	18.9 - 25 (22.1)
Jack	17.1 - 22.1 (22.1)	17.1 - 23.1 (21.1)	18.6 - 24.6 (22.1)	19.6 - 26.6 (22.1)	16.6 - 28.1 (21.6)	18.6 - 28.2 (21.6)
Outdoor	2.1 - 11.2 (6.8)	5.7 - 17.2 (11)	-0.1 - 14.7 (6.6)	3.6 - 24.8 (12)	-1.1 - 22.9 (10.8)	4.9 - 30.5 (15.7)

Table 1. Summary of participants and environmental conditions. We show the time intervals for term time and break, separately. Zoe stayed during the Easter break whereas Jack and Emily did not.

expectations. The bathroom had an external vent with a fan that was activated when the bathroom light was on.

Some caution is needed when comparing temperatures since the rooms were not located in identical thermal contexts. Two of the rooms were south-facing (thus potentially more exposed to the sun), and two were north-facing. The rooms were also exposed to different parts of the building infrastructure, such as stairways and kitchen, which might have differentially affected their thermal characteristics.

Recruitment was achieved primarily by email, sent by the college officer responsible for day-to-day management of the accommodation. Posters were put up in the hallways and the researcher engaged passers-by at this time. Four students (three female, one male) volunteered to participate. The small sample size is entirely appropriate to the design where multiple methods are used to build in-depth case studies of comfort for each participant and their room. It is not designed to be representative of the population of student residents, but rather to sample some of the comfort strategies employed here. We use the pseudonyms, Zoe, Nadia, Emily and Jack, to preserve the anonymity of participants.

We did not recruit participants based on any particular proclivity toward energy use or sustainability. As with many institutional and communal living arrangements, the cost of heating was included in the accommodation fee. Therefore, there was no particular financial incentive to conserve energy, although we note that the literature suggests such incentives have limited effects in any case [27]. Similar living arrangements, of privately occupied spaces in shared buildings where energy costs are not directly related to consumption, are common outside student halls of residence, e.g. in some apartment blocks, care homes and military barracks.

Our participants' previous homes were in different parts of England (two in the south and two in the north) and all but Zoe had grown up in these locations. Zoe moved to the UK three years prior, having grown up in a warmer climate, although she reported to us being thoroughly acclimatised to the UK, finding 'home' uncomfortably warm and instead preferring overcast skies and keeping out of direct sunlight.

There were three key parts to the study: (i) up to three interviews before, during and after the study, (ii) deployment of sensors (logging 10-minutely traces of ambient and radiator inlet and outlet temperature, door and window open and close

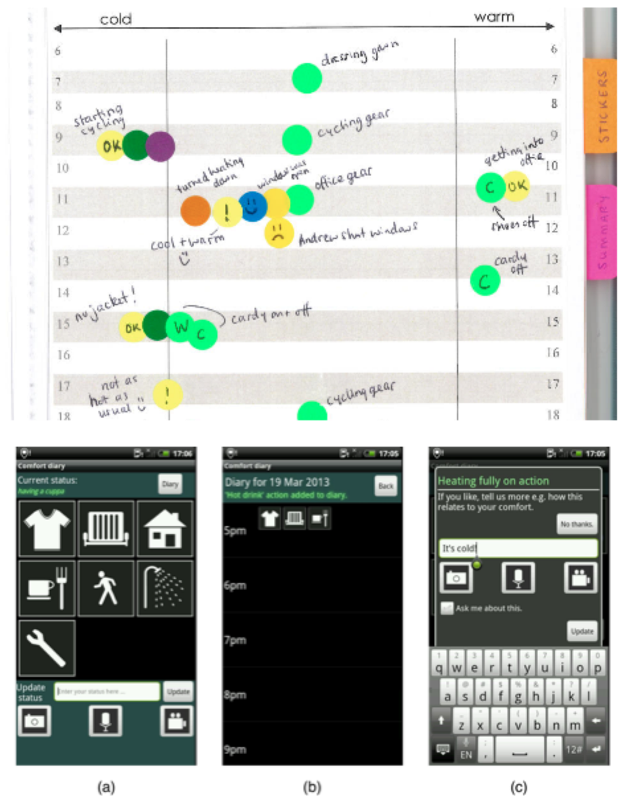

Figure 1. Top: An example log page that was provided with the paper diary. We also encouraged photo and video diary entries, particularly concerning clothing choice. Bottom: Screenshots of the diary app. (a) shows shortcuts for logging comfort related events on the diary timeline (b). Events can be accompanied by textual descriptions, (c) audio and video recordings and photographs.

events, and motion), (iii) a diary task aimed at encouraging reflection on tasks involved in achieving thermal comfort. The precise order and duration of each was agreed with participants at the start of the study. An initial interview focused on life in the flats, and meanings, perceptions and management of comfort. The second, follow-up interviews investigated reactions to seeing plots of individual and other participants' temperature data, and effects of the diary task. Interviews were recorded, transcribed, and iteratively analysed for, and coded according to emerging themes.

For the diary exercise, (both paper-based or smartphone app versions were given) we asked participants to log their thermal comfort activities (focusing on clothing and interaction with environmental infrastructures such as windows and radiator valves) and experiences (i.e. their perceptions). An extract from the paper diary and screenshots of the digital diary are shown in Figure 1. We encouraged participants to use the app-based diary to record photographs and video diary entries, especially targeted at what they had chosen to wear and changes of clothes each day. We included a quick, open questionnaire for each participant to complete in their diaries at the end of each day. We subsequently analysed and coded the diary entries for emergent themes.

Small, digital thermometers were given to all participants after the first interview. We had the opportunity at the end of the study to speak to Zoe, Emily and Jack about their experiences with the thermometer, having lived with it for several weeks. Following further agreement with Zoe, Emily and Jack, the sensor-based data collection continued for a longer period and concluded with a short final interview.

CASE STUDIES OF THERMAL COMFORT

We now introduce each of our participants and their experiences of living, managing and coping with their thermal environment in student residences through a series of short case studies. Note that accounts cover keeping warm and cool in general, and are not specific to a particular time of year, nor necessarily apply across all seasons.

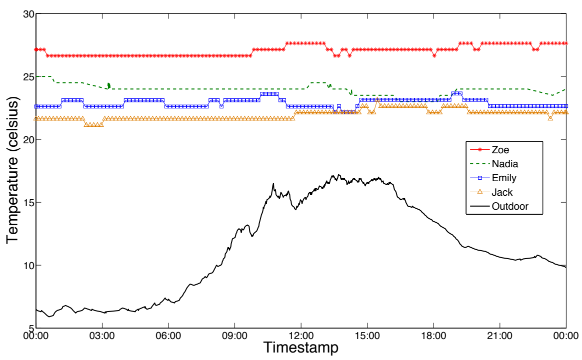

Figure 2. Temperature of each participant's room shown against the outdoor temperature on a spring day, 22nd March 2012.

Zoe

Zoe had the warmest room in our study, as we can see in Figure 2 and Table 1. Zoe left her radiator on, turned up to the maximum setting on the TRV for most of the time we observed. She did not find her room to be uncomfortably warm. As we can see from the figure, Zoe's room maintains a fairly constant temperature both day and night, despite a variation in outdoor temperature of nearly 10°C. Zoe was happy for it to be cold outside, but indoors she wanted warmth: "*If it's cold outside I'm fine with it, I mean its like 'I'm outside so it's fine to be cold' but when I'm in my room I want to be nice and warm.*"

Zoe expressed frustration with a lack of clear control over the radiator. When asked whether she turns it on or off, she explained that "*yeah it is [on]. I just leave it on, all... all day yeah.*" The linkage between the TRV setting and heat output from the radiator was far from clear to her, "*like before I used to use it quite a lot because... because the radiator would go off, I'd be like 'did I turn it off?' and then I tried to check whether it used to be on.*" If she got too hot, she simply opened the window.

Fresh air was important to Zoe. She would freshen up the room by opening the window for a spell every day. Her window was often open overnight with the curtains closed. Zoe told us that there was often noise outside, especially at night and over weekends, which was a drawback for her.

The radiator was also an important alternative to a tumble dryer for drying Zoe's clothes on laundry days: "*I use a dryer sometimes but sometimes I... use the radiator cos... I wouldn't want to waste money on getting the drier. Cos the drier sometimes it doesn't really [work].*"

Zoe found several ways to adapt if she felt cold. It had become something of a habit to drink tea at night. During one cold snap when her radiator didn't appear to be working, she would also relocate to the library, "*I'd prefer going to the library in some corner where there's a heater or something.*" She also mentioned closing curtains, taking warm showers and using a hot water bottle. During really cold days, she would remain in bed, sleeping through the morning. She even told us about a particularly cold time when "*I used to use my laptop because there's this little... bit of heat coming out, I used to try to touch that and get my hands warm.*"

When we spoke to her in the summer, we found she had also started putting water bottles in the freezer to ensure she had a supply of cold drinks to take to lectures, opening her window more and showering to keep cool. Showering was important for staying comfortable, she reported 2–3 showers per day, and during her second interview she remarked, "*now for example at the moment it's too hot for me. I feel like errrrgh, I feel like taking a shower.*"

Zoe liked to be lightly dressed indoors. She often wore her pyjamas if there were no strangers in the communal areas visiting flatmates. She would put a t-shirt under her pyjamas if she felt cold. Zoe planned carefully for what she wore outdoors to ensure she would be comfortable, by peeking outside through the open window in the morning. She dressed for cold evening visits to the library, and left her window open so it would be fresh when she got back at about midnight. A typical outfit for Zoe, according to her photo diary, would be tights, shorts, $3/4$-sleeve top, or more commonly, jeans with a vest under a jumper or a cotton hooded top.

Nadia

Nadia only participated in our study during Lent term (until 22nd March). Her room was the second warmest with a median temperature 23.5°C, despite outdoor median daytime temperatures of only 11°C (a typical day's temperature is shown in Figure 3). Nadia liked her room 'cosy' and the room to be warm when she came in. Occasionally, she would be too cold or warm in her room but said, "*I find it easy just to adjust my temperature if I need to.*"

Nadia would freshen up the room by opening the window. She would open it first thing in the morning for at least fifteen minutes to circulate the air. Nadia would also open the window when she found it too warm, but did not like it—and did not feel she could have the window open—when it was too cold outside.

Nadia found the heating system to be quite unresponsive. The heating came on when she did not want it to, "*it's like it's quite temperamental. I'll turn it on thinking it'll come straight on and it doesn't. Then a few hours later I'll realise 'oh it is actually on'...*" She found her family's fire at home to be far more responsive than radiators.

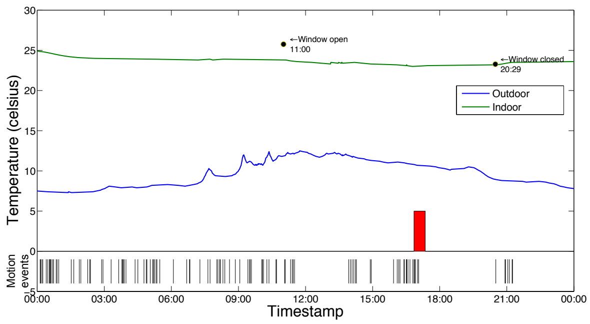

Figure 3. The temperature in Nadia's room on 16th March 2012. Overlaid are the window open/close events, here from 11am to 8.29pm (note that window sensors are binary so open states range from fractionally to fully open), and when motion is detected (the black vertical bars). The red solid bar represents the time when the radiator is on.

Nadia would drink tea and put on a cardigan when she felt the need to warm up. Sometimes "*when I'm feeling a bit cooler*," Nadia would put the radiator on an intermediate setting but "*most of the time it's off*." Nadia would dry her towels on the radiator after showering; she would put it on a low setting and "*assume the radiator comes on at some point*." She described herself as wearing comfortable clothes, normally jeans and a t-shirt but she frequently added or removed her cardigan if she found herself too hot or too cold.

Emily

Emily described herself as uncomfortable when cold and worried about getting ill. For her, heating was very much a delicate balance of radiator TRV adjustment and window control. She made good use of blankets and hot drinks to keep cosy, "*extra throw-overs and yeah... and a nice cup of hot chocolate*." Describing comfort foods she associated with keeping warm, she mentioned "*a lot of custard, erm... even hot water actually and, erm, the odd chocolate bar. It doesn't actually work... but...*"

Emily propped her door open almost every day, both for fresh air and for general convenience. She had also been known to take a walk around campus just to get some fresh air. She opened her window most days, and said she found it really hot if the window had not been open. As she put it, "*yeah, I'm so happy that I have a window that can open wide, compared to others it's restricted so yeah [I use the window a lot]*." Emily frequently adjusted the radiator so that it was not too hot or too cold and expressed some frustration at not being able to work out an appropriate level: "*cos some nights I've woken up with night sweats and the heater wasn't on at full blast. There's not really much of a medium in between... just like sustainable hot so you wouldn't feel ill and like really hot...*"

Emily dressed for outdoors. What she wore varied from day to day, in the same 'kind of style'—typically trousers and a t-shirt under a jumper or cardigan. When indoors, she would change into her 'loungewear', a t-shirt with a tracksuit trousers under a dressing gown. She did not like her clothes to be creased or smell of cooking. She would expect people to wear more layers indoors if the heating wasn't working.

Emily had something of a fascination with touch-screen devices, she would like to replace her room's 'old' radiator with a new one that "*erm, at least [has] a touch-screen so we can monitor the temperature more clearly because it doesn't stay, and clearly outline what the temperature's going to be so I'd love to see that.*" She found the digital diary quite compelling and produced the most detailed account overall.

Jack

Jack's room was the coolest in our study (up to 4°C cooler than Zoe's). Despite this, to Jack it was "*incredibly warm*." For Jack, discomfort resulted from a lack of control over his thermal environment, "*personally I don't [feel I have control] because of the situation with the boiler. I have absolutely no control over that, erm, you know when it goes on, when it goes off, when the room heats up and when it...err... doesn't*." He felt his room should come with a fan.

Jack did not use his radiator. Instead, he developed several inventive strategies for keeping the air cool and fresh involving electric fans: "*the fan is on pretty much all the time. Erm, and the window is usually on the latch all the time again to try and draw air through. And sometimes I put the extractor fan on in the bathroom as well and leave the door open with the idea of hopefully creating some kind of air current to, to cool the place*." His bedtime regime included putting the fan on full for 10 minutes before bed. He would also often leave the fan on when he went out in the hope that the temperature would be lower upon his return.

Jack had a signature clothing style. He always wore jeans, a long-sleeved shirt to cover his arms, under two t-shirts. One of the over-t-shirts could be removed if the weather got particularly warm. He admitted that at first glance his outfit could appear a little absurd indoors, but found it convenient: "*if I were to wear any less going out and about on little wanders, through the day and sometimes the evening, I'd have to get changed before I went out each time to make sure that I didn't freeze on the way.*" His clothing was a practical compromise: "*yeah, I can just about get by in here with the fan and the window and err I'm comfortable outside with that amount of layers*." Jack found it convenient to go outside if he needed to keep cool.

A REFLECTION ON DATA AND COMFORT

In the later interviews, we were able to discuss sensor data gathered in each of our participants' rooms with them. This was their first glimpse of the temperature trends they experienced in relation to the outdoor temperature, and how this varied overnight and from day to day. Also, we presented a table of average, minimum and maximum temperatures across the rooms to them to see what they thought of the temperature in their room in comparison to the others'. In this interview, we were also keen to understand how they used their thermometers, and whether this helped them engage with their heating or simply set unreasonable expectations.

Zoe recognised her room as being warmer than some of her friends' rooms and other locations on campus and was surprised that the temperature in her room did not vary as much as she had thought. She liked knowing the temperature and sometimes used the thermometer to gauge when she should open the window. Zoe discovered 24°C was about right for her, "*right now it's... my type, so I guess whatever temperature it is right now*," but wanted it cooler at night, "*. . . cos I like the fresh sort of feeling. Yeah. No I wouldn't want the same temperature all day no*."

Emily used the thermometer reading to help her gauge when to open the window. She described 24°C during the day as too hot, and 25°C at night as being '*ridiculous*.' She closed the window when she was too cold (at 21°C) and found 22.8°C to be '*about right*.' For Emily, "*forever at 22.7°C was comfortable at any time of the day*."

Jack found the information interesting, but described his perception of anything numerical as "*not good, erm... that goes for temperature and distance and time and weight and everything. [. . .] My brain just doesn't work in that way. Erm... yeah it was interesting*." Whenever he was curious about what the temperature was, he would glance over. "*Erm... but yeah I think it seems to mainly go between...21, 22 and 23 most of time. Although sometimes it's 24*."

Nadia was surprised to find her room was warmer at night than during the day, and suggested "*I don't know maybe it's just cos usually I don't have my, say if I've had my window open all day I don't usually have it open later than like six.*"

Interestingly, the thermometers encouraged participants to check their own perceptions of temperature. Zoe: "*like say supposing it was 22 degrees and I felt cold and some other day it was still 22 degrees but I.. felt warm. So yeah that surprised me.*" Similarly, Jack found knowing the temperature reassuring, "*err I've really enjoyed... having the thing there cos it's made me aware that erm... I suppose there are... large proportions of my perceptions of temperature which must be psychological rather than... err physical... erm in that you know sometimes if it's at 22 I'll be quite comfortable then, I can just go to sleep very easily.*"

All except Nadia (who participated for the shortest time) were presented with a table comparing their room's temperature with the others in the study. They were amused by the data, and it prompted a number of reactions. Jack remarked, "*it's interesting to see the temperature in relation to others, like particularly [the room that averaged 26°C] . . . err *laughs* . . . I thought I had a warm room but. . .* " Participants used others' data to interpret their own. Jack reacted with "*erm... or at least I've got the second highest temperature. I'm not making it up all completely.*" Emily responded a tad guiltily, "*Other rooms are cooler than mine *laughs**," and Zoe just giggled when it was pointed out that her room was the warmest in the study. Zoe reasoned that perhaps this is "*. . . because I'm from [a warm country] or something.*"

The diary task helped participants reflect on their own behaviour around achieving comfort, especially their clothing. Emily now considered what clothes she wore more carefully, "*I didn't quite realise that the temperature would affect what I'm wearing. [. . .] Yeah, I definitely put a lot more thought into what I wear*." Zoe seemed more aware of how she heated her room. She made more of an effort to switch off the heating when she did not need it, "*before I think I used to keep the heating on more often, now I think I... make a conscious effort to switch it off whenever I don't need it*."

UBICOMP AND THERMAL COMFORT

In this section, we use our case study findings and draw upon Nicol and Humphreys' adaptive approach to thermal comfort [21] to outline strategies for realising adaptive thermal comfort in domestic settings, and the implications for Ubicomp research that emerge (see Table 2). Briefly, Nicol and Humphreys advocate that new-build office buildings allow their occupants to actively avoid discomfort, rather than provide tightly defined thermal environments. Buildings *should* provide an environment where adaptation is possible, within a range of customary temperatures that vary across spaces and rooms, as a familiar environment is easier to adapt to. Customary temperatures should be *drifted* according to indoor and outdoor conditions, and to reduce energy consumption, subject to guidelines intended to avoid discomfort.

Facilitate Local, Short-Term Adjustment

Moving away from an environment-centric approach, a key understanding is that comfort is highly localised in space (thermal comfort is related to the condition of and/or perceptions about one's own body) and time (bodily conditions and perceptions can change quickly due to a variety of factors). Accordingly, designers should consider the wide range of local adjustments that are possible in everyday life against variable ambient (or customary) temperatures, and ensure that energy-reliant adjustments, such as putting on a heater or air-conditioner, tend to be relative and short-lived.

Unsurprisingly, participants in our study reported using an array of mechanisms that helped them manage their thermal comfort. This included the radiator but extended far beyond it: to windows, curtains, fans, blankets, clothing, hot and cold drinks, hot showers, and hot water bottles. These were often folded into well-reasoned, routinised strategies for thermal comfort. And in fact, they were employed in part to deal with the dynamic nature of bodily comfort. However, other factors, unrelated to thermal comfort, sometimes restricted or promoted the application of certain mechanisms e.g. for reasons related to appearance Jack preferred to keep his arms covered, even when it was warm.

Environments at times proved difficult to adjust and this resulted in periods of discomfort. For example, all of our partic-

	Strategy Suggestion	Evidence from our study	Open research issues
Interaction design	Create sense of control while moving away from comfort-as-product perspectives	Zoe, Emily, and Jack each described frustration due to lack of control of the radiator or room climate	How to maintain 'sense of control' following mechanical HVAC control restrictions required for drifting and local adjustment; How to promote local control without reinforcing expectations that the environment is solely responsible (comfort-as-product)
	New HVAC interfaces	Zoe was frustrated with her radiator controls; Emily would like hers to visualise how it would affect the indoor climate	How to support relative adaptations (warmer/cooler) while drifting towards the outdoor ambient; Positive feedback for genuinely lower impact behaviour (incl. beyond HVAC e.g. "layering" clothing)
Sensing & algorithms	Predictions of discomfort through diary/annotation and environmental sensing	Thermal comfort was very context-dependent for our participants. All participants recalled experiencing discomfort arriving back to a room that was too hot	What factors determine thermal comfort; how can they be sensed and mined; how can sensor data be used to support the adaptive thermal comfort approach (e.g. for mediating interaction with HVAC)?
	Drifting algorithms	Participants maintained quite different indoor climates and exhibited different tolerances to warmth and coolth	Boosting & drifting parameters; Drift rate (e.g. based on Nichol and Humphreys' recommendations) while respecting seasonality, individual differences, day-to-day weather, activities, timetables and the slow changes in clothing over time
Social interaction	Talking to building managers	Emily & Zoe described frustrations with inability to communicate with building managers	How to realise systems that encourage 2-way information flow between occupants and building managers, promoting adaptive thermal comfort and respecting privacy
	Comparison with peers	Jack, Emily & Zoe found other participants' data amusing and used it to interpret their own	A potentially powerful tool, but how to avoid upwards re-evaluation where low heating users increase their use towards the norm?
	Thermal comfort portals; Working together	Nadia, Zoe & Jack conferred with others on thermal experiences; Participants illustrated diverse strategies for thermal comfort	How to facilitate and encourage sharing of thermal comfort strategies and learning from others; how to integrate control, feedback, discussion and communication, and support (e.g.) alternative ways to keep warm and cool, into an effective tool
Engagement & accessibility	Support variation within and between individual lifestyles	Participants expressed different preferences; showed different levels of engagement; and thermal comfort was context-dependent	How to support differing practices, thermal comfort preferences, and levels of engagement; day-to-day timetable differences and spontaneity; how to minimise burden transitioning from expectations of automatic/invisible control to more active approach
	Comfort diary apps	Diary helped Zoe & Emily reflect on behaviour	How to design apps that are sticky, while supporting reflection and understanding
Reflection & understanding	Expand ways we think about clothing	Diary led Emily & Jack to reconsider clothing choice	How to generate reflection on clothing and its role in thermal comfort
	Non-absolute measures of temperature	Participants effected local adjustment prior to being given the digital thermometer	How can we encourage refection on temperature variation, its partial role in thermal comfort, while avoiding reliance on setpoints?
	Historical graphs & visualisations across the day and in other spaces	Zoe, Jack and Emily found the thermometer helpful to understand their perceptions of temperatures varied	What are effective presentations of sensor data for understanding the complexities of thermal comfort, leading to better management of it?; how to realise drifting when other frequently visited places remain static (sharp temperature differences become noticeable)

Table 2. Possible foci of Ubicomp interventions and associated open research challenges.

ipants recalled the irritation of sleeping in, or arriving back to a room that felt much too hot. To help compensate, Jack began leaving his fan on when going out, so that "*when I come back it's not a furnace that I'm walking into*." TRV controls are designed to deliver a setpoint temperature rather than respond to the dynamic and subjective nature of thermal comfort. Their operation was not well understood and radiators were not trusted to deliver heat when desired. In particular, Zoe preferred to leave the setting alone (turned up high) and manage times when she did feel warm by opening the window. A one-off adjustment to the radiator can persist even through periods of discomfort.

Acknowledging the adaptive model of thermal comfort and the experiences of participants in this study, Ubicomp research might fundamentally re-think the interfaces for the energy-reliant thermal comfort technologies. As well as providing a variable ambient temperature (see next section), the radiator or space heater might also incorporate a jog dial, which allows adjustment *relative* to the current temperature ("warmer" or "cooler"). And rather than being indefinite, such adjustment might by default be short-term (e.g. one hour), with the understanding that other methods such as hot water bottles or clothing would be applied at the same time. Researchers might also consider how passive methods (such as window ventilation) can be automatically tracked, and used to modulate mechanical heating, cooling and ventilation. This would avoid occurrences of windows being opened to cool a room, with the radiator left on. Designers should also consider new solutions to aid in making energy-reliant heating and cooling more localised and person-centric [15], such as personal hand and foot warmers [14].

As noted in Table 2, heating or cooling technology designed for local adjustment engenders a different *sense of control*, and research is required to explore how to support this transition in design. First, how can we avoid introducing a sense of *lack of* control while bringing energy-reliant thermal comfort, which has almost become a background service, back into the ongoing negotiation of thermal comfort? Naturally, technology designed for local adjustment requires a different mental model for use to setpoint systems. If the same technology also provides an ambient temperature, how is this dual functionality to be achieved in practice and conveyed in design? Research is required to investigate how new technologies and their interfaces can communicate these functions. Finally, local adjustment entails a more active role in thermal comfort, and an interesting avenue to support this transition is in designing to accentuate the sensuousness of *achieving* thermal comfort and of contrasting thermal environments [13].

Automatically Drift and Smooth

Local and short-term adaptation goes hand in hand with the idea that we should move away from energy-intensive, tight indoor temperature control. This is based on the rationale that people have the wherewithal to achieve thermal comfort goals using alternative means; and that perceived comfortable temperatures are largely variable for and between individuals, as is reflected by the variation in the temperatures of our participants' rooms (Table 1) and in their accounts.

Allowing the indoor environment to drift towards outside temperatures is naturally less energy-intensive. As an initial proposal, Nicol and Humphreys suggest variation of not more than 1°C throughout a given day, and a change in the running mean of no more than ±2–3°C every few days. But this is an open area for exploration; particularly crucial is the transition between seasons, when people tend to be slow to adapt their clothing. During the study, it was clear that external conditions were highly variable during this period of seasonal transition; and this affected participants' pursuit of comfort indoors. In this case, sudden drops in temperature resulted in radiators being turned on and left on. For Emily, the radiator was turned on following the coldest outside temperatures recorded in the study, and was left on for subsequent days when the outside temperatures actually rose to be higher than they had been in previous weeks. This apparent sensitivity to change rather than to absolute temperatures could be mediated, and energy-consuming responses be mitigated, if heating systems were able to smooth over sudden changes in indoor temperature. By investing some energy to make change less perceptible, we could avoid discomfort and associated responses involving heating systems which, unchecked as they are, probably consume more energy.

More effective heating system designs would 1) drift the indoor temperature to respond to local climate and seasonal changes that influence thermal comfort, and to shift the expectations that current systems have developed; and 2) reduce energy demand through looser ambient temperature control, within a range that allows occupants to take adaptive measures, like local adjustment or layering clothes, if uncomfortable. The guidelines presented by Nicol and Humphreys for acceptable temperature variation and drift rates provide a starting point, but further research is required to test these in practice. Related to this are the events in everyday life that could be used to trigger drifting: which events are suitable (e.g. seasonal changes, user activity, occupancy), how can they be sensed from physical and virtual environments, and how can they be adapted for different users and contexts, are all questions that Ubicomp can begin to address.

Enable Awareness of Variations

A crucial step in enabling the environment to drift towards outside temperatures in less energy-intensive ways, while retaining local adjustments to stay comfortable, is engaging people as "active occupants." Ubicomp interventions could aid recognition that (1) they already experience and deal with a range of temperatures as part of everyday life (as we've seen in our study); and (2) their perception of thermal comfort is not solely dictated by ambient temperature.

Our study showed that even a simple, off-the-shelf thermometer can be effective in developing a better understanding of thermal comfort. Participants engaged with, and even enjoyed having the thermometers that we provided as part of the study, which as far was we know, remained in their bedrooms. Insofar as we could observe, the presence of the thermometer did not lead to significant change in our participants' thermal comfort strategies. However, they kept an eye on them to the extent that they were able to describe how the temperature typically varies over time, and for Zoe and Jack, it helped them piece together why they might be feeling a certain way. Importantly, participants observed that quantitative temperature did not always match up with their own perceptions in ways that they would have expected: Zoe suggested that the temperature difference was somehow related to her physical state in such cases ("*maybe ... what I feel is sort of related to my body*").

The critical thinking instigated by simple thermometers suggests that a promising direction for future Ubicomp research is to explore how interactive technologies can expand upon and improve this awareness. Historical graphs of temperatures experienced (like those we discussed with participants in the final interview) exposed variation even more; visualisation of historical data might be done on a smartphone, perhaps tied into a digital comfort diary. People move throughout a variety of spaces in everyday life. Temporal and spatial variation might be exposed by making sensor data from public or work places more available, or might be captured with a small wearable sensor (say attached to a book-bag or jacket). With a better awareness of the range of temperatures encountered across indoor spaces and outdoors, the dynamic nature of thermal comfort, and the influence of factors beyond ambient temperature could be better understood.

While we observed that measures of temperature aided in raising awareness of variation and recognition that thermal experience is not strictly tied to the environment itself, we would caution that a heavily quantitative focus could hinder a person's transition to adaptive thermal comfort. Quantitative measures carry with them the baggage of increasingly tight indoor temperature ranges traditionally specified as acceptable or normal, and people may latch on to specific temperatures (Emily decided that her favourite was 22.7°C).

Essentially, quantitative measurements can reinforce the expectation that the environment itself should be warmer or cooler to make people comfortable, stifling efforts to adapt to it in other ways. Thus, an open issue for interaction designers might be to promote awareness, without reinforcing expectations of tight environmental regulation. Solutions might involve using measures not explicitly tied to temperature but are nonetheless familiar (such as numbers 1–5, common on European radiator valves), or use a measure whose reference drifts slowly (allowing day-to-day comparison), e.g. the difference between the current indoor temperature and a longer-term running mean of the outdoor temperature.

Support reflection on the diverse mechanisms for thermal comfort

Moving from a comfort-as-product perspective requires negotiating warming and cooling approaches that do not rely solely on mechanical systems. Digital technologies that facilitate reflection on the ways in which thermal comfort is achieved, and the alternatives to mechanical heating that are available, can serve to ease this transition and highlight effective strategies.

Reflective technologies like the diary app used in the study could be useful, more routinely, to help people make links between their thermal experiences, activities, movement and the comfort strategies that are more and less successful. This is especially so if we are to transition away from static-set-point environments and increase the prevalence of low-energy strategies in thermal comfort negotiations. An important area for Ubicomp research to address is how these technologies can be more comfortably integrated into everyday life. Context-aware technologies for reflection (e.g. in another domain [9]) could respond to interactions with the heating infrastructure (e.g. TRVs or thermostats) and predictions of discomfort through physical sensing (e.g. large variations in daily and longer-term temperatures, and large differences between indoor and outdoor temperatures). They then might prompt users to reflect on and log the factors influencing their comfort, and offer advice on alternative approaches that might be more effective. Such advice could be predefined by experts or could come from other people's documented experiences, gathered and shared by digital communities.

A *thermal comfort portal* could mediate the user's interaction with mechanical heating and cooling systems, offering useful information and services. As well as suggesting alternative ways of keeping warm and cool, and perhaps offering a means of acquiring these, it could also provide feedback on temperatures or energy consumption. Comparison of such data amongst peers may elicit curiosity, discussion and reflection. The provision of feedback on positive behaviour is also a potentially powerful tool. However, automatic sensing of alternative thermal comfort mechanisms is not always as straightforward as temperature sensing (e.g. use of blankets and drinks) and so another important research avenue for Ubicomp is in the physical sensing of these.

Not all participants engaged with the thermometer and comfort diary to the same extent. While these devices were intended more as probes than interventions in our study, we were drawn to these differences in engagement. In translating research to design, not just in thermal comfort but also in other domains that can benefit from digital interventions, Ubicomp research must also address questions of initial and sustained engagement, recognising differences between individual users, especially outside of a research context.

Facilitate thermal comfort discourse

Finally, we would like to emphasise that while thermal comfort inheres in the relation between individual bodies, activities, clothing, places and climates, it is also defined and experienced in relation to others. It is thus simultaneously a wider and ongoing social negotiation. In this study, all participants reported some form of communication about thermal comfort-related issues, whether it was agreement about thermal experiences, a joint problem-solving approach to cooling the kitchen down, or communications (actual and imagined) with the building managers. We can also point to contentions about environmental conditions in shared spaces (e.g. "thermostat wars"). So interactive system designers will need to support effective communication among co-occupants (active in their pursuit and maintenance of thermal comfort) and those who have authority over resources such as property managers and bill-payers.

Ubicomp researchers can offer insight into the design of digital tools (e.g. a *thermal comfort portal* leveraging social networking or microblogging) to support thermal comfort discourse, and to tie these in with raising awareness of variation and reflections on strategies. But especially as we begin to transition from tightly-controlled environments to more adaptive thermal comfort, clear communication and ongoing renegotiation of expectations will need to be supported. This is so that people can work together to achieve comfort in environments exhibiting variation, and to ensure realistic and just treatment of occupants [7] as resources put towards environmental conditioning are reduced.

CONCLUSIONS

The human factors and social considerations abound in effecting such a fundamental shift for climate-controlled societies. Technology and interaction designers have a crucial role to play in moving towards significantly lower-energy, adaptive comfort standards: we should improve the way infrastructural systems are controlled (both automatically and by user interface); we should promote improvements in the active pursuit of thermal comfort; and for those people already accustomed to highly regulated environments, we should work to ease the transition to adaptive thermal comfort. In doing these things, we can take a part in broader debates about how new comfort strategies should be adopted and come to be perceived as "normal" ways of being.

It is important to note that the study presented here is an explorative one that draws data from a particular demographic and living situation, and so should be treated as such. Further research is required to explore the appropriateness and completeness of the adaptive thermal comfort strategies that we outline here for demographics and environments beyond able-bodied, twenty-something-year-old's living in shared flats. While we expect the general principles to be widely applicable, we expect that the content and functional requirements of supporting technologies will vary.

Fundamentally, adaptive thermal comfort is about reducing our dependence on energy-reliant heating and cooling, and each of the strategies outlined in the previous section reflect this. They are designed to minimise the difference between indoor and outdoor temperatures, localise thermal comfort, and reconfigure practices so that low-energy mechanisms play a bigger part. A quantification of the actual energy reductions requires further research, and will certainly be context-dependent, but in envisioning that we could shift the temperatures that we saw in our participants' rooms closer to the 16°C that was common in British homes in the 1970's, and even lower in low-occupancy rooms, the potential reductions are undoubtedly significant.

Ubicomp is ideally situated to impact this area: the strategies that emerged from our study rely on HCI, physical sensing, context-awareness and information presentation. For example, for drifting to be successful, it should account for location-awareness, user activity, outdoor temperature, and so on; eliciting reflection relies on context-sensitive prompting and appropriate information presentation. The strategies and research questions that have emerged from our study provide an important basis for the Ubicomp community to bring about less energy-intensive indoor thermal environments that support the comfort goals of occupants.

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