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Living with an autonomous spatiotemporal home heating system: Exploration of the user experiences (UX) through a longitudinal technology intervention-based mixed-methods approach

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ABSTRACT

Rising energy demands place pressure on domestic energy consumption, but savings can be delivered through home automation and engaging users with their heating and energy behaviours. The aim of this paper is to explore user experiences (UX) of living with an automated heating system regarding experiences of control, understanding of the system, emerging thermal behaviours, and interactions with the system as this area is not sufficiently researched in the existing homes setting through extended deployment. We present a longitudinal deployment of a quasi-autonomous spatiotemporal home heating system in three homes. Users were provided with a smartphone control application linked to a self-learning heating algorithm. Rich qualitative and quantitative data presented here enabled a holistic exploration of UX. The paper's contribution focuses on highlighting key aspects of UX living with an automated heating systems including (i) adoption of the control interface into the social context, (ii) how users' vigilance in maintaining preferred conditions prevailed as a better indicator of system over-ride than gross deviation from thermal comfort, (iii) limited but motivated proactivity in system-initiated communications as best strategy for soliciting user feedback when inference fails, and (iv) two main motivations for interacting with the interface – managing irregularities when absent from the house and maintaining immediate comfort, latter compromising of a checking behaviour that can transit to a system state alteration behaviour depending on mismatches. We conclude by highlighting the complex socio-technical context in which thermal decisions are made in a situated action manner, and by calling for a more holistic, UX-focused approach in the design of automated home systems involving user experiences.

1. Introduction

Mankind is currently facing one of its greatest ever challenges in climate change, which is primarily caused by human activity resulting in large quantities of pollutants emitted to the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) has suggested that in order to maintain global warming below 2 °C over 21st century, a reduction of 40–70% of global anthropogenic greenhouse gas (GHG) emissions by 2050 and reduction to near or below zero emission levels by 2100 are required (Pachauri et al., 2014). This poses great challenge as global population relies heavily on fossil fuels in satisfying energy demands and these fuels contribute significantly (74%) to global CO_2 emissions (Sims et al., 2007). In the UK, domestic energy use (26%) is the second largest contributor by sector (Department of Energy and Climate Change, 2014) and the majority of that, at 66%, is required for space heating (Palmer et al., 2011). In order to reduce energy demands for space heating, "occupants need better guidance and vastly improved systems" (Stevenson and Leaman, 2010). This highlights the complexity of tackling domestic energy usage, with building fabric, heating delivery systems and user interfaces (UI) (in this research used to denote any tangible or graphical computer mechanism for users to control the heating system) all playing a role in satisfying users' comfort requirements.

Research has shown that theoretical domestic energy usage based on the building's and occupants' characteristics does not

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often align with actual usage (Audenaert et al., 2011) and the poor performance of many advanced buildings has been attributed to poorly designed controls, occupants' inability to understand the building's functionality, and lack of user control (Stevenson and Rijal, 2010; Tuohy and Murphy, 2012). Peffer et al. reviewed a large body of work into thermostat usability and user perceptions, highlighting many misconceptions and usability barriers of regular and programmable thermostats (Peffer et al., 2011). It has been proposed that automation can solve these issues by operating heating controls on the human's behalf and simulations have demonstrated potential energy savings between 7 and 28% (Gao and Whitehouse, 2009; Gupta et al., 2009; Krumm and Brush, 2011; Lu et al., 2010; Scott et al., 2011). These savings were proposed to be achieved by minimising heating based on users' location within and absences from home, as well as different temperature setback settings. These authors share the belief in this technology's promise for solving the complex issue as automation can perform the tasks users are unwilling or unable to perform (Parasuraman and Riley, 1997) as regulating heater settings forms a minute part of a highly complex social, environmental, and technical setting in which occupants perform a multitude of activities.

However, the notion of 'ironies of automation' (Bainbridge, 1983) has been widely recognised, highlighting unintended consequences resulting from delegating human tasks to automation. In this context, it has been suggested that if automation chooses on the human's behalf to take environmentally friendly action, the consequences, on top of reduced autonomy for the humans, may include diminished understanding of their actions' impacts on the environment (Jaffari and Matthews, 2009). Such disengagement their energy and heating behaviour is likely to encourage "creative ways of working around the system rather than straightforward, energy-efficient compliance with it" (Jaffari and Matthews, 2009, p. 9). Disengagement poses a real threat as ambient intelligence or ubiquitous computing systems (which include autonomous home heating) fade into the fabric of life and thus aim for little to no interaction with the end user (Borgmann, 1995). These interactions (used here to denote actions that users take in order to control or obtain information from their heating system, not to be confused with interpersonal interactions) and their implications have not been sufficiently researched in their correct context. Several 'lab homes' have been built incorporating home automation technology to investigate user experiences (AIRE Group MIT, 2012; Amigo Project, 2012; Brown and Wyatt, 2010; Georgia Institute of Technology, 2012; Herkel et al., 2008; Mozer, 2012; Ruyter and Pelgrim, 2007; University of Essex, 2012; University of Florida, 2012), but this approach lacks ecological validity when one considers the manner in which this technology penetrates mainstream. Already various home automation products are being commercially introduced into everyday use such as smart thermostats (Ecobee, 2015; Nest, 2012), home security products (Glate, 2015; Kwikset, 2015; Nest, 2015), lighting solutions (Philips, 2015), wifi-enabled plugs to turn standard home appliances 'smart', or general home-automation products (Fibaro, 2015; Smartthings, 2015). This has validated Rodden & Benford's argument that 'smart' homes (by which we mean homes with computational capability to make decisions on the occupant's behalf and act these out in the environment) will be an evolution from existing homes, rather than a revolution with new homes being built with the 'smart' infrastructure built in (lab-homes). Furthermore, commercial devices we see introduced rely heavily on smartphones and tablets as interfaces for these systems, which introduces another interesting dynamic – heating systems and their operation becomes more invisible to us, while the control interfaces become more personal, causing potential issues in multi-occupant households where conflicts or unawareness as a result of multiple controllers may arise. The implications of these factors and the users' experience of them remains poorly explored in a true-to-life setting, limiting our abilities as designers to be able to design systems that engage users and nudge them towards more sustainable behaviour.

Therefore, research for home automation systems needs to focus on user experiences in the real world – in their own homes, as that is where these devices will exist and the energy behaviour of their users emerge. In this paper we present the results of a mixed-methods study investigating the user experience of a quasi-autonomous (system utilising sensory input from the environment and minimal occupant input through thermal feedback to automatically create and implement a heating schedule matching heating times to predicted occupant presence, while providing users with input and over-ride capabilities) spatiotemporal heating system in the wild. We present the highly ecologically valid research methodology of a technology intervention utilising a smartphone control application and a mixture of qualitative and quantitative research methods to understand and explain the emerging user experiences and their implications.

2. Material and methods

For reasons presented above, this methodology focuses on a technological intervention approach situated in individuals' homes. This approach is very intensive in terms of technology deployment, recruitment, and data collection, therefore typically involves a small number of participants over an extended period of time.

2.1. Participants

Sampling was done on availability and self-selection basis. However, several requirements were posed to participants to be eligible. Namely, (1) participants had to be responsible for their household heating expenses, (2) preferably their existing heating system was electricity based and not storage heating (electrical heater storing thermal energy during low electricity cost at night and releasing heat during the day), (3) they lived in a house/flat no bigger than 5–6 rooms, (4) apartments had a minimum of 2 rooms, and lastly, (5) to be eligible, participants were required to own and use an iOS or Android operating system smartphone. While electricity-heated households were preferred, (this was only due to smaller differences in potential heating cost in comparison to participants switching from gas-based to electric heaters), no limitations to households with other fuel types were set. Participant recruitment was done using the academic participant recruitment service callforparticpants.com, by distributing the study page from the site on University of Nottingham email mailing lists, and on social media network Facebook. In total three households (see Table 1 for full detail) were recruited out of several who showed interest, but despite qualifying, chose not to take part.

2.2. Apparatus

Participants' houses were fitted with a spatiotemporal quasi-autonomous heating system that consisted of stand-alone electric convector heaters, Wi-Fi-enabled plugs and a Raspberry Pi computer equipped with temperature and motion sensors, highlighted in Fig. 1. Each room was fitted with a kit of these components that all communicated to a central database on a university server that also hosted the control algorithm for heating.

Users were presented with a smartphone or tablet application that acted as their interface for communicating with the heating system. The heating algorithm (seen in Fig. 2), which was implemented as a server-side script was a combination of existing mathematical expressions and principles. It created a different heating schedule for every day of the week and every room in the house. Triggered every midnight and at key user interactions, the algorithm calculated the presence probability in every room based on previous calculations and motion sensor data (1 on Fig. 2) for every 10-min time step that the day was divided into. Subsequently, it assessed if the presence should be heated for (steps 2 and 3 on Fig. 2) and so, a heating period was scheduled. The Raspberry Pi computers retrieved these schedules and performed heating, using an optimum start algorithm that determined the duration of pre-heating prior to users' predicted arrival in order to ensure suitable conditions for predicted presence.

These calculations were performed and acted out almost invisibly to the user, except for feedback through the control application interface.

The interface, seen in Fig. 3, had three primary functions – (i) providing users with thermal information about their house and allowing manual over-rides if requested (a on Fig. 3), (ii) soliciting thermal sensation & preference feedback as well as perceived control votes (b on Fig. 3), and (iii) allowing users to create and manage "away" schedules that denoted uncharacteristic absence periods from home (c on Fig. 3).

Two configurations of the application were deployed – the "visible" version displayed a graph of thermal conditions in each room 2 h into the past and 2 h into the future, which the "blind" version did not (see Fig. 4 for comparison). This variation was used to see whether differences in the user's understanding of the heating system functionality, resulted from feedback or feed-forward data provided by the interface.

Users were free to utilise the smartphone application as they wished and Fig. 5 highlights all possible interactions and use cases. Initially, the app checked if the user was registered (1 on Fig. 5) to keep user data private and differentiate between users. If this was not true, the user was asked to enter information from the experimenter to register their app (2 & 3 on Fig. 5). For registered users, their house-specific data was retrieved and either a feedback screen (used for asking feedback on heating decisions when users were present in a room without the algorithm predicting their presence (5 & 6 on Fig. 5)), or the home screen (5 on Fig. 5) displayed. On the home screen, users could view different rooms in their house (8 on Fig. 5), or alter the temperature in those rooms (7 on Fig. 5).

Users also had the option to submit a vote (12 on Fig. 5), which consisted of selecting the room they were providing feedback for, indicating their thermal sensation and preference on the ASHRAE scale (7-point likert scale: cold, cool, slightly cool, neutral, slightly warm, warm, hot) (ASHRAE, 1966), and their perceived level of control over the heating system (scale from 1 to 7 – no control at all to absolute control, respectively). Users were also directed to this screen after every temperature alteration, and an option to dismiss the vote was provided. Lastly, Users could access the Diary screen (9 on Fig. 5) where they could create and delete (11 on Fig. 5) short and long away schedules, which addressed "I am coming home later than usual" and "I will be away for a couple of days" scenarios respectively (10 on Fig. 5). These were seen as methods for the user to inform the heating system about irregularities in behaviour and prevent heating when they were not around. Interface design was not a key element in this study, but rather served its part as the wider technological intervention that was used to explore UX.

2.3. Data capture

The deployed technology acted as primary method for data capture. Table 2 describes the captured data as various measures at different intervals for different reasons were captured.

In addition, users were probed on using questionnaires, interviews and depictive explanation tools. Prior to the experiment's launch, an online-questionnaire was used to obtain algorithm's training data from users. This questionnaire asked users to provide the number and names of all rooms in their dwelling, preferred temperatures for those rooms, and indicate in 1-h slots their assumed presence. Over the course of the experiment interviews were conducted to solicit participants' feedback regarding their UX and ideas regarding the heating system functionality. The open-ended questions of all three interviews can be seen in Tables 3, 4 and 6. Household-specific questions derived from Google Analytics app usage data for the second and third interview can be seen in Tables 5 and 7. For the first interview, the participants were asked to prepare a diagram explaining how they thought the heating system worked.

2.4. Design

The experiment was a semi-longitudinal experiment lasting

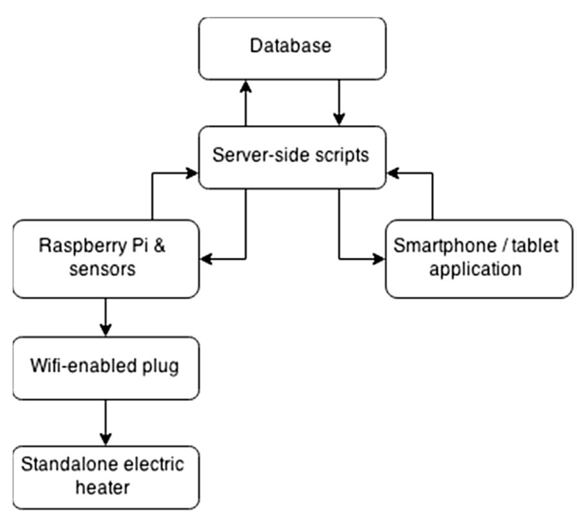


Fig. 1. Illustrating system design of field study technology.

Table 1
Displaying characteristics of participating households (all names are pseudonyms).

Characteristics	House 1	House 2	House 3
Occupants	Postgraduate student (male) - Carl	1 postgraduate student (male) - Paul, 1 professional (female) - Diane	2 postgraduate students (1 male - John, 1 female - Mildred)
Heating strategy	Maximise comfort (algorithm aims for 'neutral' thermal sensation)	Minimise discomfort (algorithm aims for 'slightly cool' thermal sensation)	Minimise discomfort (algorithm aims for 'slightly cool' thermal sensation)
App visibility	Visible (app displays future temperature predictions)	Blind (current temperature snapshot only)	Visible (app displays future temperature predictions)
Dwelling type	Purpose built flat	Converted flat	Converted flat
Rooms deployed with equipment	5 rooms – Lounge, Bedroom, Second bedroom, Bathroom, Kitchen	4 rooms – Lounge/kitchen, Bedroom, Bathroom, Hallway	3 rooms – Lounge/kitchen, Bedroom, Bathroom
Existing heating system	Gas central heating	Electric convector heaters	Electric convector heaters

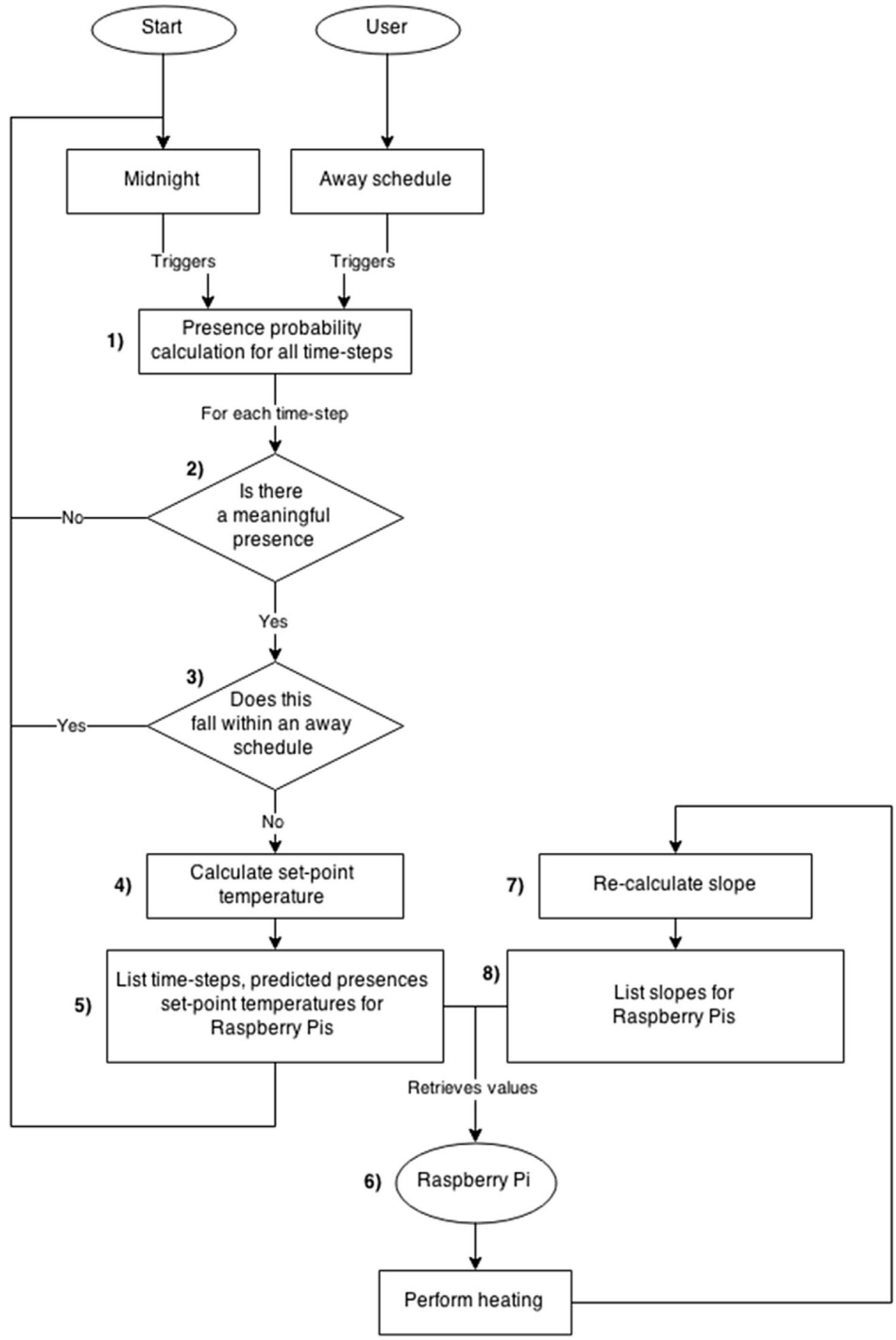


Fig. 2. Depicting the functional flow of the proposed control algorithm.

5–6 months. The multitude of different collected data facilitated an explorative study design, rather than a strict independent-dependent variable isolation via highly controlled set-up. Regardless, the experiment can be described as utilising a between measures study design with two independent variables – smartphone application condition (users' ability to see the feedback/feed-forward graph - see Fig. 4 for graphic differentiation), and the heating strategy condition (control algorithm opting to maximise comfort or minimise discomfort). However, due to individual differences between the usage of the systems and the algorithm's innate quality of adapting itself to its user, the conditions could not be analysed directly and rigorous inferential statistical analysis was impossible. Rather, the conditions were observed individually and descriptive statistics used across conditions. Dependent variables were the thermal experience of living with an automated heating system, and the user experience of the heating system and control interface. Due to the large amount of data collected, results regarding the system technical performance, algorithm performance, and thermal experience of different heating strategies are omitted. Despite contributing to the home environment, these

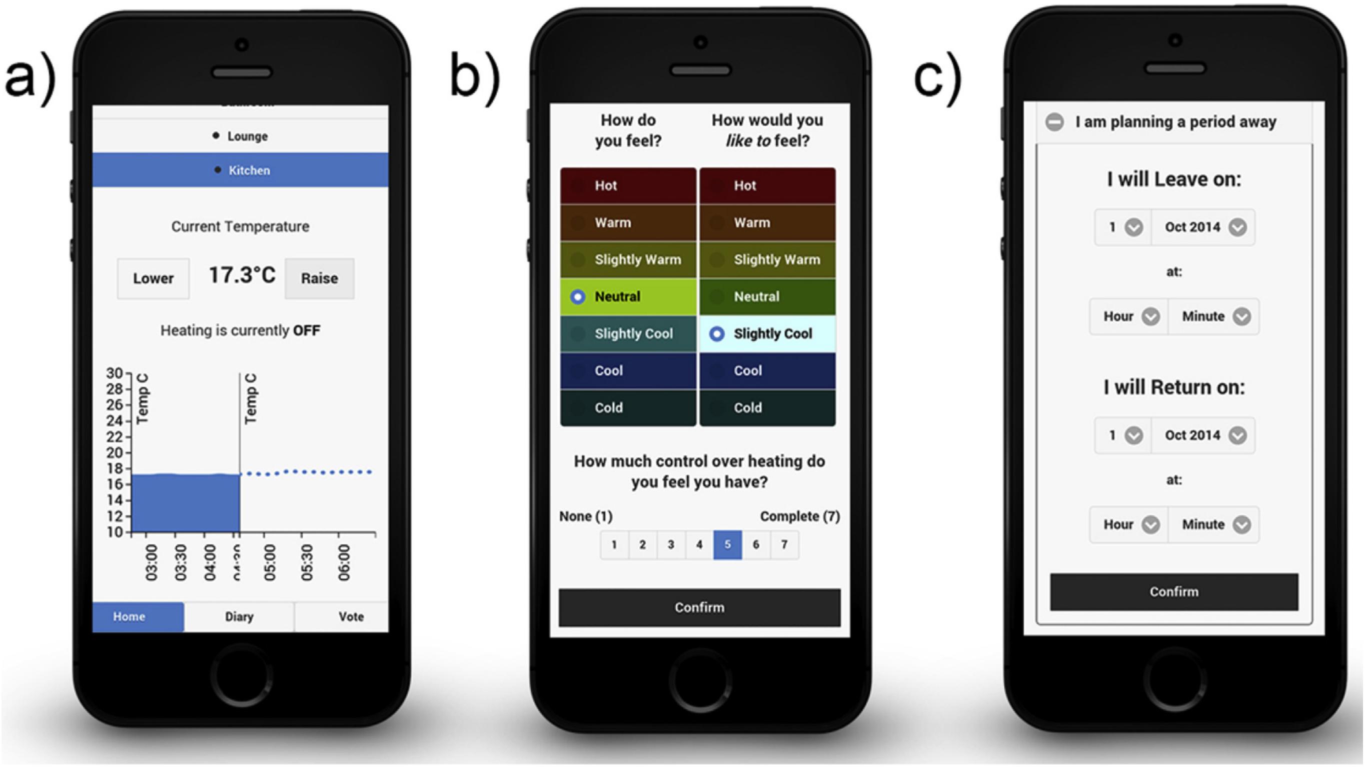


Fig. 3. Illustrating the smartphone application given to study participants.

Fig. 4. Comparing the 'visible' (left) and 'blind' (right) versions of the home screen.

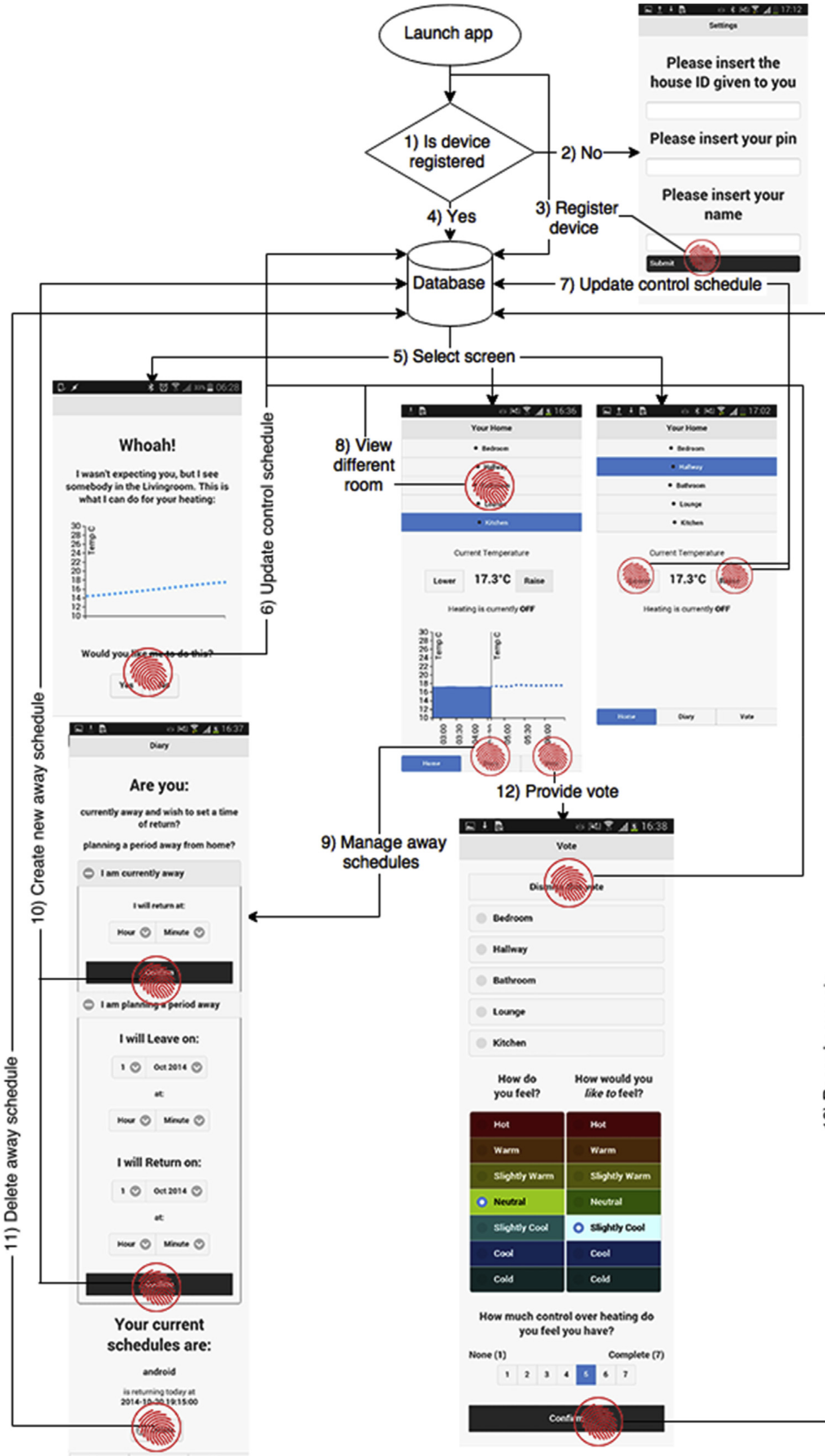


Fig. 5. Illustrating the user interaction flow and functional logic of the smartphone application.

Table 2
Detailing the quantitative data obtained during the field study experiment.

Type of data (measure)	Method of obtaining	Reason of data gathering
Temperature (°C)	Taken by Raspberry Pi every 10 min using temperature sensor	Apparatus functioning (temperature set-point calculation by algorithm) Answering questions about thermal comfort
Presence (time start, time end)	Taken by Raspberry Pi when motion was detected using motion sensor	Apparatus functioning (heating schedule creation by algorithm) Answering questions about algorithm functioning and user experience
Calculated slopes (number)	Calculated & stored in database by system algorithm after every time heating occurred	Apparatus functioning (heater optimum start calculation by algorithm) Answering questions about algorithm functioning
Thermal sensation votes (number)	Obtained from user whenever the user chose to submit value	Apparatus functioning (temperature set-point calculation by algorithm) Answering questions about thermal comfort
Thermal preference votes (number)	Obtained from user whenever the user chose to submit value	Answering questions about thermal comfort
Control votes (number)	Obtained from user whenever the user chose to submit value	Answering questions about user experience
System set-point alterations (°C)	Obtained from user whenever the user chose to change the prevailing temperature in the room	Apparatus functioning (temperature set-point)
Away schedules (time values)	Obtained from user whenever the user chose to submit value	Apparatus functioning (heating schedule creation by algorithm) Answering questions about user experience
Application launches (timed instances)	Automatically logged by Google Analytics when user opened the smartphone application	Answering questions about user experience
Application page views (timed instances)	Automatically logged by Google Analytics when user used the smartphone application	Answering questions about user experience
Application events (timed instances)	Automatically logged by Google Analytics when user accepted or dismissed a suggested schedule, provided a vote, changed temperature, provided or delete an away schedule, or viewed a room overview in the smartphone application	Answering questions about user experience

Table 3
Detailing questions for field study Interview 1.

Question Number	Question
1	How would you describe your original heating system, not the one we installed?
2	Could you please explain to me with the help of your diagram, how the heating system works?

factors did not influence the questions asked of the data in this paper. Out of 4 total conditions, only 3 were used due to the lack of participating households. The maximise comfort – blind application condition was not deployed (other conditions are detailed above in Table 1).

2.5. Procedure

Ethical approval for the technology intervention was gained from the University of Nottingham Faculty of Engineering Ethics Committee prior to commencement. The experiment took place over 6 months between February 2015 and July 2015 (inclusive). Potential participants were asked questions about the heating and communications infrastructure in their homes to assure their ability to partake. Suitable participants were asked to fill in the pre-study questionnaire and the obtained data used to set up the experimental equipment. Interview 1 was conducted 1–2 weeks after deployment, second interview 2 months after deployment, and third interview during equipment collection. Throughout the experiment, check-up emails were sent to participants ensuring everything was running as expected and to keep a dialogue with participants. The researcher checked the experiment database daily to make sure the system was functioning properly. When errors occurred, the apparatus was restarted using built in remote troubleshooting capabilities. If this was not possible, the participant was contacted with a request to manually restart the equipment by removing and replacing power supply. Participants were sent reminder push notifications as means to prompt thermal comfort vote submission. The rate of push notifications decayed over the course of the experiment with a notification sent every 2 days in February, every 3 days in March and every 4 days until the end of the experiment thereafter. Following experiment completion, participants were compensated with £20 Amazon shopping voucher per month of participation.

Table 4
Detailing questions for field study Interview 2.

Question number	Question
1	Is there anything you would like to add or change about how the system works?
2	How do you as a household use the heating application?
3	How often have you changed the heating settings using the app in comparison to other strategies such as adjusting your clothing or having a hot or cold drink?
4	[Household-specific application usage questions – please see Table 5 below for full detail]

3. Results

The experiment generated a vast amount of quantitative and qualitative data and subsequently, the results are divided into a brief description of the user types that emerged, followed by a more detail look at some of the potential user interactions and experiences that emerged. Finally we explore the relationships between some emerged interactions with the smartphone application and

Table 5
Detailing household-specific questions for field study Interview 2.

Household number	Question
1	How do you decide when to change the temperature using the App?
1	When the app notifies you that it wasn't expecting you, how do you decide whether to accept or reject the suggestion or ignore the notification altogether?
1	Have your habits in doing this changed over time?
1	Has the way you use the app or when you use the app changed over time?
1	Please describe how and when you use the away schedules?
2	Has the way you use the app or when you use the app changed over time?
2	Most of the temperature changes in the house are done from one device, does this mean that it is one user making the decisions, are devices shared, or do you discuss temperature changes before putting them in the app? Could you describe how these changes happen between you as a household?
2	Please describe how either of you use the app - when do you open the app, and what do you do when you have opened it?
2	You have a third device in the household, could you please describe how the app is used on it - who uses it, when etc.?
2	Over time the number of times you change the temperature has decreased a lot. Please describe how these changes have occurred and the reasons behind them.
2	When the app notifies you that it wasn't expecting you, how do you decide whether to accept or reject the suggestion or ignore the notification altogether?
3	Has the way you use the app or when you use the app changed over time?
3	Both of you have the heating application on your phones, could you describe how you as a household make any changes - do you consult among each other before submitting anything to the app, is it individual, etc?
3	Over time the number of times you change the temperature has been consistently low. Please describe how you decide when to change temperature or when not to.
3	Please describe how you have used the away schedules?
3	When the app notifies you that it wasn't expecting you, how do you decide whether to accept or reject the suggestion or ignore the notification altogether?
3	Please explain your usage of the voting - when do you submit a vote, when do you dismiss it and how do you decide which to do?

Table 6
Detailing questions for field study Interview 3 (Debrief interview).

Question number	Question
1	For the last time, I would like for you to take a look at the diagram we have been working with and tell me whether you would like to add or change anything about how in your mind the system works?
2	Did the heating system behave the way you expected it to behave?
3	[Household-specific questions – please see Table 7 below for full detail]
4	What would you say are the most important differences between this type of a system and conventional heating controls?
5	Did you encounter any funny incidents or disagreements over the course of the experiment regarding the heating?
6	If you had a choice, would you prefer to keep this type of a heating system or would you like to revert to your previous system and why?
7	Could you please describe the experience of controlling the heating through your phone rather than a more conventional method?
8	Similarly to the pre-study questionnaire, would you be able to estimate your expenditure on heating per month over the duration of the experiment?
9	You were not the only one controlling your heating. A computer also made decisions about when to turn the heating on or off. What do you think, how did the heating system make these decisions?
10	[Researcher explained what how heating decision were made] How does it make you feel knowing that this was happening?
11	If you knew at the time that this was occurring, would you have done anything differently than you did now?
12	Could you describe your overall experience in living with this type of a heating system?
13	How in control of the heating did you feel over the course of the experiment?
14	If this heating system was available on the market today, would you buy it for your home?

Table 7
Detailing household-specific questions for field study Interview 3.

Household number	Question
1	You have told me over the last few interviews that you had a guest often stay with you. Could you describe the way in which your guest had any control over the heating application?
1	Over time, your use of changing temperature on the app decreased. Was this due to warming weather or did anything else affect this?
2	You have used the long away schedules on occasion throughout the experiment. Could you describe why you have carried on using these while your overall usage has decayed?
3	The one feature that you have used on occasion throughout the experiment was setting a long away schedule. Could you explain why this was a feature that you used so often?

factors affecting those.

3.1. Three behaviour types

We expected some difference between our participating households in their use of the automated system, reflecting existing knowledge from classical heating system usage. The results confirmed this and showed distinctly different emerging thermal preferences and thermal adaptation behavioural patterns. Exploration of those establishes an understanding of the collected data and sets the scene for exploring UX in more detail. The emergent user types of ‘fashion user’, ‘frugal user’ and ‘everything's fine’ user were not attempts to classify all behaviours, but rather to explore some typical and potential behaviours and interactions that may arise when a sub-set of users live in their natural environment with a spatiotemporal heating system.

3.1.1. The 'fashion user'

The 'fashion user', Carl, was observed in House 1 and can be characterised by his expectations of the heating system to deliver thermal comfort to him, matching his chosen garment choices:

> *"I'm very much with the approach that I will get to a comfortable position clothing wise and then get the building to adjust around me."* [Carl]

Personal thermal adaptations such as clothing level alterations or hot/cold drinks consumption were rarely utilised and subsequently, Carl was the heaviest user of both the interface and the heating system. The user reported varying working-from-home behaviour and life patterns greatly around work demands creating an erratic presence profiles across rooms (Fig. 6).

Long periods in late afternoons can be observed, where the user was recorded in different places. In addition, Carl sometimes had a partner stay over for long weekends, who was often in the house when Carl was in the office. These factors caused the control algorithm to heat several rooms, which was perceived by the user as having 'made mistakes'.

> "*The only reason why I have noticed this is because … I tend to work at night. And if I was doing a lot of heavy working, and then stopped, in the lounge it would turn on at like 2 in the morning even though I was not up still.*" [Carl]

Such noticeable alterations in personal habits made Carl aware of the system's intent to establish a schedule around his presence, making him forgiving towards the system at times, but also frustrated when these changes occurred.

Manual system state alterations were primarily motivated by user's thermal sensations and wishes to match thermal conditions to clothing choices, which provoked the formulation of a heater state alteration decision prior to engaging with the application. User's responses to system-initiated contact (unexpected presence notifications) were addressed based on their alignment with thermal sensations and pre-existing alteration decisions. These interactions delivered suitable conditions in the living quarters (Fig. 7). As environment was matched to clothing choices, Carl experienced different thermal sensations at same temperatures, resulting in a varied thermal sensation distribution (Fig. 7) and causing the heating algorithm to continuously adapt to ensure user's comfort. E.g. the prevailing temperatures in the bathroom (orange line in Fig. 7) showed that 75% of experiment duration, Carl was most likely to experience a 'cool' or 'slightly cool' sensation. In contrast, while in the lounge (green line) he was most likely to feel a range of sensations between 'slightly cool' and 'warm'.

3.1.2. The 'frugal user'

House 2 were labelled 'frugal users' for their reported prioritisation of avoiding expenditure on heating above other considerations. This was reported collectively and retrospective, while during usage, conflicts existed between Diane preferring higher temperatures and Paul, who prioritised personal thermal adaptation to save cost. Interestingly, this led to thermal feedback from the application being used as justification for turning heating on:

> *"Occasionally I use it to prove a point. Especially when it was really cold and I would be like "Paul, it's really cold in here" and he'd be like "No, it's fine, put a jumper on" and I would check the temperature and use it that way."* [Diane]

Furthermore, despite having three devices equipped with the control application (both users had a smart phone and a shared tablet), only Diane ended up engaging with the interface, leading to a dialogue between users regarding thermal behaviour and preference.

Prevailing temperatures were slightly higher than measured for fashion user, but frugal users had a very narrow range for neutral sensation (Fig. 8), highlighting not only the conflicting views reported by Diane, but also the manner in which they operated the system – as a novel way to control heating (telling it to turn on when they were cold and subsequently turning it off when they were hot). Such operation also caused users to attribute automatic heating periods to randomness or system errors and often leaving them surprised at the outcome:

> *"And then a couple of times, one time at the start when we came in and it felt like we just went to the centre of the earth. And all of them had been on … and we were like "oh wow"."* [Paul]

One user often worked from home while the other left for the office on weekdays (Fig. 9 top), causing the algorithm to adapt to various presence profiles. On weekends, the users preferred to spend more time at home, which also gave the algorithm different patterns for 'start of day' activities such as eating, washing and dressing. Due to this, the heating system often resorted to unexpected presences, triggering push notifications to users that provoked interesting social nuances regarding personal location data protection as users became aware of each other's location. These are discussed in more detail below.

3.1.3. The 'everything's fine' user

Users in House 3 were characterised by their lack of necessity to engage with the heating system and control interface. Their flat's building envelope and high heat gains from neighbouring flats ensured their comfort expectations were naturally met and additional heating was rarely required (Fig. 10), but they could potentially be re-classified to one of the other types if building characteristics were different (most likely to frugal type due to reported preference to personal thermal adaptation for cost saving).

These users displayed a stark difference between weekday and weekend presence (Fig. 11), displaying highly active mornings and afternoons contrasted with absence during working hours on weekdays. On weekends (Fig. 11 bottom), users had different times of waking up, sometimes being out of the house, or spending weekends in. The algorithm had to adapt to these behaviours and subsequent differences in needs for thermal comfort.

Long absence and little need for additional heating meant the control interface was primarily used individually, often leaving users unaware of each other's changes. Heating behaviour was rarely discussed, with some conversations occurring when personal thermal adaptations failed to deliver comfort. Initial excitement of novel technology and testing of all features was replaced by diminished interest in organic and system-initiated interaction.

3.1.4. Implications of emerged behaviours

These results from a highly ecologically valid setting demonstrate that given virtually identical equipment, three households displayed vastly different system use strategies, thermal behaviour, and thermal preference; each adjusting the manner of use to their existing social, occupational, presence, and thermal adaptation habits. Furthermore, the emerged behaviours did by no means represent a full set of possible behaviours, highlighting that domestic heating behaviour is indeed complex and highly personal.

Fig. 6. fashion user average measured presence profiles for all weekdays (top) and weekends (bottom).

Subsequently we explore the user experiences further across the three behaviour types, answering questions formulated around specific themes.

3.2. Potential user experiences emerging from a spatiotemporal home heating smartphone control app

3.2.1. Explaining heating system's operation & use strategies

The authors expected users to anticipate automation capabilities from what little explanation was provided and for this to come through in users' explanations of the system. Users of the 'visible' interface configuration were expected to provide more accurate and extensive descriptions due to the forward-planning nature of the graph. However, our results contradicted this and showed little difference between 'blind' and 'visible' conditions in explaining the automation. The indifference was attributed to the subtlety of the graph as an explanatory tool within the interface. Furthermore, the graph's forward planning based on predictions was not explicitly communicated anywhere within the application, which meant that users relied on other indicators to explain system's behaviour. This filtered through to the occupants' use strategies of the system and users' perceptions of the heating system and their use of it. These were analysed through user-generated diagrams of how the system worked and interview data from all three interviews, which was used to extract their interaction strategy (Table 8).

The explanations provided in Table 8 were reportedly based on the hardware that users could observe. In addition, the 'frugal 'users said the unexpected presence notifications made them realise the system knew their location, and the 'fashion' user noticed learning behaviour upon changing their daily routine.

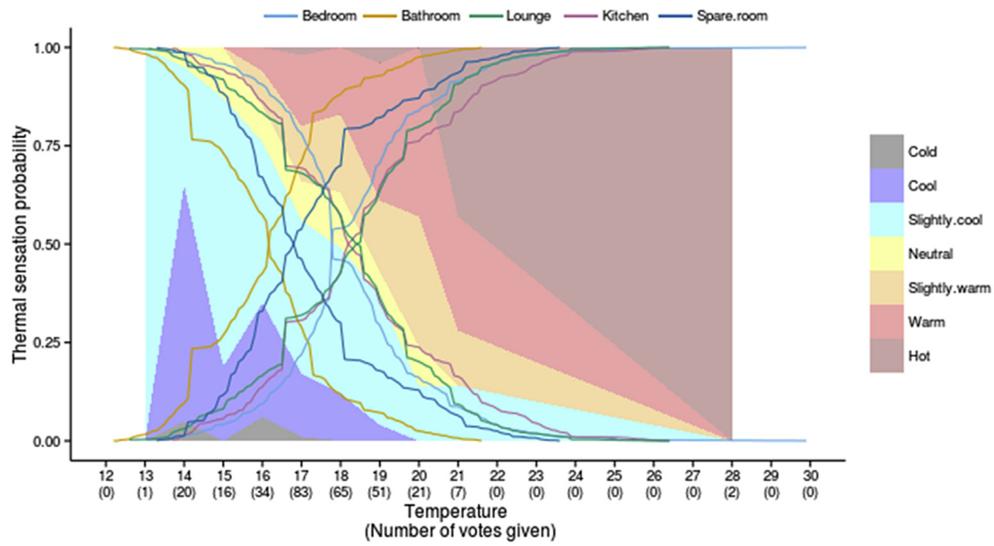


Fig. 7. fashion user thermal sensation probability distribution based on user-given votes, with positive and negative accumulative temperature distributions fitted for all rooms.

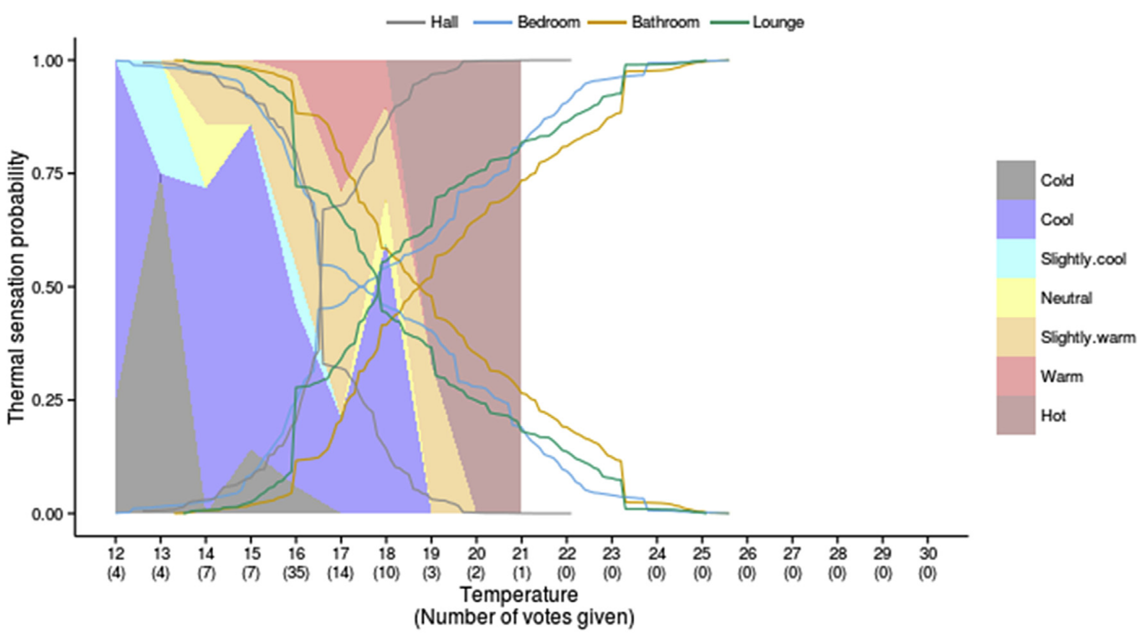


Fig. 8. frugal user thermal sensation probability distribution based on user-given votes, with positive and negative accumulative temperature distributions fitted for all rooms.

Because of the users' low awareness of automation capabilities of the heating system, the heating system was used as a temporal solution. Meaning that users saw the control application as a novel way to tell the heaters to turn on or turn off. Little interaction prevailed regarding planning ahead, especially within the context of a single day. All users except one noted not obtaining feedback of the system activities or thermal conditions from the application before any personal or system-related heating decisions were made and all decisions were reached based on their sensation.

This data showed that even when users are not explicitly aware of the capabilities of the automation, they can deduce its behaviour. However, lack of explanations regarding system functionality meant that initially, users relied heavily on guess-work made possible by opportunistic audible feedback from the Wi-Fi-plugs switching on, or through delayed thermal feedback from the environment. These elements allowed users to build a mental model of the system functioning that was often inaccurate or incomplete. The results above highlight that users who were presented with the thermal feedback-feedforward graph (Fig. 4) did not explain system functioning through it, illustrating that prevailing environmental conditions and heater system functionality are not innately linked in the users' perceptions.

As the interface type seemed to have no effect on users' understanding of the system's capabilities, the conditions will not be isolated in the rest of this article and all participants will be treated as a single group.

3.2.2. Experience of control over the heating system through the control application

It was expected based on automation literature that users experienced diminished sense of control due to increased automation capability, which would be compensated by the interface's

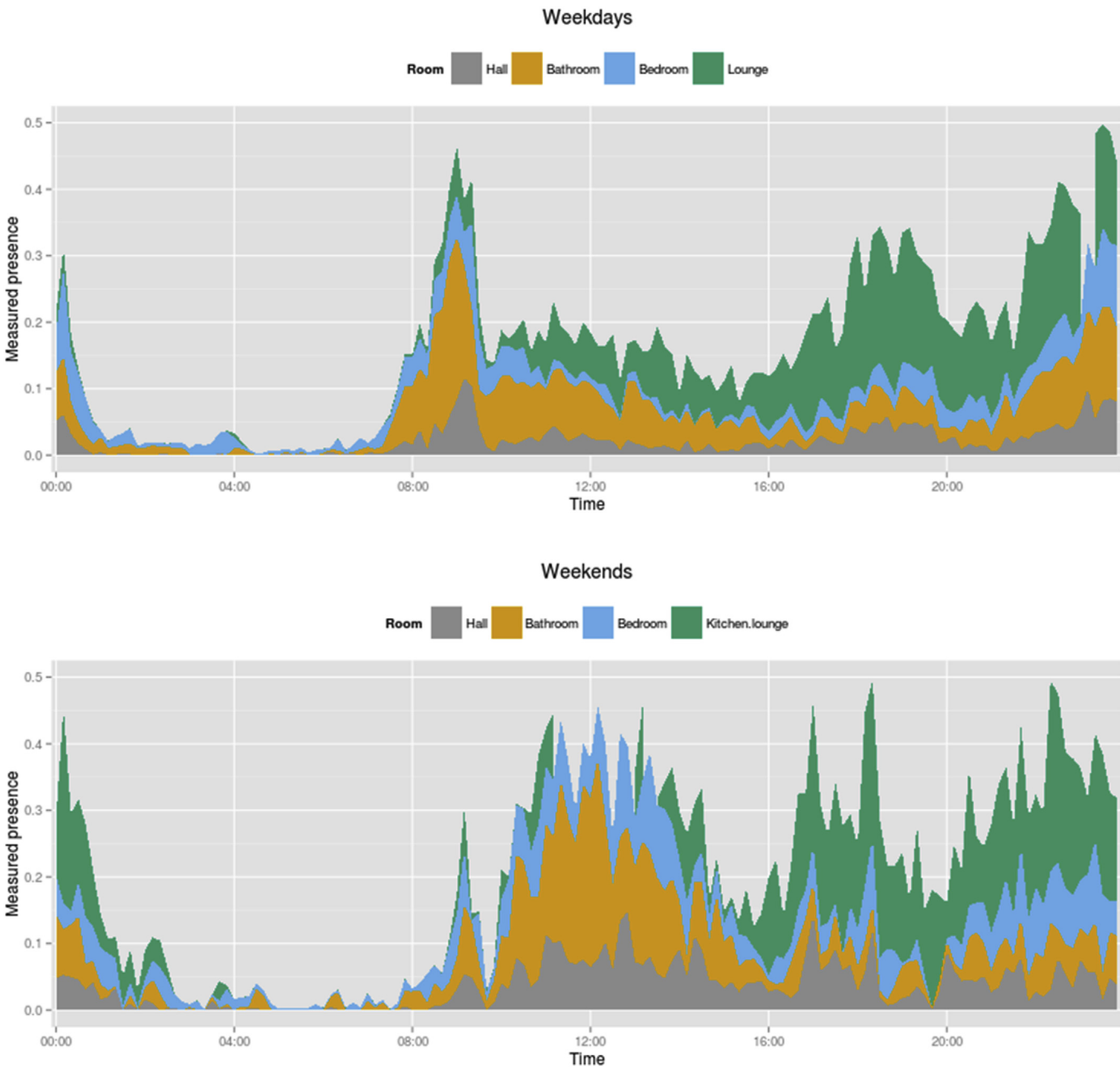


Fig. 9. frugal user measured presence profiles for all weekdays (top) and weekends (bottom).

explanations. However, the results showed this dynamic to be more complex.

UX of control was analysed using interview data and user-submitted control votes. Fig. 12 depicts an even distribution of given control votes, highlighting that users experienced various levels of control over the course of the experiment, with average rating across participants at 4.3 (4.4 fashion user, 4.5 frugal user, 2.3 everything's fine user).

The users explained their control experience and voting reasons as diverse, ranging from habit to system functionality or responsiveness:

> *"…because we were not really using it for turning on or turning off the heaters, so control over the heaters was like not really control because I am not doing anything."* [Mildred]

> *"…when it did what I wanted it to do, straight away I was like "Yeah very in control" and then again when it took a few minutes to do it I was like "Not in control at all, I have no control." But over time that kind of steadied out and usually felt pretty in control"* [Diane]

> *"Because it was slow in the beginning I was getting angry at it. So at first my scores were very low and I think somewhere along if you look they would randomly flip to high. Because I realised I was giving it low scores, because I had been giving it low scores. And then I realised that most of the time it was alright."* [Carl]

Retrospectively, the users reported to experience a satisfactory level of control, with all houses making reference to specific instances during the deployment when the system acting

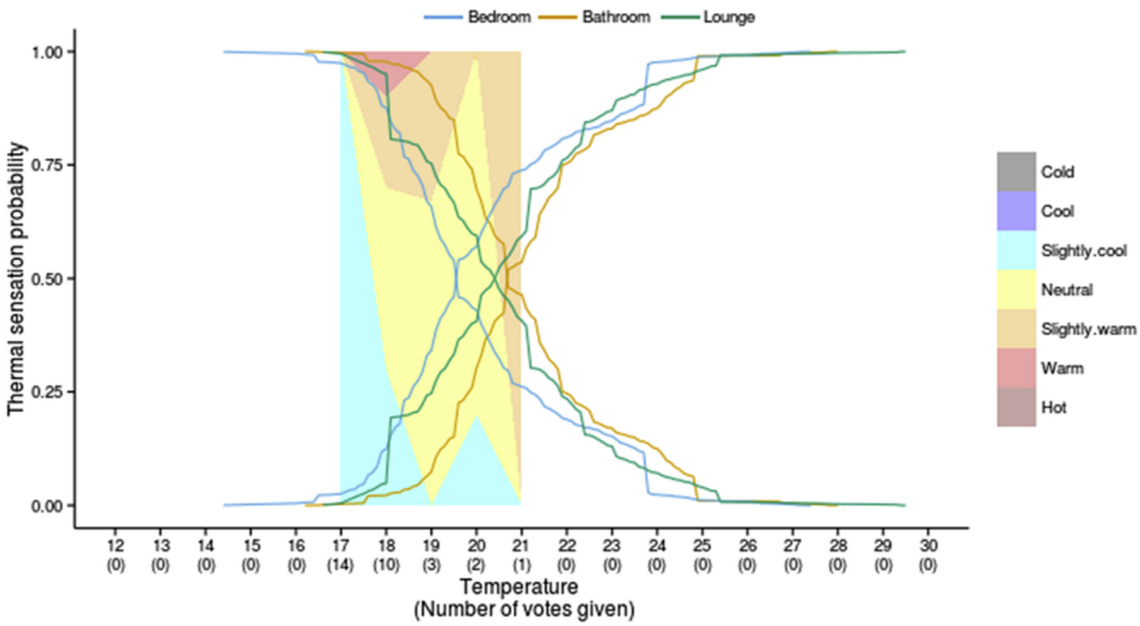


Fig. 10. Everything's fine user thermal sensation probability distribution based on user-given votes, with positive and negative accumulative temperature distributions fitted for all rooms.

autonomously and deviating from their expectations, causing distrust in them towards the system:

> *"…the few times when it came on when we weren't expecting it to... The first thing was to go on the app, try to turn it down from there, vote that I didn't feel in control. I don't know why I did that, maybe I thought that would have some immediate effect…"* [Diane]

> *"Yeah generally I felt in control. Every now and again there was the odd random increase. And every now and again I would be sitting there and be like "why have you turned the heating on"."* [Carl]

> *"For example I haven't ever put the heating on before I have come back. I don't know whether that is out of not being aware of it, not thinking about it or sort of hesitation that it might come on or might not come on. Or just paranoid that it would turn the heater on when you are not there and it would start a fire … I would only put it on in the bedroom once I actually go to that room."* [Paul]

These quotes highlight situations in which users' expectations did not match system functionality, causing experienced loss of control. However, over the course of the experiment participants did not consistently submit lower control votes during automatically initiated system-planned heating periods (Fig. 13), meaning loss of control was not solely a result of automation. In fact, during automatically planned heating users were more likely to have a slightly higher perceived level of control in comparison to non-automatic heating periods (Fig. 13) suggesting other factors in addition to system state influencing perception of control.

Interviews highlighted system responsiveness in combination with feedback playing an important role. The relationship of which was further complicated by the multiple channels of obtaining information for users. The interface gave them feedback on their actions, but users additionally used environmental feedback, often prompting multiple interactions with the interface and highlighting an added intricacy in the aspect of control for quasi-autonomous heating:

> *"All I got at the start was... you sitting on this sofa and asking me there "is the heater on?" and you'd put it on 3 minutes ago and it wasn't on... "Has it gone off?" was another one so..."* [Paul]

> *"On the downside, it gives you a feeling of less direct control. So when you are using the conventional you are cold, you just... [does a flicking motion] whereas with this you are relying on a system that you haven't actually...[prompt from researcher] It feels less immediate. You are not in control of each immediately."* [John]

These descriptions highlight how users used the interface, environment, as well as lights and sounds from heaters to establish an understanding of system state and how changes to it either involving them or not, caused them to experience loss of control when the system state didn't match their expectation.

Users' thermal sensation was neither a reliable indicator for loss of control, despite feedback votes often being motivated by thermal discomfort − i.e. discomfort caused alteration of system state, which was followed by providing a vote. Fig. 14 highlights users' thermal sensation during given votes and shows that discomforting sensations dominated both high and low control experiences.

It was also noted that certain interface features allowed users to increase the level of control they felt, notably setting away schedules when users were absent for longer periods of time:

> *"I think it was just that security just to make sure it didn't come on when you were away, because you weren't there to react and turn it down. You could use the app to turn it down but I think it was just that double security."* [Paul]

> *"Telling the system that you were not there was something that gave us the feeling of control. Like, turning it off."* [John]

Furthermore, several users speculated that increased familiarity with the automation could have inspired more trust in them, allowing more autonomy for the without loss of experienced control:

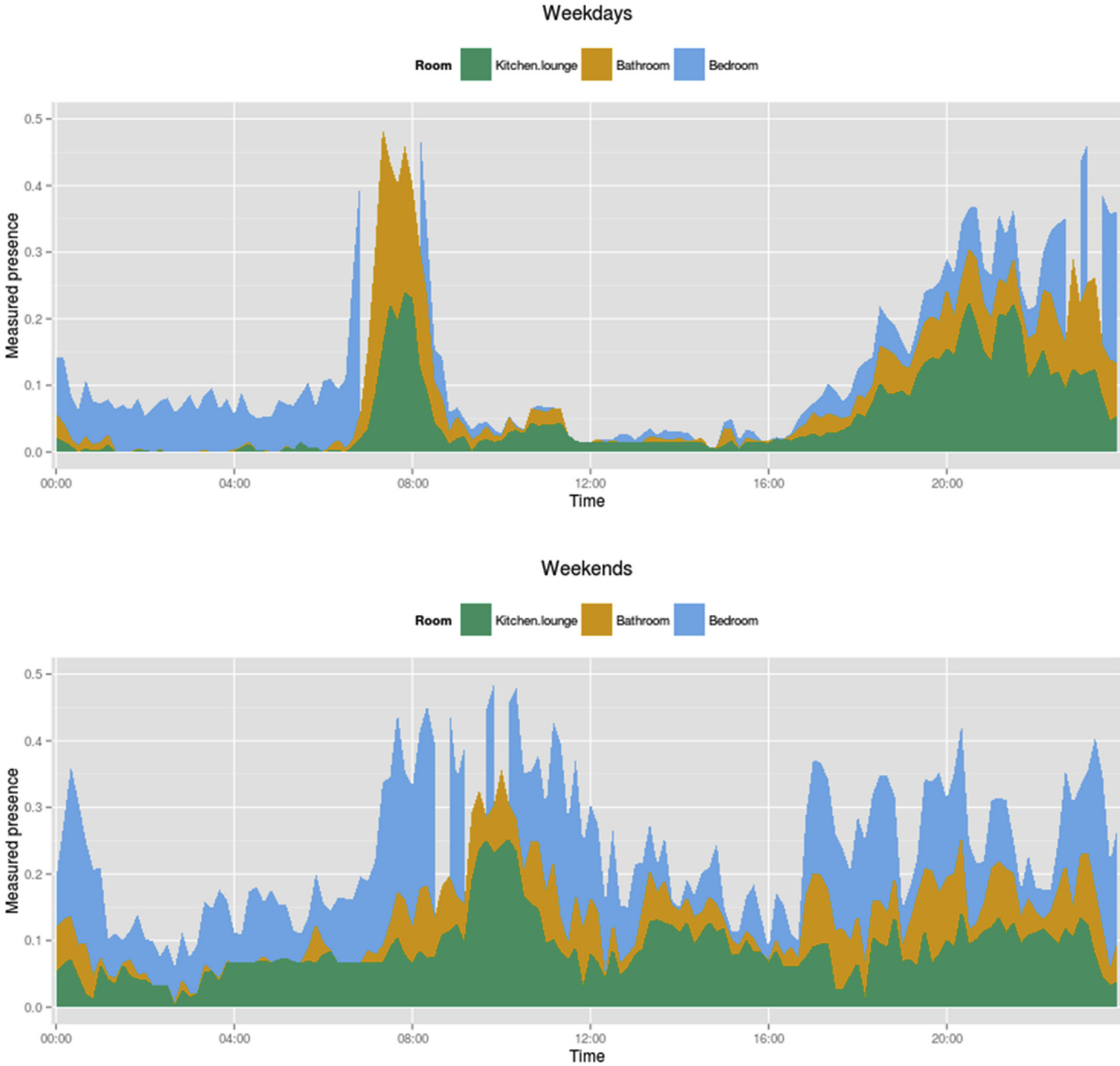


Fig. 11. Everything's fine user measured presence profiles for all weekdays (top) and weekends (bottom).

> *"…maybe if you had it longer... like a year or two years, you would trust the system more and trust the actual heaters more, then you would be more inclined to then put it on like: "I'm going to be home in 10 minutes and it is in the middle of the winter you knew it was going to be cold"."* [Paul]

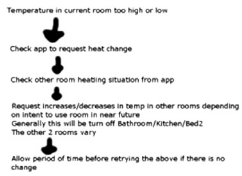
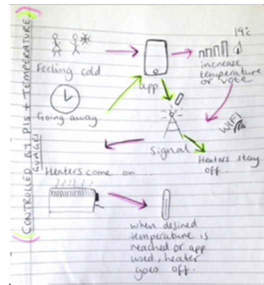
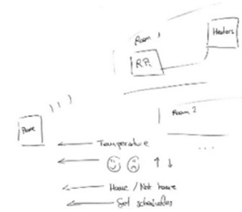
> *"If I had known exactly how the system works, like time intervals and things like that?… I don't know I would have trusted the system instead of, for instance having tried to turn off the system at some point, maybe would have just trusted that the system will know that it needs to be turned on. Maybe knowing how the system works would have given me more trust in it."* [John]

These results show that increased autonomy alone does not promote a UX low in control. It has been demonstrated how the experience of control, or the lack of, was the result of several concurrent factors. Experiences of control can be most enhanced by reducing mismatches between system state, thermal preference, and feedback on user actions; and the user's expectations of these factors, which supports existing knowledge (Bunt et al., 2012; Kulesza, 2012; Lim et al., 2009) highlighting the value of system rationale communication. In addition, we suggest explaining thermal behaviour, as well as responsiveness in delivering feedback throughout the observable environment in order to limit mismatches in expectations from occurring.

3.2.3. Social context of use and effects of introducing a smartphone heating interface to the social environment

No specific elements of the social context were being observed in isolation and the experiment was used as a way to establish a

Table 8
Participants' explanations of heating system's operation.

	Fashion user	Frugal User	Everything's fine user
User-generated diagram			
Researcher's explanation of diagram	Diagram started with user thermal discomfort, proceeding to explanations how their interactions are translated into environmental change.	Diagram started with user thermal discomfort, proceeding to explanations how their interactions are translated into environmental change, referencing communications between components.	More focused on the technical set-up of the system as interacting with it was less common in their home, making references to all the different functionality the phone application offered and communications links between components.
User's explanation of automation	*"The way it comes across to me is just trying to work out when I am generally in that room. … generally in the afternoon all the rooms turn on. So I guess this is generally when I come home. … the bedroom for example, the master bedroom, is off most of the time. … but I have noticed that it has become quite good at predicting vaguely when I am going to be in my bedroom, but during the day it seems to be just off, almost like a timer system that it's trying to work out for me." [Carl]*	*"The heaters, after a while they'll go. For example if we put the temperature in the bedroom to 18 degrees, it will come on for a few minutes and then the heater will click off. And then maybe a little while later it will click on again. I guess it kind of maintains the temperature that you've asked."* [Diane]	None provided, heating system was described as a subservient only to their commands through the application
Explanations of automation after told a computer also made decisions	Suggested system was replicating their input. *"And then some level of variance depending on whether it could see me or not. Based on the motion"* [Carl]	*"It probably either learned our behaviour, so maybe if we were in and if it was below 16 degrees it would maybe learned that we were maybe would turn the heating on in that instance." [Diane]*	*"…the only thing I can guess, is that from the temperature and the answers that we give to the app. I can't remember now, but it was like if you feel warm cold... So I am guessing that the system could try to fit our ideal temperature, that's all I could say." [John]*
Comfort strategy	Heating system as primary strategy to achieve thermal comfort	Personal adaptation (clothing changes, hot/cold drinks) as primary adaptation, heating system as secondary	Personal adaptation (clothing changes, hot/cold drinks) as primary adaptation, heating system as secondary

better understanding of the social element of autonomous heating systems as a whole.

In general, participants noted that there was a social element to the control application use and some common traits to regular heating system operation were reported. For example, in multi-occupant households, participants reported conversing about decisions to turn the heating on, which is assumed to be also the case in a 'standard' heating control. The 'frugal' household installed the application on 3 devices for 2 people, but only Diane ended up performing bulk of the interactions. When Paul wished for alterations, he usually asked Diane to perform them. This was reported to be due to 'being faster' or simpler if one person performed the actions. In the 'everything's fine' household, users had a more individual approach, but still noted making decisions jointly when the social situation facilitated it:

> *"for instance if we are watching TV and we are like with the blankets and really-really cold, we talk to each other and say "okay we need to do something because we are not like this"* [John]

However, these users also noted that generally they were very individual in their actions as a result of not being together when making these decisions. This even lead to unawareness of the other's alterations, which could mean diminished understanding for users, but poses questions regarding the appropriateness of notifications for other user changes and whether this should be configurable at the send or receive stage:

> *"Except for one night that I turned the heating on." [John] "By the app?" [Mildred] "Yeah!" [John] … "So it turned on?" [Mildred] "Yeah. I had to do it twice."* [John]

Furthermore, in some cases, the interface became a critical part in discussions when disagreements occurred and was used to settle arguments or justify heating behaviour:

> *"Occasionally I use it to prove a point. Especially when it was really cold and I would be like "Paul, it's really cold in here" and he'd be like "No, it's fine, put a jumper on" and I would check the temperature and use it that way."* [Diane]

Overall, users were inclined to think a smartphone control application was a more social, yet personal experience for controlling heating, that may be particularly useful in shared households:

> *"I think it's more of a collaborative thing than normally if you turn the heater on, it would be one person walking to the heater and turn the heater on, but with this if you have different people*

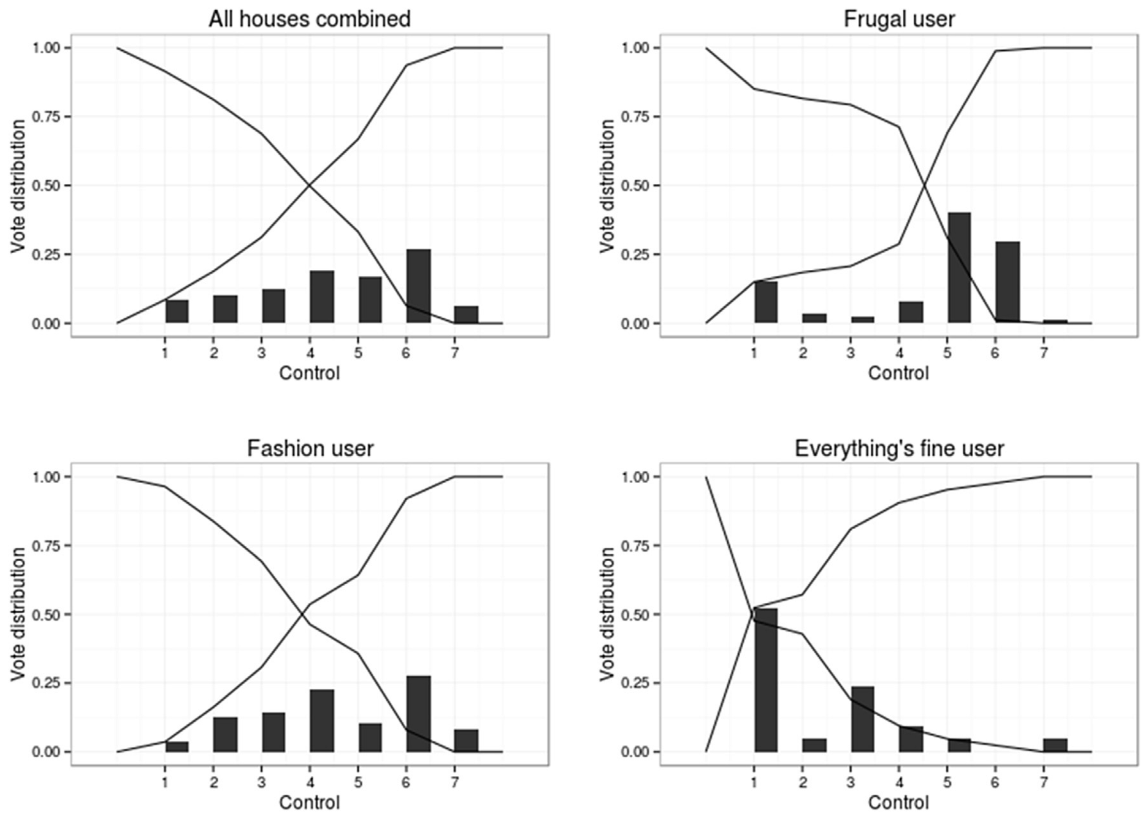


Fig. 12. Distribution of control votes for all houses (top-left), fashion user (bottom-left), frugal user (top right), and everything's fine user (bottom-right) from 1 – none to 7 – complete control, with cumulative distribution function in both directions.

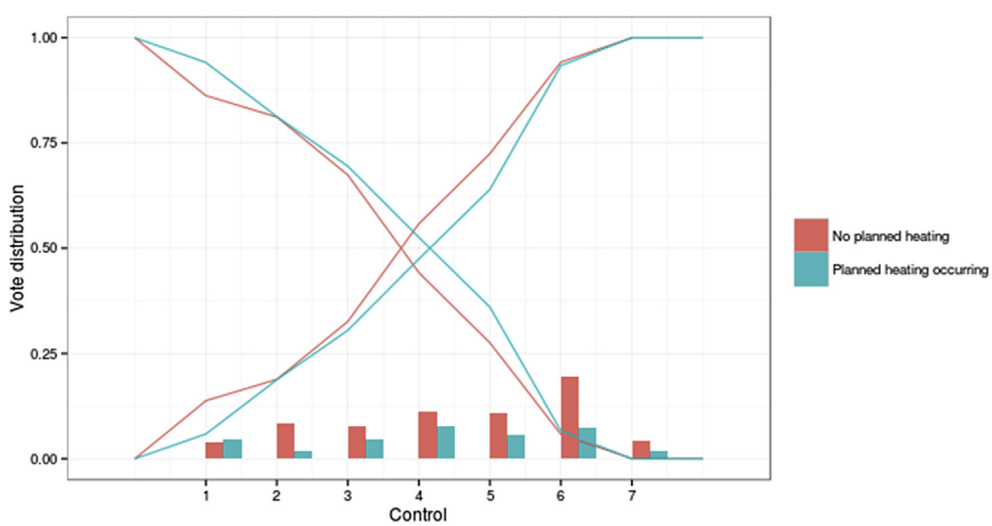


Fig. 13. Distribution of control votes, broken down by system state at the time of vote & cumulative distribution functions in both directions for either system state.

accessing the same thing on their own devices. Or you know the thing where you can give a vote, although we never really did that because it was just me and Paul and we either wanted it on or we didn't. But say in a shared housing if you had like 5 people I can see it being used that way like "Okay, we will vote to have the heater on or not." or like the workplace or something, I guess that's more … like a shared element." [Diane]

However, this shared element created an interesting dynamic for houseguests. The 'fashion' user occasionally had their partner stay over for long weekends, which sometimes meant the user with the control application was not home, when the guest was. Removing control from a physical location in the home meant the user had to make a decision whether to involve the guest as a member of the household and give them access to the house data:

> *"Generally, because it was my other half, I just said to her, if it is too cold, just text me and I will turn it up. Just because it was easier than to get her to install the app. Because it is just like, short periods of time, it never seemed worth for her to get the app. Looking back now, it probably would have been worth [it]"* [Carl]

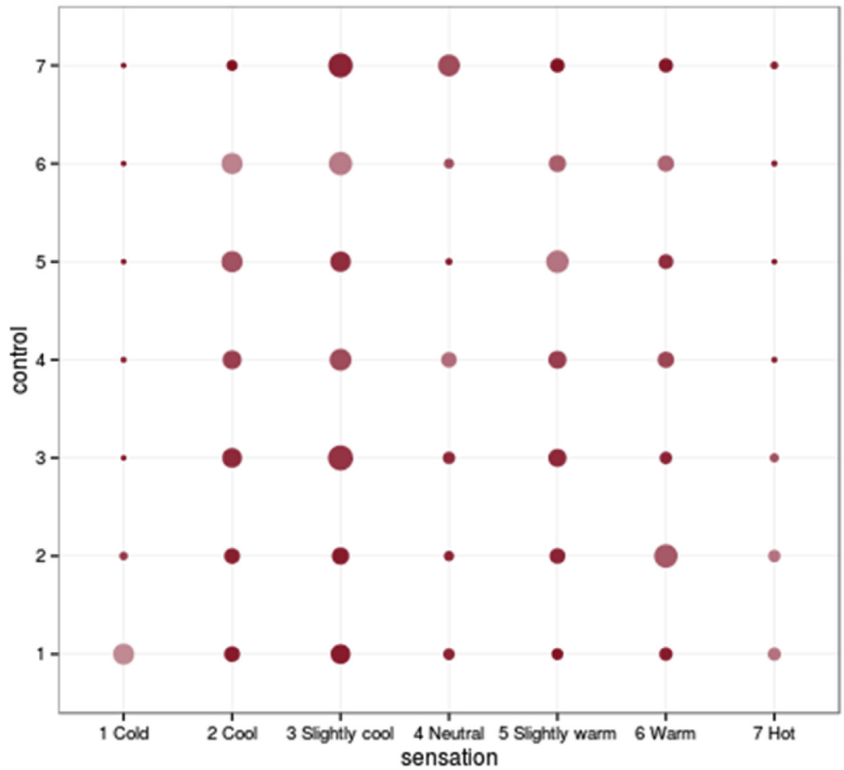


Fig. 14. Distribution of control votes, broken down by user's thermal sensation at the time of vote, size of node indicating probability sensation being felt and intensity of colour indicating the probability perceived control vote given. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

These results show that the control interface is used in various social situations and subject to social and privacy dynamics. Moving the control interface from a shared physical location to personal digital device means the user experience design needs to consider the implications of dividing and distributing control over a shared space in individual domains. Furthermore, the results highlight how the interface can influence both heating behaviour and the social interactions surrounding it.

3.2.4. Unforeseen interactions that emerged from the application use

Several unforeseen behaviours emerged, highlighting the unpredictable nature in which users may adapt their use of a 'connected' or 'smart' home. In the 'frugal' household, Paul often worked from home, meaning the heating system experienced variation in presence patterns and used push-notifications to solicit users' feedback. This provoked interesting social nuances regarding privacy:

> *"That's something quite funny because quite a lot of the time when I am at work and Paul is at home, I know when he gets up, because that notification come on. Like Paul goes in the bathroom and it's like "Hey, should your heating be on?" and it is like half past ten in the morning and I know he has just moved."* [Diane]

This even prompted conflicts between users because of the system disclosing presence data:

> *"But like I know when Paul is like... you've said to me before that oh "I will leave uni[versity] at 4 o'clock" and then I will get a notification from home at half 3 and I know that you've left work early..."* [Diane]

These results highlight important problems caused by the data that this technology innately holds, as well as the privacy concerns it raises. In contrast, remote control also provoked interesting benefits as Carl reported utilising temperature readings as a home security surveillance method:

> *"… because of the way my house is laid out - the front-facing windows to my lounge are road-side and the temperature sensor for the lounge was semi-near a window. And so when I was away I would check the temperature, because before [the weather] got extremely hot, I was keeping all the doors shut so I was getting almost complete separation between rooms. And I was basically as a safety blanket going - "Is that room the same temperature than the other rooms, because if the temperature changed significantly … between this room and the other rooms, something may be up. Because a window now has been opened and there is no reason for a window to be opened. And this was particularly true before I got my security system fixed."* [Carl]

This highlights additional benefits for users merely stemming from a technology intervention that they did not have available to them before and how this enriched their UX adding value above the system's function.

The results demonstrate potential problems and opportunities arising from increased sensory technology in people's homes, suggesting that successful designs must navigate personal privacy retention without compromising ability to explain system's functional logic.

3.3. Interactions with the smartphone control application

The researchers were interested in gaining an insight into the dominant interactions with a smartphone heater control interface that prevailed over long-term in-situ use. Three major use cases prevailed – a checking behaviour (users would go through the different rooms to monitor temperature and system state), a control behaviour (users would use the application as a control device to change the temperature to eliminate discomfort), and programming behaviour (this prevailed most dominantly for long away schedules, motivated by a wish to ensure the heating stayed off during absence).

> *"But I used it when I could remember to basically. So if I knew we were going away for more than say 3–4 days, I used the away feature then because I wanted to make sure the heating definitely didn't come on basically."* [Diane]

> *"…last week I went to London and then I programmed it and then when I went to Spain I did it again. So at the beginning I wasn't using it that much and within the last week I used it 3 times which is more than usual."* [John]

Fig. 15 left highlights that users primarily interacted with the rooms and temperatures visible on the home screen, sometimes managing away schedules, and almost never providing a vote without being provoked for it. Fig. 15 right further illustrates this and depicts the events that were logged on these screens – a large majority of all events regarded clicking through rooms, which sometimes led to a change temperature event. Interestingly, the 'create long away schedule' event was second lowest by occurrence, yet all three households mentioned its importance in the interviews. This reinforces an interesting dynamic in UI design where usage frequency and importance and not synonymous and providing a meaningful user experience needs to observe a wider array of interactions that may not prevail in a snapshot UI test (households would not have required this feature if the system was deployed for 1–4 weeks).

All users described discomfort as the catalyst for interaction, but the 'fashion' and 'frugal' users also referred to the checking behaviour as a key part of their interactions, while the 'everything's fine' users experienced fatigue in this behaviour due to lack of discomfort:

> *"I am in a given room and I find the temperatures either too hot or too cold. Which then proceeds to me checking the app. To adjust the temperature in that given room. … So say I am sitting in the living room, I think it is too cold, I go into the app to turn the heating up in the living room and I will then instinctively go through all the other rooms in the house. Just to see what the heating scenarios in those rooms are. Just because I get very irritated if the heating is on in a room that I am not in. … And then it should kind of, wait for a small period of time to see if it adjusts or not."* [Carl]

> *"…beyond actually like activating the heating or deactivating depending on the temperature, I do find it quite interesting just to monitor the temperature, just occasionally see what the temperature is. And I keep meaning to use it for the diary function."* [Carl]

> *"So I just choose the room I want to look at. I normally just scroll through the rooms and see what it is like anyway. … So if we are in the bedroom, I select bedroom and just raise it by a few degrees normally and make sure that the message comes through that says "okay I will do that" or whatever it is. And then sometimes I would do the vote and that's it. And then generally then once the heaters get to a certain point, then they will be off anyway, and they heat up quite quickly. I think they are more efficient than the ones we have now. Like it gets really warm and then I will go back into the app and just lower it by a few degrees and that's it really."* [Diane]

> *"…at first I always looked at it because it was so funny to see the temperature but then at some point I stopped looking at it."* [Mildred]

These results point to a common use case of checking and alteration – better highlighted in Fig. 16, which indicates the number of 'view room' that occurred within a 10 min time step and the volumes of these that translated into 'change temperature', and 'submit vote' events. From the graph, it is evident that two event flows occurred: (1) there were many occasions when users viewed one room and altered one room – they acted to make their immediate surroundings comfortable. And (2) when users viewed several rooms and altered one or more rooms – users acting to establish an overview and potentially guide the system's overall behaviour. Few interactions led to a submitted vote, indicating that explicit feedback submission was not part of a natural interaction.

Analysis of the view room and change temperature events over time (Fig. 17) showed that the checking behaviour was dominant during the first months of the experiment with a high number of view room events per change temperature event, followed by a decay to similar levels. This was consistent with the users' explanations demonstrating initial learning period substituting with more goal-orientated, controlling interactions.

Therefore, it has been demonstrated that users have two main motivations for interacting with the interface – managing irregularities when absent from the house and maintaining immediate comfort. The latter compromises of a checking behaviour (dominant during novelty or unfamiliarity with the system) that can transit to a system state alteration behaviour depending on mismatches.

3.4. Were specific interactions with the system dependent on prevailing conditions?

In order to understand reasons behind users' interactions with the heating system, the prevailing conditions – both regarding the environment and system functionality were mapped against the most predominant interaction that altered system state – users changing room temperature.

Firstly, data from different loggers (sensor data and user feedback data logged directly in experiment database, app interactions logged via Google Analytics) was cleaned and thermal feedback votes matched to existing change temperature events in the same 10-min time step. Only data with both matching entries (174 pairs in total) were used.

Interestingly, the temperature distribution (black lines) in Fig. 18 highlight that there was around 70% probability that change temperature events took place while the prevailing temperature in the room was most likely to make the user feel sensations between "slightly cool" and "slightly warm".

However, there was no significant change in the temperature between the overall and temperature change-specific temperatures, which meant that prevailing temperature was not solely a useful indicator of an impending temperature change event.

These are interesting findings since logic would dictate that users are most likely to perform system state alterations when thermal output was near the extremes of their discomfort. When the thermal sensations during votes were isolated (Fig. 19), it emerged that the highest number occurred at "slightly warm" and "cool" sensations.

These results tell an intriguing user experience story of proactivity. The data suggests that users acted not only to maintain comfort, but also in anticipation to pre-empt system 'overshoot' and curtail heating functionality as soon as they felt a warmer

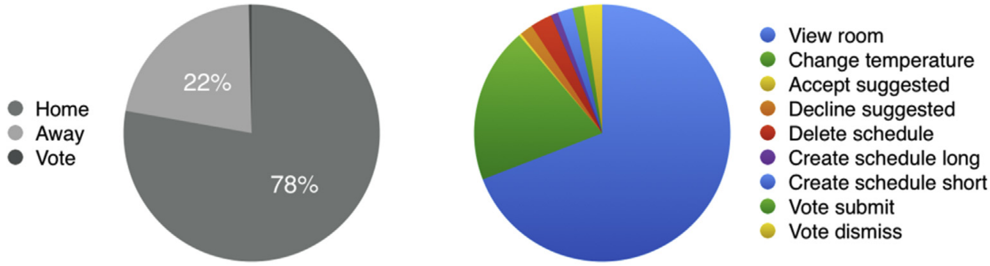


Fig. 15. Illustrating the interactions for viewed screens (left) and logged events (right) from all participants.

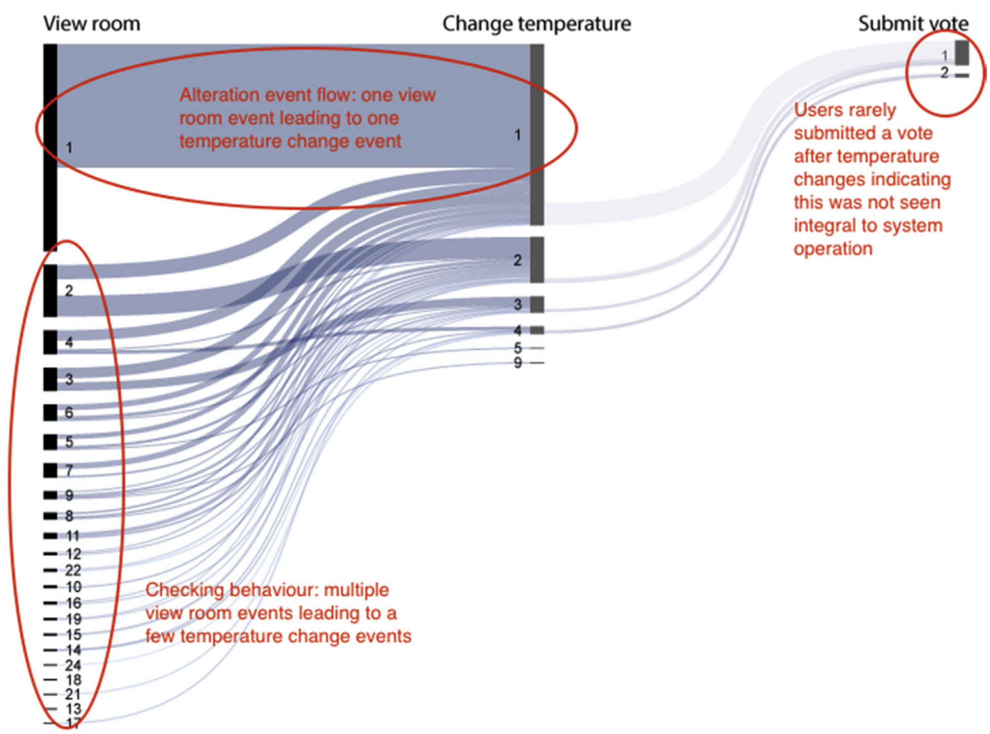


Fig. 16. Number of times an event occurred in a 10-min time step, arranged in the designed dominant use case of viewing a room – changing the temperature – providing a thermal feedback vote thereafter.

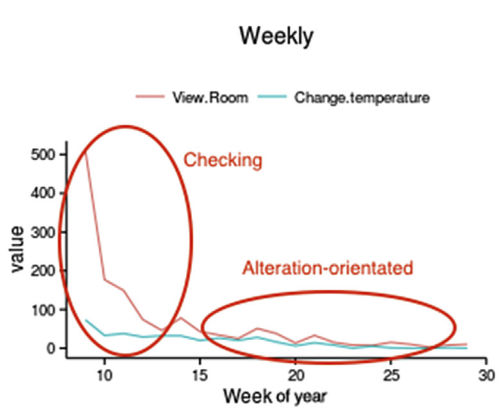


Fig. 17. Total number of View Room and Change Temperature events weekly over the course of the experiment.

sensation.

These results suggest suggested "maintaining" comfort and "managing" automation output to be better predictors of interaction than "restoring" comfort and "correcting" automation, also highlighting occupants' willingness to behave proactively alongside the system.

3.5. Dialogues with the system

User interactions throughout the duration of the deployment revealed interesting dynamics in the types of responses users are willing to give to system-initiated dialogues, as well as the timing of those dialogues. Throughout the experiment, users were prompted continuously to submit thermal sensation feedback through a push notification. Despite this, only two instances were recorded where the users viewed the vote screen without being directed there from a temperature alteration event. In total, over 400 votes were submitted, meaning users were much likelier to perform this action when they initiated the interaction and required alteration on system state than if the system asked for feedback on its performance.

> *"Probably I did at the beginning when I was trying everything but then I think you forget. Like you don't want to be thinking about it right."* [John]

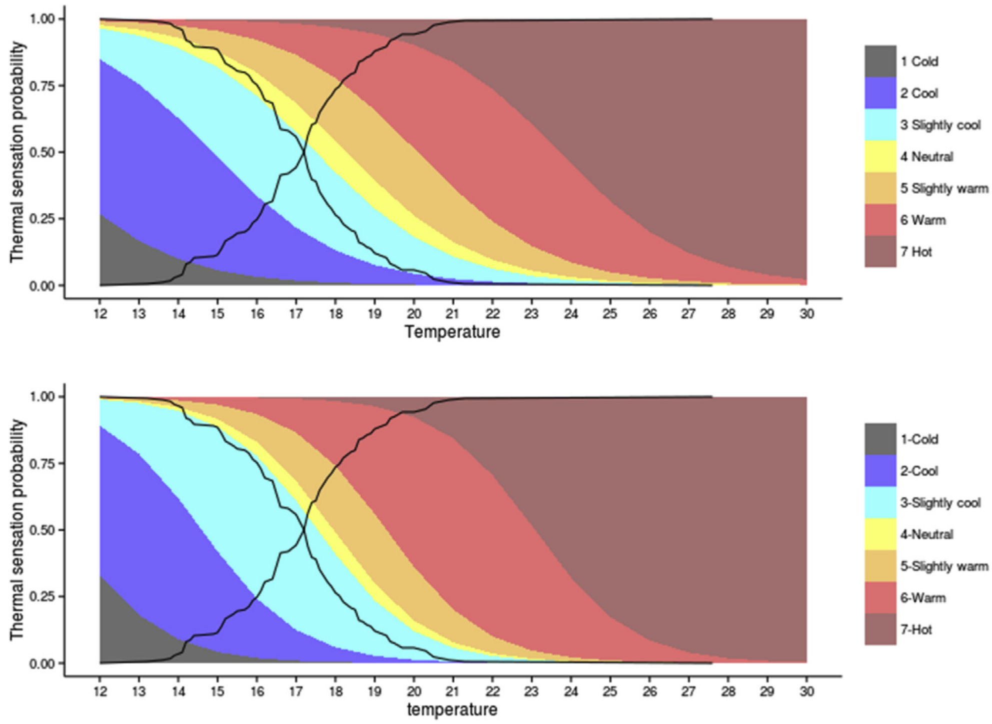


Fig. 18. Cumulative distribution functions for change temperature events plotted against thermal sensation probability distribution functions for all submitted votes (top) and votes given during temperature set-point changes (bottom).

> "…*your default thinking is just to ignore it you know like when you get a lot of notifications on your phone you just cross them off or whatever*" [Diane]

Similarly, users were very unlikely to respond to system prompts to give feedback on whether to heat or not when it was not predicting them to be in a space. 84.3% of responses declined proposed strategy and only a total of 38 responses were received despite often there being more than one notification per day. Furthermore, users experienced a high level of fatigue from the system push-notifications. An average of 6.8 push notifications per household per day were triggered by the system, which included prompt notification sent to solicit thermal feedback. Users opened just 1.8% of all sent notifications (3059 in total):

> *"The only thing I get is "hey, should your heating be on?" Ah, it's the same. I ignore it. They are all... the ******* things. And I stop it. I mean when I see it, it is probably that I am never thinking about it, so you don't want it."* [John]

As noted above, users enjoyed using the away schedules as it

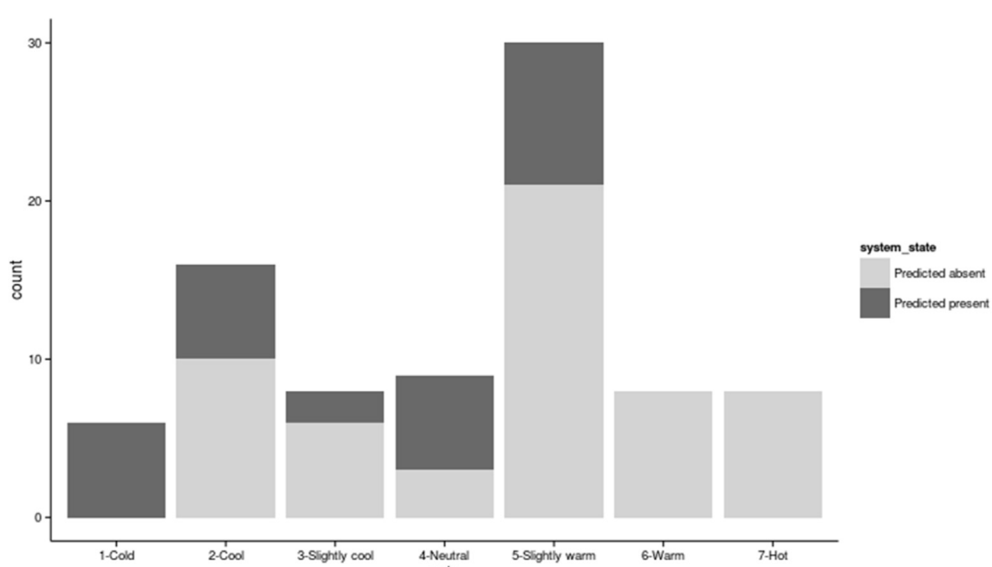


Fig. 19. Distribution of "change temperature" interactions by thermal sensation and predicted presence.

gave them an easy way to establish enhanced feeling of control, however, it was noted by some users that this was not a natural interaction for them:

> *"It is the kind of thing where … I had been out the house like 3–4 hours, before I went: " oh yeah, I should probably tell it that I am out." And then I get like half the weekends away ... And I went: "Oh yeah, I should tell it that I am not there."* [Carl]

This highlights interesting elements about the types of dialogues the system should be proactive about and which not. Furthermore, system proactivity in interaction should be tied to user motivations. It has been highlighted how exercising override on heater state generates feelings of control in the user, suggesting the system shouldn't rely on user proactivity in highlighting absences, but should rather inform the user when it makes absence-related changes to the environment – for example, when it turns heating on to pre-heat the house, when the user is not present. At that moment, the user is motivated to administer over-ride if they will be home later, as they would not want heating to turn on without them there. Similarly, notifications at moments of confusion for the system i.e. 'should I be heating or not because the user is here and I didn't predict them to be' should be limited, alongside with proactive action. Instead, the system should learn from user-initiated interaction, relying on the fact that the user will alter the system state if the proposed strategy is not suitable.

It has therefore been highlighted how the system should aim to limit proactivity (which needs to be aligned to user motivations) for interactions and aim to maximise learning from user-initiated interactions.

3.6. Overall experience of living with the heating system/control application and whether users would prefer it over their existing systems

All study participants reported an enjoyable experience using the deployed system as a result of different reasons. Carl, the 'fashion' user benefitted from individual room control, which allowed him not to heat spare rooms while maintaining comfortable temperatures in the rooms he occupied. He described a high lack of control with his existing central heating solution, which eventually pushed him to taking part of the study. Carl and 'frugal' user Diane noted that taking part in the experiment allowed them to think of heating more as a 'system' rather than individual heaters on the wall. Both of these households reported to be more engaged with their heating behaviour because of the system, as well as the UI.

Several households highlighted the benefit of remote access for both monitoring and control purposes. Despite loss of some direct control as discussed above, it was noted that using a smartphone as an interaction device was regarded completely acceptable as "*you use your phone more and more for … everyday things like online banking and everything like*" [Diane]. In fact it was noted that the medium facilitates ease of operation for more complex and out-of-the ordinary operations such as irregularities in behaviour:

> *"For example whenever we go away, my dad would be in the cupboard for ten minutes to make sure everything was 'just so'. Whereas with this system, once you know how to use it, it's very simple to say whenever you are away for a week and it adjusts it quite quickly because you can check on the temperature if you wanted to. So I think user friendliness … especially for people maybe who aren't very mobile or who don't know how the boiler works or how the heating system works…"* [Paul]

Personal data concerns were only mentioned by one user, who noted they didn't feel like they were being recorded or watched, but would feel uncomfortable if their energy company started "bombarding" them with savings because of this. Interestingly, this was one of the users most concerned with minimising the cost of heating, highlighting that attitudes and behaviours may not align. All households agreed they would buy this type of a system if it was on the market and particular conditions such as cost (both purchase and savings delivered) were met. In addition, living in rented accommodation was a barrier to several participants, as well as home type – several users noted that relatively small number of rooms would mitigate the system's potential. Interestingly, the 'fashion' user noted they would miss the system as it had become a part of their home:

> *"Just as a whole, it was nice having the system in. It was a nice little system to have, it is going to be weird not having it here. Because I realised the other day that I have lived here longer now with the system than without the system."* [Carl]

4. Discussion

Our study involved participants living with a quasi-autonomous home heating system, the capabilities of which they were not aware of. Qualitative and quantitative data obtained gave an insight to UX of living with and controlling such a system.

Firstly, our methodological approach highlights the attainability of context-specific long-term research required to fully understand the manner in which human beings interact with home automation systems. Existing body of research commonly overlooks UX exploration in a highly ecologically valid setting over extended periods, preventing emergence of potential use strategies and interactions resulting from the rich use context. This was here demonstrated through the emergence of unexpected home-security and inter-occupant 'spying' behaviours, observed manner in which interactions changed over time, heating behaviour change from initial excitement by a new technology through learning stages to knowledgeable usage, and usage of specific UI functions (including scheduling long periods away from home), all of which would not have emerged during a short deployment and users' subsequent lack of thorough familiarity with system behaviour. Furthermore, the 'spying' behaviour further demonstrated the importance of data privacy. While a commonly acknowledged issue, we have shown how even keeping data within the household can cause social issues within the user group. This poses interesting questions regarding the extent to which one's personal life really is personal or whether certain personal privacy limitations such as a parental awareness of their child's presence in the house are acceptable. Furthermore, whether such instances are the users' problems, or whether it is the responsibility of the autonomous system interface to protect privacy at the potential cost of fragmenting the collective awareness and engagement with the heating decisions and behaviours.

Secondly, we have described the emergence of three distinct user behaviour types that contrast significantly and are motivated by various factors including thermal preference, heating system control strategies and perceived co-operation with the autonomous system. These user types were not generalizable to the whole population and were not intended to be so. Humans are fundamentally stochastic in their nature and vary highly in their behaviour. Therefore, we do not attempt to classify behaviours, but to explore some typical and potential behaviours and interactions that may arise when a sub-set of users live in their natural environment with a spatiotemporal heating system. Our results highlighted the complexities of this context within which energy behaviour decisions are taken and the differences, as well as similarities, in factors affecting those decisions between different users. Furthermore, we have shown how these factors are not permanent, meaning that users primarily motivated cost, can at times act solely motivated by comfort and vice a versa.

Thirdly, we have presented several pieces of evidence for users making sense of the alterations in the environment that the heating system acts out. This type of behaviour is consistent with the tendency of novice users to construct mental models of the system to explain its functionality and guide their actions in operating the device. Alignment of the system's behaviour according to the constructed model to users' expectations emerged to be an indication of the user's acceptance of the system and trust in this. Misalignment to user's thermal preferences inspired a lack of trust and doubt in the system's health. Similarly, we have highlighted how applying a mobile interface can cause disarray through concurrent system alterations by multiple users. This disarray is subject to further complication by personal thermal preference, as well as the personal habits, economic and comfort priorities, and communication dynamics, which all affect thermal behaviours. Our users' display of unexpected behaviours regarding interpersonal dialogue highlighted how availability of information and engagement with the system can alter not only heating decisions, but the communication process leading to the decisions.

Fourthly, our results highlight several implications regarding the user experience of quasi-autonomous home heating systems, which are arranged according to our conceptual model (Fig. 20).

As indicated under item 1 in Fig. 20, the user interface becomes part of social environment, influencing the social interactions and subsequent energy decisions. Furthermore, (item 3 in Fig. 20) transferring the control interface from a cumbersome interaction in a physical location in the home to a convenient interaction in the smartphone that the user has constant access to, promoted more frequent heating system monitoring behaviour. Arguably, this increase could instead be attributed to users' lack of familiarity with the system and subsequent need to ‘keep an eye on it’. Regardless of the origin of increased engagement, this initial monitoring behaviour not only facilitated users' understanding of and experience of over-riding control over the system, but also educated them of their thermal preference, which subsequently affected the actions they performed to maintain their thermal comfort (item 3 in Fig. 20).

We have also provided insights into qualities of dialogues users have with the heating system. As interfaces transfer into our smartphones, technology makes it easy for automated systems to trigger communication with users through push notifications at times of uncertainty or when system state changes are broadcasted. We have highlighted the need for assessing the essence of these dialogues in order to limit noise and prevent disengagement of users. We propose system-initiated dialogues to be aligned closely with critically perceived utility of the communication and the user's motivations for engaging with it. In other words, users need to be prompted when otherwise unnatural interaction (such as telling your home you will be away) would result in user-desired goals such as energy saving, while aiming to minimise all communications. Notification settings should be utilised to allow users to define the varying level of system-initiative in dialogues, as any system initiated dialogue can be a barrier to user engagement.

All of the aforementioned in combination with our examples of the manner in which users utilised sounds, thermal, and visual cues from the various technological components to monitor and make sense of the system's behaviour highlights the need for a holistic design approach if a successful implementation is required. We can observe that our users displayed a situated action pattern of behaviour (Suchman, 1986) when making decisions regarding the system functionality and their thermal behaviour. While they were able to outline broad strategies and goals for their decisions (such as curtailing expenditure for frugal users), their decision-making in natural situations displayed the quality of reacting to prevailing conditions in order to fulfil a number of goals within various constraints. We, therefore, suggest an entirely holistic approach focused on the interactions of users embedded within the domestic context (context affected by architectural factors, dynamics of the

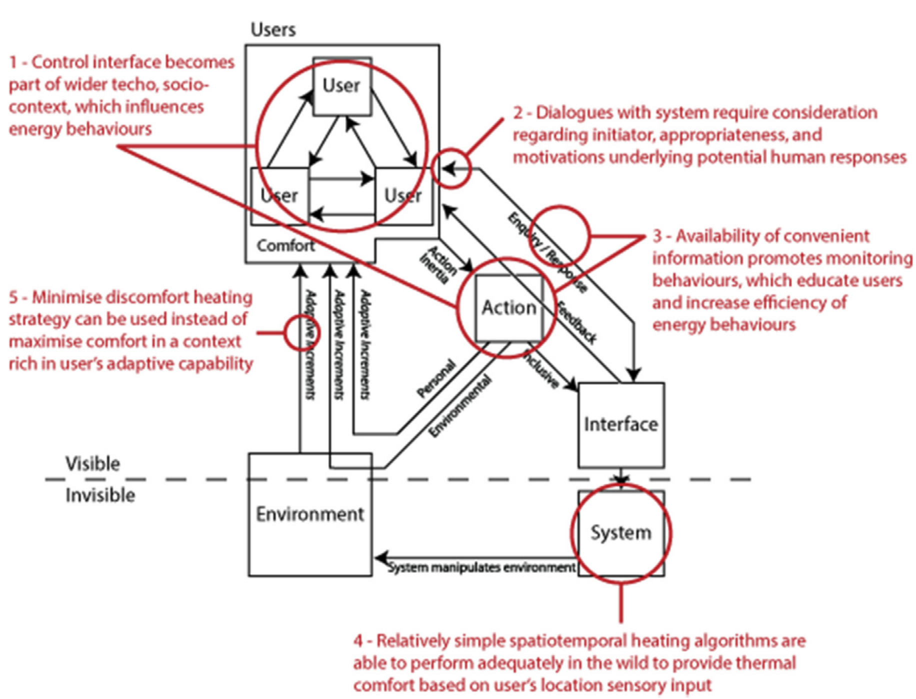


Fig. 20. Conceptual contributions & implications of field study results.

heating system, nuances of thermoregulation and thermal behaviour, social interactions, the system control interface and multi-user interactions with it), to be central to the design of automated home heating and other systems.

5. Conclusions & future work

In this paper we have demonstrated the ability to achieve a fine degree of spatiotemporal heating control in the domestic setting and the socio-thermo-technical complexity of the setting by deploying a quasi-autonomous heating system. The deployed technology not only allowed us to identify diverse behaviours, but it also supported them in situ by nudging, facilitating dialogue about, and engaging users with their energy behaviour. We have highlighted how the interactions with the interface naturally exist in the background fabric of life and the control interfaces' UX needs to be built to be invisible and fit within the user's existing behaviour in order to best nudge them and maximise efficient energy use.

In our future work, the knowledge obtained here of the interactions taking place, their impact on the energy behaviour, dialogues with the system, interfaces role in the social context, and other uncovered user experiences will be triangulated with simulation and prototype analysis work to synthesis a design agenda for enhancing the design of user experiences for smart home heating systems. In addition, key limitation of this study regard its generalizability and as such, the experiences uncovered in this work would benefit from validation through replication with a larger sample size and a more rigorous study design to discover potential causalities and correlations between interface qualities and users' understanding of the system, control, and likely desired interactions. As an exploratory study, this research involved several independent and dependent variables that should be separated and each observed appropriately utilising a representative sample, if any saturation of responses is to be achieved. It is crucial, however, that the rigour in study design focuses on delivering results for a wider design agenda – distinction needs to be made between assessment of an interface and its underlying qualities that exist separate of specific form or function.

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