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Catch My Drift? Achieving Comfort More Sustainably in Conventionally Heated Buildings

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ABSTRACT

Tightly regulating indoor building temperatures using mechanical heating and cooling contributes significantly to worldwide greenhouse gas emissions. One promising approach for reducing the energy demand associated with indoor climate control is the adaptive model for thermal comfort. In this paper, we explore the challenges and opportunities for supporting the transition toward adaptive thermal comfort in conventionally heated buildings. We replaced the heating control system for eight university undergraduates living on campus for fifty days from January–March 2013. We report on the participants' experiences of living with and adapting to the change in conditions. We reflect on the lessons arising from our intervention for researchers and practitioners seeking to design for sustainability and thermal comfort.

Author Keywords

Thermal comfort; sustainability

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION

In industrialised societies, there is a common expectation that buildings provide an acceptably comfortable indoor climate. For the most part, this has been implemented using tight mechanical control of the temperature indoors. This control of the indoor environment is energy intensive, accounting for a large proportion of the energy demand of the home (estimated at 24% in the UK, and 18% in the US). Central heating of the home is hardly new, with examples dating back to the hypocausts in Roman villas. But in the UK at least, central heating proliferated in the twentieth century, as a modern convenience. Prior to this, UK homes relied on radiant sources of heat (fires), and other ways of staying warm, including bedspreads, hot water bottles, additional indoor clothing, and

often plenty of blankets. Central heating (and indeed cooling) has since co-developed with how we use the space in our homes [6] and helped establish new norms and expectations around what it means to be comfortable indoors [2].

Researchers have challenged this assumption that personal thermal comfort can only arise from a tightly temperature-controlled indoor environment, such as the uniform set-point temperature defined by building standards BS EN ISO 7730 [8] and ASHRAE 55-92 [1]. Rather, thermal comfort has been observed worldwide at a wide range of indoor temperatures [7]. In fact, heated or cooled air is just one of the factors influencing how we perceive our comfort. Equally important are personal physiology, how active we are, what we are wearing, as well as a range of other influences and expectations arising from our local culture and climate [4]. Thermal comfort is then *a personal experience, highly localised in time and space*—and not simply met by the provision of a static, standardised indoor temperature ('comfort-as-product').

More significantly, as we consider reduction of energy demand and carbon emissions, maintaining such tightly controlled environmental conditions indoors is intensive and increasingly unsustainable [2]. Moving toward more sustainable passive and free-running buildings, where natural (non-mechanical) heating and cooling is designed into the form and fabric of the building (e.g. shaded areas and strategic placing of windows to maximise solar-gain on cold days), maintaining these tightly controlled temperatures is not possible, as acknowledged by newer standards with looser temperature specifications for such buildings.

This paper is concerned specifically with this *adaptive model of thermal comfort*, in which indoor temperature control is relaxed, and building occupants reasonably achieve thermal comfort using other means (e.g. blankets, hot drinks, clothing layers, and adjustment of indoor shading and ventilation). They thus work actively in harmony with their indoor environment ('comfort-as-goal') [14, 15]. In essence, thermal comfort becomes more localised, and hence more closely related to the dynamics of inhabitant activity and physiology. By reducing the burden on the infrastructural provision of tight climate control, and reshaping norms and expectations around how comfort should be achieved indoors, comfort is also achieved more sustainably (using less energy).

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Yet adaptive thermal comfort is a very different model, and implies significant change for inhabitants whose practices have been shaped by conventionally heated buildings. We believe that HCI lends itself well to a reconsideration of the attempted provision of static temperatures in existing buildings, moving toward a more adaptive approach. Interactions with mechanically-provided heat might be redesigned to support a transition to this adaptive model. Importantly, this debate moves sustainable HCI research beyond the reported limitations of eco-feedback approaches within existing space heating control and its assumptions; and begins to ask how we can transition everyday domestic practices which have come to be supported and implicated by over-standardised control of indoor environments [19].

In this paper, we report on a study of an adaptive thermal comfort probe designed to further our understanding of people's transition towards this more dynamic view of comfort. Our probe replaces the conventional heating controls with a new non-temperature based user interface that embodies two core principles identified from prior work [3]. First, to lower reliance on the static provision of heat, we *drift the running mean temperature* over time toward a target 'driftpoint' that is related to outdoor temperature. Second, to encourage active participation in the achievement of thermal comfort, we provide *local, short-term adjustment*, where inhabitants can make it warmer, but only for a limited period of time unless they interact further. This local, short-term adjustment opportunity is meant to supplement other common adaptive measures such as adjusting one's clothing.

We observed the effects of our intervention on the achievement of thermal comfort *in situ* over a period of about fifty days in eight single-occupant, student rooms. We compare actions, experiences and meanings to those we observed with the participants during a prior observation (baseline) period. We contribute a detailed understanding of the transitions experienced by our participants toward incorporating more thermal adaptivity in their everyday practice. We explore to what extent adaptivity and engagement have emerged as a result of the deployment; and highlight the opportunities and challenges arising from our study. Our intervention shows the potential for computer-supported adaptive thermal comfort in the existing building stock, the majority of which is equipped with conventional thermostat-controlled HVAC systems.

RELATED WORK

The challenges faced by household occupants in controlling their heating and cooling systems are well known [11]. Programmable thermostats are complicated and difficult to understand, leading to inefficient schedules and wasted energy. Replacing the thermostat with a 'smarter' alternative that avoids the need for programming, has long been a goal. Typically, "smart" thermostats build a model of household occupancy and use this to achieve a setpoint temperature when the building is predicted to be occupied [9, 10, 16]. A lower 'setback' temperature is used when the house is assumed to be empty. Various techniques have been proposed as input to the occupancy model, including use of occupancy sensors [10]; tags carried by the occupant [16]; the location of the user (and

their journey time to home) [5, 9]. In all of this work, optimal heating is defined as that most closely delivering a fixed setpoint temperature when the building is inhabited.

These systems are effective in showing, first, that end-user programming of the thermostat can be avoided, but also secondly, that some efficiency savings are possible through not heating the home when it is unoccupied. While this can lead to energy savings, it can also require more energy, as the heating system can be on at setpoint for longer periods by more accurately matching heating to presence or the "demands" of occupants [9, 16]. By working with a setpoint, these systems serve specifically to reify 'comfort-as-product': the maintenance of certain temperatures when homes are occupied. By definition, they aim to disengage the participant from active monitoring and involvement with their thermal environment. Our goal is precisely the opposite.

Recent commercial developments (e.g. the NEST learning thermostat) similarly use algorithms to 'learn' the setpoint temperatures and preferred heating schedule, and uses integrated motion sensing to trigger the setback temperature. However, the users' motivation for adjusting the temperature is difficult for the system to gauge, leading to over-complex schedules and not necessarily energy savings [20].

We are influenced by Nicol and Humphries' later *adaptive thermal comfort* proposals [14], in which buildings facilitate the achievement of comfort by occupants, but the occupants themselves are centrally implicated in adapting themselves, e.g. their clothing [12], and their environment in the pursuit of thermal comfort in dynamic indoor climates. This is important as there is a strong link between thermal comfort supported practices and energy demand [18]. And so, in contrast with an approach that seeks to reduce energy demand automatically, or through eco-feedback—convincingly argued as limited by a failure to account for the realities of everyday life [19]—we advocate an adaptive thermal comfort approach suggesting a reconfiguration of thermal comfort supported practices of which everyday life is composed.

SYSTEM DESIGN

Our probe was designed to replace the existing heating system interface with a new form of access in accordance with the comfort-as-goal approach. Our requirements were, 1) to allow the indoor temperature to vary more with environmental conditions and occupant practice i.e. to avoid endowing the system with the ability to maintain a fixed setpoint temperature; 2) to facilitate local and temporary adaptation of the indoor temperature by the occupant; and, 3) to avoid discomfort to the occupant resulting from large temperature changes over a short period of time. Nicol and Humphries suggest such discomfort might be avoided by decreasing the running mean temperature by no more than 1°C throughout the day; and by not more than 3°C over a week [14].

We developed a web-based user interface that communicates with a wirelessly-controlled, motorised radiator valve through a small custom transmitter (connected via USB to a small quiet networked PC installed in the home). The new motor replaces the manually-set thermostatic radiator valve

(TRV), and enables us to control the valve from 0 (closed) to 255 (fully open). By default our new control system opens and closes the radiator valve whenever the temperature falls outside $\pm 0.8^{\circ}\text{C}$ of a dynamic ‘driftpoint’ temperature. Initially, the driftpoint is set to a temperature close to temperatures observed in the home prior to installation. Thereafter, the driftpoint is reduced in small decrements of -0.2°C each day. The driftpoint is decreased every day unless it has not been reached during the preceding day, or until the indoor temperature reaches the 16°C recommended minimum by WHO (World Health Organisation). The driftpoint was manually set, remotely, by one of our research team.

The system’s UI consists of five buttons (Figure 1). The ‘Make it warmer’ button ‘boosts’ the indoor temperature by temporarily raising the driftpoint by 3°C for 90 minutes (the radiator valve opens). Repeated clicks of this button restart the 90-minute timer. In contrast, ‘Make it cooler’ lowers the driftpoint for 90 minutes (the radiator valve closes). Note that heating cannot be scheduled in advance—it is always accessible, but only for a fixed duration, and setpoint temperatures cannot be specified. The ‘Auto’ button returns the system to its default state of maintaining the driftpoint. ‘AutoLow’ turns the system off, for example if participants are going to bed, or leaving the room for an extended period (AutoLow can be set from 1 to 7 hours in duration). We do not display the current room temperature on the interface.

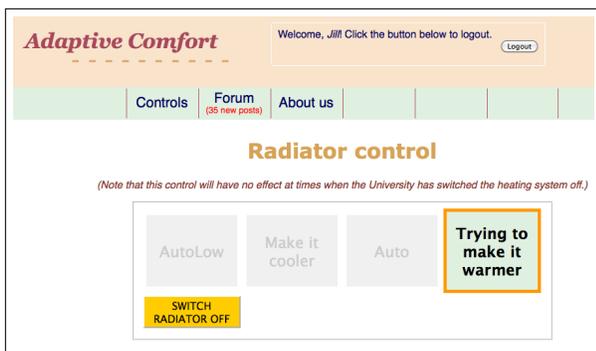


Figure 1. Web interface for radiator control. The ‘Make it warmer’ button has been pressed to switch the radiator on.

To scaffold the transition to a more adaptive thermal comfort approach as best as we could, we linked the UI to a discussion forum where participants could share their experiences, ask us questions, and report potential problems.

METHOD

Following ethics-board approval, we recruited eight participants for the study, four female and four male. All were University students living in on-campus accommodation. We recruited our participants using a range of methods including email and Facebook via college residence officers, posters, flyers, and via already-recruited participants.

The study took place between 22 November 2012 and 23 March 2013, and consisted of a baseline observation phase (Phase 1) of around 18 days, followed by an intervention phase (Phase 2) of about 50 days (see Table 1). We intentionally chose winter for our study, when outside temperatures are

Pseudonym	Phase 1 (days)	Phase 2 (days)
Chloe	23	46
Kate	23	51
Nathan	23	52
Jill	22	50
Stephanie	16	50
James	17	49
Darren	12	50
Luke	10	52
Mean	18	50

Table 1. Participants and durations of the study phases (in days).

comparatively low (-4.5 – 16.2°C , median: 5.5°C), and central heating demand is at its greatest. Note that throughout this paper, we use pseudonyms to refer to our participants.

Participants resided across four flats in the hall of residence. They each had an independent study bedroom with en-suite shower room. Their bedrooms adjoined a common corridor with a shared kitchen. Some noteworthy living arrangements are: James shared a flat with Stephanie (i.e. their bedrooms adjoined the same corridor); Chloe, Kate and Nathan shared a flat; Darren shared a flat with Luke; and Jill did not share with any other participants.

During Phase 1, each participant could change their room’s temperature using a single radiator fitted with a ‘thermostatic radiator valve’ (or TRV), and by opening and closing the window and the door to the common corridor. The TRV could be closed (no heat), or set from 1 to 5 stars (where 5 is the highest setting). Whenever the room temperature falls below a threshold related to the TRV setting, the valve begins to open and the radiator starts to warm.

We established a baseline of temperature and thermal comfort related practices, using a mix of sensor data and follow-up interviews. We instrumented each participant’s room and the shared corridors with temperature data loggers: 8 Dallas Semiconductor DS1921G-F5 ‘Thermochron’ iButtons were placed in each bedroom: one two meters from the floor, one by the bed (a half-metre from the floor), one in the shower room, one at the window, one on the bathroom tap, and two on the pipes to and from the radiator (allowing us to establish when the radiator was providing heat to the room). The iButtons were set to sample the temperature in 0.5°C increments at ten-minute intervals. Oregon Scientific THGN132N temperature/humidity sensors, a motion sensor and reed switches on the doors and windows allowed us to capture richer context of how the room was used and adjusted by participants. The Oregon temperature sensor also provided the real-time temperature readings that we used to regulate the control algorithm in ‘Auto’ mode during Phase 2.

In Phase 2 we observed participants’ experiences of living with our probe, and its effect on their thermal comfort perceptions and practices. After deploying the probe we explained to our participants the functionality of each of the interface buttons, and told them that ‘Auto’ was designed to be more responsive to environmental conditions (e.g. the weather), while still allowing them to be comfortable. We did not ex-

plicitly mention energy conservation or the adaptive thermal comfort goals of the study. We deliberately did not suggest how we expected them to use the system or adapt their ways of getting comfortable, as we wanted to remain open to how the system would be perceived and appropriated by participants. We logged all the interactions with the web-based UI.

We also used the quantitative temperature data during a round of interviews at the end of Phase 2 to discuss the impact of our intervention and help us unpack any changes arising from it. Interviews in Phase 1, the middle of Phase 2, and the end of Phase 2 typically lasted between 1 and 2 hours and were audio recorded for later transcription. For this paper, two researchers independently developed thematic codes from interview transcripts. The codes were reviewed, merged and the data recoded using an enhanced set with NVivo. In reporting the resulting themes, we also use the quantitative temperature and sensor event data to help us put the testimony of our participants into context.

The confines of a conventional, institutionally-controlled HVAC system necessarily bring with them certain constraints. The University retained overriding control of the boilers heating participants' flats. Except for on a few very cold nights, the boilers were automatically turned off between midnight and 6am. This was consistent across both Phase 1 and 2. In Phase 2, this meant that if participants clicked 'Make it warmer' late at night, their radiator would remain cold.

FINDINGS

In discussing our findings, we first provide some reflections on the general usage of the system and the impact on the environment experienced by our participants. We then move on to discuss how our system was adopted (or not); broadly reporting on three main participant approaches that emerged using illustrative case studies that are also used to contextualise some implications for design in the next section.

During Phase 2 our system certainly had an impact on reducing the heat input into participants' rooms. While we were unable to directly monitor the energy input into each radiator, the length of time the radiator was on reduced in all our participants' rooms. Consequently, their room temperatures varied more with environmental conditions such as outside temperature and the heat bleeding from adjacent rooms, as Table 2 illustrates. Overall, we saw a small reduction in median room temperature in all but Nathan's room, and a slight increase in the range of temperatures (median +0.5°C) experienced. The decrease in heat input from the radiator suggests a potential for energy savings of 19.2%–76.4% (mean reduction 42.2%). This *excludes* the interval where heating is not available overnight (during both study phases).

Our system did sometimes lead to temperature changes greater than those recommended to avoid discomfort [14]. Kate, Jill, James and Stephanie all reported at least some temporary discomfort due to significant variations in temperature. Jill and Chloe both felt the rise in temperature after clicking 'Make it warmer' was too steep, and all three experienced discomfort when the temperature dropped following periods

of heating. Chloe may have clicked 'Make it warmer' more if the temperature variation was lessened: "*even though it's just going back to like the same sort of level... it feels colder than if... than, you know if you hadn't pressed 'Make it warmer'.*" Some periods of the day were more problematic than others. For many, getting up in the morning was particularly uncomfortable because the radiator had not been on. It is worth noting that mornings were sometimes problematic (too warm or cold) before our system was installed during Phase 1 too, and this was linked to the heating usually being switched off overnight by the University, and the fact that participants were getting out of their warm bed.

All of our participants changed their use of the radiators, and sometimes windows and doors, as a result of the probe. Five of the participants opened their windows for more than five minutes on average each day in Phase 1. Of these, however, this time reduced to 20–60% in phase 2. All participants recounted wearing extra layers of clothing indoors. A variety of other mechanisms of keeping warm were observed: from the use of a hot water bottle (Stephanie, Nathan) and going to bed (Chloe); to preheating clothes on the radiator (James), and leaving the room while it heated up (Stephanie, James). The number of mechanisms employed varied across participants. The participants who showed the most diversity were Stephanie (e.g. jumpers, blankets, remote preheating) and Jill (e.g. remote preheating, scarf, onesie¹, dressing gown). Kate and Chloe, on the other hand, usually just wore jumpers more often.

Three broad approaches emerged from our data that reflect the different ways that the system was integrated in participants' lives, how it shaped everyday practice, and the perceptions, meanings and expectations around thermal comfort that underwrote the process. We will describe each in detail in the rest of this section and then follow on to explore what they might imply for the design of adaptive thermal comfort. Table 2 suggests a primary approach for each participant, but it is important to note that not all participants neatly matched one single approach.

Comfort in control

Some participants, including Jill, Darren, Chloe and Kate, exhibited an approach to thermal comfort that might be described as *reactive*, where they responded to unfavourable conditions rather than pre-empting them. Chloe and Kate are distinctive in that, unlike the others, they never expressed a desire to be able to schedule heat provision in advance. They were happy for comfort to be unplanned and not routinised, a spontaneous pursuit. In fact, their approach was already a comfort-as-goal one.

In Phase 1, this approach led them to frequently adjust the setting on their TRV, which was always on to some degree. With the exception of Darren, all participants described their radiators, as being "*pretty much on all the time*" in Phase 1 (9–20 hours from Table 2). Chloe and Kate expected their radiators

¹For those unfamiliar with this term, the *Oxford English Dictionary* defines a onesie as "a loose-fitting one-piece leisure garment for adults, covering the torso and legs".

	Phase 1 (Michaelmas Term: up to 14 Dec)						Phase 2 (Lent term: 11 Jan-22 Mar)						
	Average daily temp. in Degrees Celsius: Median (Range)			Window Avg. daily open time (minutes)	Typical Indoor Clothing	Radiator (% of day on)	Average daily temp. in Degrees Celsius: Median (Range)			Window Avg. daily open time (minutes)	Clothing changes	Radiator (% of day on)	Avg. daily (Total) 'Make it warmer' clicks
	Midnight - Dawn	Dawn - Dusk	Dusk - Midnight				Midnight - Dawn	Dawn - Dusk	Dusk - Midnight				
Chloe (C)	21.8 (1.93)	22.4 (1.38)	23.1 (0.88)	0	Jeans, t-shirt	51.0	20.9 (1.60)	20.9 (1.47)	21.6 (0.94)	0	Extra hoodie	12.0	0.6 (29)
Kate (C)	22.5 (1.04)	22.9 (0.92)	23.4 (0.73)	5	Jeans, t-shirt, long-sleeved top	36.9	21.9 (1.10)	22.4 (2.33)	23 (1.52)	0	Hoodie more often	19.5	2.1 (108)
	21.3 (1.44)	21.9 (1.19)	22.5 (0.97)	295	Trousers, jumper	47.8	21.3 (1.34)	21.9 (1.33)	22.4 (0.72)	123	Jumper more often	14.3	1.3 (69)
Jill (R)	22.9 (0.88)	23.2 (0.85)	23.4 (0.9)	27	Leggings/jeans, thick socks, warm slippers, t-shirt; sometimes thermal top/jumper	51.1	22.7 (1.21)	23.1 (2.20)	23.4 (1.65)	8	Added onesie and dressing gown (morning); scarf	30.1	3.5 (173)
	21.5 (0.75)	21.6 (0.76)	22 (0.74)	120	t-shirt; jumper on cold days	79.5	20.8 (1.22)	20.6 (1.43)	21.1 (1.20)	53	Wears "big jumpers" more	60.2	5.2 (260)
James (A)	21.9 (0.74)	22 (0.98)	21.9 (0.96)	655	Shorts, t-shirt; pyjamas (at night)	84.3	20.9 (0.77)	20.9 (1.21)	21.2 (0.91)	410	Mostly same; warm clothes while room heats	62.8	5.1 (248)
	20.9 (0.14)	20.6 (0.09)	21.3 (0.1)	0	Jeans, thermal top, thermal trousers, hoody	12.5	19.4 (0.60)	19.7 (1.49)	19.7 (0.73)	90	Cotton t-shirt, no shoes; slippers (night); sometimes fleece	7.2	0.6 (29)
Luke (A)	21.5 (0.41)	21.6 (0.41)	22.2 (0.27)	40	Jeans, t-shirt; Shorts, t-shirt (after 3pm); no shoes, no socks	40.2	20.1 (0.60)	20.1 (0.72)	20.4 (0.53)	8	Added trousers, shoes, socks; sometimes hoodie	32.5	1.4 (70)
	Outdoor			Min: -3.8, Max: 12, Median: 4.5							Min: -4.5, Max: 16.2, Median: 5.5		

Table 2. Summary of thermal environment and participant adaptations in Phases 1 and 2 of the study. We also suggest each participant's primary approach to thermal comfort during the study: (C) Comfort in control, (A) Automatic comfort, and (R) Thermally reflective.

to be on most of the time because of the time of year: “*obviously it is winter so... you'd expect it*” (Kate). They reported more frequent adjustments to the heat setting than the others, but this level of interaction was not considered ideal (“*with the old system, I couldn't quite find the temperature... that, I was comfortable at*” (Kate)). They would have preferred an indoor climate that was more “*consistent*” (Chloe) and required less adjustment i.e. did not get uncomfortably warm or cool.

This reactive approach continued into Phase 2 and influenced the way that these participants used the new heating system. They clicked ‘Make it warmer’ in response to feeling cold, e.g. for Chloe, “*if I was, you know, significantly colder than I wanted it to be then I'd... press 'Make it warmer.'*” For Chloe and Kate, their level of interaction with the heating system reduced from Phase 1 to Phase 2. Chloe clicked ‘Make it warmer’ 0.6 times/day on average, compared to Stephanie and James who clicked it more than 5 times/day. Importantly, they demonstrated the successful incorporation of other thermal comfort mechanisms into their overall strategy for keeping warm: they began to regularly wear multiple clothing layers indoors and radiator-use reduced to a supporting, and often secondary role.

It became clear, however, that while these participants would have preferred to have had to control the heating less before our system was installed, they actually felt being in control of it was more important for their thermal comfort. Kate and Chloe became satisfied that an extra layer could serve as an alternative to turning the radiator on in Phase 2. But, it was important to them that “*I know the option is there so it's like... if I do get cold I will, just go press 'Make it warmer.'*” (Chloe). Likewise, they considered some discomfort to be tolerable as long as the room was in the process of heating up.

The lower levels of interaction with the heating that we observed for these participants are in part due to the new web interface being more cumbersome to access, and this sometimes led to adaptation using alternative methods that perhaps

would not have occurred otherwise. Kate recounts how “*at night... it will be a bit cold, and then I can't be bothered to turn my laptop on... to turn the temperature up... 'cause it doesn't make me too uncomfortable.*” Likewise for Chloe, “*a lot of the time I just don't feel like it's worth it.*” Kate and Chloe's responses may have been different if a more accessible means of turning the radiator on was available. Interestingly, Chloe discovered in Phase 2 that an unheated room was not as uncomfortable as she had initially expected.

Overall, the system was more suited to, and accepted by, the participants that used it in a reactive manner in combination with other thermal comfort mechanisms. By the end of the study, Kate, Nathan and Darren felt that their thermal comfort had improved, and Chloe and Jill liked that they had to think less about turning off the radiator and experiencing less uncomfortably hot situations. Three of the participants appreciated the more consistent climate that they felt the intervention produced. For Kate and Chloe, who gave thermal comfort little forethought in Phase 1, the impact of the new system on their practices was minimal. They were accustomed to a flexible approach to thermal comfort, and as long as they perceived themselves to be in control of the indoor temperature, the extra effort in doing so locally using the UI had little negative effect.

Automatic comfort

In sharp contrast to the reactive approach of e.g. Chloe and Kate—Luke, Stephanie and James approached thermal comfort proactively, taking action to avoid encountering unfavourable (i.e. low) temperatures in the future. In Phase 1, they set their TRV's to a high setting and rarely, if at all, adjusted them. They regularly used the window to regulate the indoor temperature and usually wore light clothes indoors.

In Phase 2, Luke, Stephanie and James used the system to keep the radiator on *as continuously as possible* rather than using it to get warm if they were feeling cold, which quickly became laborious for them: “*I have to keep going back on*

and clicking it ... whereas before I could just crank it up and leave it" (Luke). These participants maintained a strong reliance on the infrastructure for heat—they were generally interacting with the system *more* than the other participants e.g. Stephanie and James both averaged over five 'Make it warmer' clicks per day. They were less personally adaptive to changing thermal conditions: James continued to wear his shorts and a t-shirt indoors.

Luke, Stephanie and James felt that their comfort was more *at risk* with the new heating system, and that work was required to avoid becoming uncomfortably cold. James and Luke would click 'Make it warmer' whenever they became aware that the radiator was not emitting heat. For Luke, this was a process of 'filling the room up with heat': "I just kept clicking it so like... to keep building up the heat, you know, in it." For James, it was "Just to keep the temperature ... [so as] not to become chilly." These participants used state changes on the UI and the sound of the motorised radiator valve closing as triggers to turn the radiator back on again. Luke considered periods where the radiator was off as missed opportunities to get heat: "obviously it's not as hot as it should be, because I'm missing out on periods when I'm like... not here, or when I've... forgot or didn't notice," and James saw this as "losing part of the heating that is provided."

The intervention clearly challenged participants' preconceptions of where infrastructural heating could be relied upon: for Stephanie, she sometimes wanted to "come home and sort of... be warm and sort of, be like in a cosy home," which was no longer possible. Preheating the room before waking up was something all participants noted—James responded by keeping his laptop by his bed so he could turn the radiator on ten minutes before getting up and preheat his clothes on the radiator. Chloe, Nathan, Jill and Stephanie sometimes wanted their rooms to be 'warmer than warm enough', and this was usually associated with being cosy when the weather was bad, or if they were feeling tired or unwell.

For Luke, Stephanie and James, the probe led to discomfort, and frustration with integrating the system into their everyday lives. For example, James left his radiator on most of the time so that he could leave his window open to ventilate his room while he was out and still come back to a warm room. The new system made such arrangements, which were very important to him, difficult or impossible to achieve. Similarly, Stephanie wanted to avoid the possibility of arriving to a room that had not had any heat input that day: she used to leave her radiator on low for the purpose of unplanned visits "because it kept the room at a slightly warmer than 'just nothing' temperature." This was no longer possible in Phase 2, and like Luke, she reported a desire to be able to arrange "quite a nice temperature to come back to" after participating in outdoor sports.

Expectations of heat provision were tied to expectations of what is appropriate to wear indoors. Stephanie, James and Luke generally wore less indoors than the other participants in Phase 2, and used extra layers of clothes as a coping mechanism, but only temporarily until the room was at a higher temperature. Stephanie expresses her disagreeable, cooler

thermal environment as one of "having to wear jumpers all the time," and James associates leaving a jumper on for the evening with exceptional circumstances. Extra layers, beyond shorts (James) and t-shirts (all three), were for 'undesired periods' of transition between a cold and a warm room.

Nathan and Stephanie believe the lack of an obligation to pay heating bills was also a factor in their heating use. Stephanie felt that "you do abuse it a little bit [...] I'm paying for everything so why not whack the heating on." For Chloe, Stephanie and James, the geographical location also played a part: "you know at this campus... you know, as opposed to down South or something, It can get very cold, very snowy, very icy" (Chloe). and Luke thinks he "take[s] a long time to warm back up [when cold]." James suggests that he heats his room more than others because he is accustomed to higher temperatures in his home country, and Stephanie thinks that her room "can't seem to cope... can't retain... heat so well."

Luke, Stephanie and James all reported frustration with the extra effort that they had to go to in order to emulate the always-on conditions that they had previously been accustomed to. James felt it was "time-wasting" and Luke did not want to be "micro-managing" his heating. However, their level of interaction seemed unaffected by the effort required: it was a nuisance, but a necessary one. Stephanie and James also accessed the system remotely using smart phones (Stephanie), laptops (James, Stephanie), and public computers (James) from elsewhere. Nevertheless, thermal comfort had become difficult and tedious for Luke, Stephanie and James, and they were biding their time until the study ended.

Thermally reflective

Darren, Jill and Nathan's thermal comfort practices fit somewhere between a reactive and a proactive approach. While being responsive to local thermal conditions, they also give quite a lot of consideration to their future thermal comfort. This included not only thinking about when they might need a heated room later in the day, but also times when the heating could be off because it was not needed.

Interestingly, this group of participants showed the most variation in terms of average room temperature and extent of radiator use: Darren's room was the coolest at 20.4°C, and Jill's the warmest 23.5°C. Darren didn't use his radiator much in Phase 1. Instead, he wore more warmer clothing indoors than the other participants, including a thermal top and, less frequently, thermal trousers. He was accustomed to wearing these during outdoor activities like hiking and camping, and his previous room was a cool attic. Jill sometimes also wore a thermal top indoors but this was combined with much higher radiator use than Darren, as Table 2 illustrates. Jill reckons she "feel[s] the cold quite a lot quite naturally," and needs warm clothing and a room temperature that is "higher than average."

Nathan's radiator and clothing use was somewhere between Darren and Jill's. But, all three turned their radiators on and off according to their occupancy and/or their thermal comfort. Adjusting the radiator, and their expectations of appropriate indoor clothing were tied to notions of energy conservation.

Jill remarks, *“I don’t see the point in having it on if I’m not here.”* Nathan has reservations about opening the window to cool a room while the radiator is on. And, he thinks *“like even in winter, even if you’ve got the radiator on . . . it shouldn’t be on that much that you can walk around in a t-shirt really.”*

This variation remained in Phase 2. Darren, Nathan and Jill clicked ‘Make it warmer’ 0.6, 1.3 and 3.5 times/day on average, respectively. Jill and Nathan adapted to less radiator use in various ways. For example, Nathan opened the window for less time each day, and Jill began wearing a onesie after getting out of bed to an unheated room in the morning. The system seemed to have little negative effect on the thermal comfort of these participants, although Jill and Nathan did talk about getting used to the extra interaction effort involved. Jill sometimes found adapting more difficult in the evening. She posted in the forum about working late and forgetting to click ‘Make it warmer’ before the boiler was turned off: *“finding it a tad frustrating when it goes off a few hours before the University turns the heating off.”*

When reflecting about the system functionality, all participants except Kate wanted to be able to prepare their room’s climate in advance. Jill, Darren and Stephanie, already frequently used remote access in order to prepare for their return, e.g. on cold days Darren would turn the radiator on at the end of his lectures so it would be warming up ten minutes later when he arrived at the flat. Jill often turned the radiator on remotely an hour before leaving the library, and felt that it would be more convenient to be able to program this earlier in the day before leaving her flat. Darren and Nathan, both felt that if they knew it was going to be cold because of the outdoor temperature, they should be able to direct the system’s operation to avoid this *“if I’m [. . .] out for the day and I know it will be cold when I get back, um it would be nice to have it make it warmer for when I get back”* (Darren). Luke and Darren would also have liked to be able to program the system around their University timetable.

By the end of the study, Nathan and Darren felt that their thermal comfort had improved. Jill, Darren, and Nathan all expected that their use of the radiator would change as a result of taking part in the study: they would leave it switched off more, or put it on a lower setting when feeling cold to avoid getting too hot later on. Darren enjoyed many aspects of the system, and remarked when we uninstalled it, that *“I’d quite like to keep it in”*. It seems these participants were already more organised and better equipped for thermal comfort management and continued to be so—making the transition to a system requiring more engagement with mechanical heating control more satisfactory as a result.

DISCUSSION

While the notion of adaptive thermal comfort, in practice, is not a new one—all of our participants already used an array of mechanisms to get warmer or cooler before our study began—the idea of a mechanical heating system designed to embrace this approach to thermal comfort was significantly different to what they were used to. As we have seen, perceptions of the system were mixed and, unsurprisingly, some participants found it difficult to incorporate this approach

into their everyday lives. Importantly, however, all of them adapted, and their thermal comfort practices necessarily transitioned to account for this more local and short-lived mode of access to mechanical heat.

From an energy-use perspective, we saw that indoor temperatures dropped and fluctuated more. However, considerable potential for lower-energy adaptation still remained: we found no statistically significant correlation between the indoor and outdoor temperature, and generally indoor temperatures remained a few degrees higher than the WHO minimum guideline of 16°C (Table 2). Indeed, shortly after the study began, our drifting baseline no longer factored in temperature regulation. This was partly due to insulation and heat from adjacent rooms, but also from the heating potential that the intervention enabled and the levels of interaction with it. We effectively changed the bounds on mechanical heat access, and our participants reconfigured their thermal comfort practices to fit within these bounds. It is interesting then to consider how practices were mediated by this technology and why in some cases the intervention led to anxiety and frustration. The participant approaches outlined in the previous section offer some insight.

Although the participants having the ‘automatic comfort’ approach altered their practice to some extent, they maintained the highest reliance on mechanical heat. This reliance was necessary to support both their preferred ‘house clothes’ and their existing practices: James, Luke, and Stephanie all wore light clothes in their rooms; James ventilated his room throughout the day; and Stephanie valued a what she experienced as a “cosy” indoor climate. Rather than reworking such expectations and meanings, these participants negotiated the intervention so that it became compatible, even if it was frustrating to use. The access to mechanical heat that the intervention provided, allowed (if only just) these existing heat-reliant elements to persist.

The other participants appropriated the system differently. For the ‘comfort in control’ participants, their lack of organised or routinised comfort enabled the intervention to fit more easily into their lives, resulting in little disruption of their everyday practice. The ‘thermally reflective’ participants were arguably better equipped to take on this mode of heat access: they all had experience of indoor environments that relied less on energy for heat, and Jill and Darren brought experience of the use of thermal clothing from other environments and practices (e.g. Darren’s outdoor activities).

As Shove et al. discuss, materials (in this case the heating system), are but one element in the make-up of social practice: equally important elements are meanings and competence [17]. So while we introduced a common new material (the intervention) to all our participants, different meanings (e.g. *“it’s not okay to be cold”*), materials (e.g. onesies, smartphones), norms (e.g. “cosy” lounging, ventilation), and competences (e.g. when to use thermals) shaped how thermal comfort in everyday life was ultimately done. In the next section, we explore what our findings and these broader issues imply for the design of future systems supporting adaptive thermal comfort.

IMPLICATIONS FOR DESIGN

In interpreting our participant experiences, perceptions and suggestions, we must recognise that these are bound up in existing norms and expectations relating to indoor space heating—including their prior expectations relating to clothing use indoors, hot drinks and other ways of creating thermal comfort. In trying to maintain these expectations with the new system, some participants found the increased interaction with the system time-consuming and burdensome. Yet for others, participants reported improvements to their comfort—one even requested to keep the system installed.

To design for adaptive thermal comfort, particularly in existing buildings, is to a large degree to attempt to change the expectations and norms around indoor heating—a significant challenge for HCI! Interestingly, Chloe and Stephanie had arrived at University expecting the accommodation to be poorly heated—and quickly found that this was not the case. So, perhaps there are significant times of transition in life (such as leaving home to live at university) that provide ready opportunity for shifts in expectation.

In considering our implications for design, we would caution the designer to recognise that the three participant approaches we call out are convenient simplifications. We would not recommend tailoring designs to assume that each inhabitant will neatly match one of these approaches, all of the time.

Developing thermal comfort competence and experience

A key element in our participants ability to cope with the new system seems to be their competence and breadth of experience with adapting to thermal extremes. Our findings point to a few opportunities where enhancing the probe could better support our participants' adaptive thermal comfort practices.

Experience and reflection

The more engaged of the study participants were also the ones who seemed to be more 'thermally experienced.' For example, they were already used to adapting their clothes to the weather (e.g. Jill and Darren wore thermals). They also seemed to have had more experience of how their indoor environment changed with different amounts of heat input from the radiator (e.g. Chloe experienced what no heat input was like in Phase 2 by simply not interacting with the intervention). This had the effect of alleviating fears of getting cold, fears which Stephanie and James reported, led them to laboriously try to keep the room temperature up. Stephanie's and James's norms and competencies had perhaps not been challenged as much, through their experience.

There is an opportunity to enhance this thermal exploration and experience in the design of new HVAC control systems. Researchers should explore ways to encourage inhabitants to try different mechanisms for achieving comfort faster and to reflect on the experience of using them. By explicitly directing inhabitants towards using and appreciating different ways to keep warm or cool, they might become more accepted as solutions to discomfort. Hand-in-hand with this, researchers should also explore ways to prompt users to explore different indoor thermal environments so that they, like Chloe, can quell fears that the temperature would drop to an extreme

level. One approach to this *thermal exploration* might be to frame it as a playful game, setting challenges (e.g. 'don't turn the radiator on for X hours'), and rewarding with achievements for reflecting on the resulting environment and sharing experiences with friends. These new indoor climates could also be framed as a range of potentially delightful thermal experiences, rather than as undesirable extremes.

Alternative mechanisms and planning

The engagement of the 'thermally reflective' participants suggests that they might respond favourably to contextual prompts or gamification exploring new experiences in and approaches to adaptive thermal comfort. This group also expressed a desire for scheduling functionality in the system: if they knew in advance that they wanted their rooms to be heated, they should be able to program the system to provide this, e.g. if they were on the bus home on a particularly cold day. Although thermostat programming affords a non-adaptive approach to space heating, there is scope for design to explore how thermal comfort scheduling functionality might be provided in an adaptive spirit. For example, the scheduling might focus on thermal comfort more broadly, encouraging inhabitants to reflect on how they might adapt to future environments in ways that include, but are not exclusive to mechanical heating. And such systems could prompt users when forecasted conditions change, so that they can adapt planned strategies.

Transitioning to adaptive thermal comfort

Those strongly reliant on 'automatic comfort', with desires of convenience, 'cosiness', and 'instant' comfort, were hampered by the new technology. Participants wanted to avoid arriving to a room that they experienced as thermally inadequate. They wanted to be able to preheat their rooms, and experience warmth when getting out of bed in the morning. Generally, these participants wanted little interaction with the system, and for these interactions to be less cumbersome. It is particularly challenging to consider whether these wishes for constant heat and minimal interaction can or even should be balanced by the system; raising uncomfortable yet fundamental questions about entitlement to constant, relatively high indoor temperatures.

Interface, operation, and accessibility

We explored but one approach to controlling indoor space heating. It is worth considering the wider design space, particularly where the appropriation of the system was at odds with adaptive thermal comfort. For some, use of local, short-term adjustment evolved into a routine action—the 'Make it warmer' button being clicked out of habit, rather than being a reflective, deliberate change applied concurrently with other adaptive measures. The question arises as to whether a better design would be one *without* the potential for manual adjustment. Rather, we could entrust all radiator control to Auto mode and drifting. This would have the effect of smoothing the sharp temperature rises and drops some participants experienced, as well as ensuring that room temperatures drop uniformly throughout the week according to our design. Such a system would suit some of our participants, and it would go a way towards increasing the daily temperature consistency that

was appreciated. But accounts suggest that the lack of overt control would lead to frustration [13] and a sense of control was certainly important to our participants. Another approach might be to drift the parameters of ‘Make it warmer’ (e.g. its maximum temperature or timeout period) alongside the drift-point. Rather than climbing in relation to room temperature, it could climb in relation to the driftpoint, allowing a ‘boost’ but effectively capping the maximum available temperature.

The technology probe also made creating a cosy room more challenging. It is not clear how our intervention could be adapted to support such notions of ‘cosy,’ without moving significantly back toward reliance on mechanical warmth, e.g. by adding an overriding *on indefinitely* button or allowing for special ‘periods of cosiness’. But perhaps efforts should be directed towards encouraging other, more sustainable strategies for thermal cosiness. For example, Stephanie would close her curtains in the evening to ‘contain’ the heat. Or, for sedentary work (such as being seated at a laptop), might a hot drink in conjunction with a low-energy heated chair cushion be experienced as cosy?

It was clear that for some participants, a more accessible ‘Make it warmer’ button would simply have led to more interactions and thus more reliance on mechanical heat. In fact, a number of participants held high expectations of accessibility and heating efficiency of the probe precisely because it was a ‘new technology’, and domestic technologies have a long history of being couched in terms of improved efficiency and convenience. Moving towards adaptive thermal comfort, then, raises interesting questions about these qualities. Designers *should* consider ways to bring radiator heat to the users’ fingertips *but*, at the same time steer inhabitants away from non-adaptive interactions such as routine reliance on mechanical heating to the exclusion of other adaptive measures. An important design goal is to engage inhabitants in this new approach of dynamic adaptivity, rather than accommodating existing expectations of indoor heating.

Communicating intended use

We purposely did not provide participants with an explanation of how the system worked or was intended to be used in order to avoid introducing any prejudices. This is because we were interested in barriers to adoption of adaptive thermal comfort in a traditionally heated building. Certainly, we had envisioned how our system should be used: essentially, that the inhabitant considers an interaction with the room’s heating system, as a supplement to faster adjustments to their person (e.g. clothing or a hot water bottle). However, as we have found, three of the participants turned the radiator on to *avoid cold*, rather than in response to it. For them, *short-term adjustment* became routinised and long-term.

The Auto mode was particularly problematic, with all of the participants noting that it was not working as they expected. For the most part, it kept the radiator turned off as the room temperature was above the driftpoint. Some participants considered the system broken. The main reason for this was a mismatch of expectations: the radiator was intended to be used alongside other thermal comfort mechanisms (i.e. clothes, drinks, activity). We envisioned that this realisa-

tion would occur organically, but this was only the case for some participants. The uncertainty about what the system was or should be doing played a part in the *chain-clicking* of the ‘Make it warmer’ button to ‘build up’ (Luke), or ‘avoid a drop’ in temperature (Stephanie, James).

An important question for design is how to better communicate the system operation and intended use within the context of an adaptive approach to thermal comfort. Some initial approaches might be the use of prompts when buttons are clicked; or contextualised prompts when a button is chain-clicked or when room temperatures are consistently higher than the driftpoint or historical norms. The state of the heating system could also be more transparent in the interface, for example, why the radiator is on or off, as well as outlining assumptions that it is based on (e.g. clothing layers, states of windows and doors). Such transparency might help build confidence in the operation of the system (e.g. when the radiator remains cold in Auto mode), as well as being more explicit about its overall role in adaptive thermal comfort. Highlighting the motivating factors behind the system’s design in this way, might even itself play a part in challenging existing thermal comfort and heating system norms. We believe care should be taken to work in terms of comfort levels and relative measures of temperature, rather than allowing inhabitants to fixate on the maintenance of a particular, absolute setpoint.

For participants having an ‘automatic comfort’ approach, the adoption of thermal adaptivity requires a significant commitment to change in practices and expectations. It is clear from their accounts that they are averse to thermal comfort becoming an extra concern in their already busy lives. And so, a more promising design approach for these participants might be to design for a longer term transition. Rather than directly introducing an adaptive thermal comfort system like our study probe, designers might instead consider how a heating system might evolve from conventional to adaptive in a number of stages that slowly shift the expectations toward more variation of temperature, more diverse thermal experience, and use of alternative approaches to thermal comfort.

CONCLUSIONS

In this paper, we examined the role of HCI in transitioning to an adaptive thermal comfort approach that moves away from uniform conditioning of the indoors, and moves reliance to lower-energy methods for keeping warm and cool. The promise of this approach has become well-recognised in buildings research for passive buildings, but little is known about how we can design for the transition in existing buildings with mechanical heating and cooling (e.g. retrofitting) and in the face of established expectations of uniformly conditioned environments.

Our *in situ* study of an adaptive thermal comfort technology probe illustrates the feasibility and potential for a computer-supported transition to this approach, but also highlights the challenges in designing to reshape existing norms and expectations of indoor heating. We have outlined future directions for design, considering engagement specifically, but also the wider design space, and illustrated the potential for HCI to

make thermal adaptivity, rather than thermal uniformity, the norm.

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