DESIGNING THE USER EXPERIENCE OF A SPATIOTEMPORAL AUTOMATED HOME HEATING SYSTEM: A HOLISTIC DESIGN AND IMPLEMENTATION PROCESS

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ABSTRACT

This research explores technological interventions to reduce energy use in the domestic sector, a notable contributor to the global energy footprint. In the UK elevated challenges associated with renovating an outdated, poorly performing housing stock render a search for alternatives to provide immediate energy saving at low cost. To solve this problem, this thesis takes a holistic design approach to designing and implementing a spatiotemporal heating solution, and aims to investigate experiences of comfort, thermal comfort concepts for automated home heating, users' interactions and experiences of living with such a system in context, and the underlying utility of quasi-autonomous spatiotemporal home heating.

The mixed-methods research process was employed to explore and answer four questions: 1) what is the context within which these home heating interfaces are used, 2) to what extent can spatiotemporal automated heating minimise energy use while providing thermal comfort, 3) how are different heating strategies experienced by users, and 4) How do visibility of feedback, and intelligibility affect the user experience related to understanding and control? Ideation techniques were used to explore the context within which the designs are used with regard to all factors and actors in play and resulted in a conceptual model of the context to be used as a UX design brief. This developed model used mismatches between users' expectations and reality to indicate potential thermal comfort behaviour actions and mapped the factors within the home context that affected these mismatches. Potential user inclusion through participatory design provided stakeholder insight and interface designs concepts to be developed into prototypes. The results of a prototype probe study using these prototypes showed that intelligibility should not be an interface design goal in itself, but rather fit in with broader UX design agenda regarding data levels, context specificity, and timescales. Increased autonomy in the system was shown not to directly diminish experience of control, but rather, control or the lack of originated from an alignment of expectations and reality.

A quasi-autonomous spatiotemporal heating system design (including a novel heating control algorithm) was coupled with the design of a smartphone interface and the resultant system was deployed in a low-technology solution demonstrating the potential for academic studies to explore such automated systems in-situ in the intended environment over a long period of time. Assessment of the novel control algorithm in an emulated environment demonstrated its fitness for purpose in reducing the amount of energy required to provide adequate levels of thermal comfort (by a factor of seven compared with EnergyStar recommended settings for programmable thermostats), and that these savings can be increased by including occupants' thermal preference as a variable in the control algorithm.

Field deployment of that algorithm in a low-tech sensor-based heating system assessed the user experience of the automated heating system and its mobile application-based control interface, as well as demonstrated the user thermal comfort experience of two different heating strategies. The results highlighted the potential to utilise the lower energy-use "minimise discomfort" strategy without compromising user thermal comfort in comparison to a "maximise comfort" strategy. Diverse heating system use behaviours were also identified and conceptualised alongside users' experiences in line with the developed conceptual model. A rich picture analysis of all previous findings was utilised to provide a model of the design space for home automated heating systems, and was used to draw interface design guidelines for a broader range of home automation control interfaces.

The work presented here served as important first steps in demonstrating the importance of assessing UX of automated home heating systems in situ over elongated periods of time. Novel contributions of (i) conceptual model of automated systems' domestic context and thermal comfort behaviours within, (ii) nudging this behaviour by selecting a "minimise discomfort" heating strategy over "maximise comfort", (iii) using UX to influence user expectations and subsequently energy behaviour, and (iv) inclusion of thermal preference in domestic heating control algorithm were all resultant of examining naturally occurring behaviours in their natural setting. As such, they are important exploratory discoveries and require replication, but provide new research directions that would allow reduction of domestic energy use without compromise.

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PUBLICATIONS

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1 INTRODUCTION

1.1 Chapter overview

This chapter sets the scene for the research by stating the problems that it intends to solve. The aims of this research are explained through key methodological, empirical, and theoretical contributions. Finally, the organization of the thesis is addressed, demonstrating the activities through which the research aims are intended to be achieved.

1.2 Problem Statement

"Given the profound changes that housing design is currently undergoing to meet the tough low-carbon agenda set by governments around the world, occupants need better guidance and vastly improved systems." (Stevenson and Leaman, 2010, p. 440)

The statement above captures the essence of the problem this research aims to help solve. In order to understand the problems this research addresses, attention should be first drawn to the global situation that our planet faces. While it is commonly accepted that earth's temperature naturally fluctuates, the average global temperature at the beginning of the 21st century was higher than the long term-average and current warming is occurring more rapidly than in the past events" (Riebeek, 2010). Greenhouse gas (GHG) emissions have been highlighted as a major influencer of climate change over the last thousand years (Crowley, 2000). Fossil fuels currently account for 74% of all CO_2 emissions (Sims et al., 2007), making carbon emissions reduction one of the greatest challenge of the 21st century. The Intergovernmental Panel on Climate Change (IPCC) has suggested that 40-70% global anthropogenic GHG emissions reduction by 2050 and near or below zero emission levels by 2100 is necessary to maintain global warming below 2°C over the course of 21st century (Pachauri et al., 2014). In order to achieve that, the UK government has established legally binding targets with the Climate Change Act to lower the UK net carbon account 80% below 1990 baseline by 2050 (UK Parliament, 2008).

Domestic energy use is the second largest energy use sector (27%) in the UK after transportation (Department of Energy & Climate Change, 2014a) and space heating accounts for 66% of that (Palmer et al., 2011). The government has invested heavily in the development of smart grids in hopes of reducing energy usage through technological intervention (Department of Energy & Climate Change, 2014b). Smart grids' potential for limiting high demand in peak times and reducing consumption through two-way communication of energy demand and supply, giving utility providers and customers more information regarding has been noted (Darby, 2010). However, technological interventions often bring social implications, highlighted by protests in California in 2008 against a law enabling utility companies overriding households' thermostat settings during peak hours (Chetty et al., 2008, p. 243). This illustrates the importance of correct implementation of smart systems for home controls.

At the time of writing, interest in home automation technologies from end-users was also on the increase, primarily through a variety of specific 'smart' technologies (in other words, adoption of 'smart lighting' rather than a 'smart home' overall). In this research, the terms "smart home", "intelligent home", and other variations of these terms are used interchangeably to denote a domestic space in which an amount of quasi-autonomous technology (encompassing capabilities to observe its environment, make decisions about it, and act these decisions out) could be observed. Similarly, 'home automation' is used to describe products that automate specific functionality in the home setting, rather than a 'connected home' where all automation is integrated in a 'bathroom door tells coffee maker to turn on' scenario. In other words, this research focuses on a single application (home heating), but it is acknowledged that such applications would exist within an Internet-of-Things digital environment.

Personal devices such as smartphones, tablets and wearable technology have become commonplace and equipped with a plethora of sensing and communicative capabilities, they provide ideal means for interfacing with home appliances that have also experienced an increase of connectivity and sensor integration. Early commercially successful examples of such devices include the Nest Learning Thermostat (Nest, 2012) that learns user's temporal temperature set-point preferences and acts out a heating schedule based on these. Subsequently, other devices have entered the marketplace, including similar smart thermostats (Ecobee, 2015), home security products (Glate, 2015; Kwikset, 2015), lighting solutions (Philips, 2015), enhanced fire alarms (Nest, 2015), Wi-Fi-enabled plugs to turn standard home appliances 'smart' , or general home-automation products (Fibaro, 2015; Smartthings, 2015). Interestingly, the similar trends activity could, at the time of writing, be observed in the start-up community, manifesting in new company and product launches through crowd-funding platforms such as Kickstarter (Kickstarter, 2015a, 2015b, 2015c) demonstrating the industry's interest and penetration into mainstream.

These commercial advancements have highlighted academia's need for keeping pace, which thus far has fallen short of its potential. Several pieces of research into energy use and users have been conducted (See Chetty et al., 2008; Leaman and Bordass, 2001; Revell and Stanton, 2012 for a few examples) but these either 1) do not assess the emerging smart technology in situ, 2) ignore influencing factors from other academic disciplines involved, or 3) do not consider the complex environment that these systems are used in. Therefore a more holistic approach should be taken.

To firstly elaborate on assessing the technology and human interactions with it in situ – so far, several 'lab-homes' have been built to simulate the environment and investigate the potential of smart homes (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). While these projects have taken important steps towards understanding the benefits and challenges that smart homes face, their critical shortcoming is their purposeful construction as an intelligent space, meaning that they are not a realistic representation of a real-life dwelling or its occupants. As demonstrated above, focus is shifting from a unified intelligent living space created by a single company towards a utilitarian approach of device- and application-specific functionality that can be integrated with other similar systems. The latter is the essence of Internet-Of-Things and its growing popularity has been demonstrated. In short, this author shares the view that intelligent homes will be an evolutionary development from existing homes (application-specific automation), rather than a revolution of new homes (unified lab homes) (Rodden and Benford, 2003), meaning that in-situ assessment of such systems needs to take place in the contextually correct setting.

Secondly, research focused on implementation of automation technology in an existing home, requires a certain level of technical input which has rendered much of the work in this field solely technology driven. By that it is meant that work has focused on assessing the computational models of presence, heater control, thermostat settings, sensor data, etc. but has either almost entirely ignored the occupant who would live with said system, or treated them as a deterministic being who fully complies with the system and displays no stochastic behaviours. A more recent occurrence – a multidisciplinary approach – has usually been long-winded and required a significant amount of university resources to combine computing, psychology, design, and other domains. In this researcher’s opinion, while this approach is superior to the technology- or computation-driven approach in its adoption of a holistic view, this researcher suggests a more low-tech design-driven multidisciplinary approach is more appropriate. By that it is meant that designers are problem-solvers by nature and place the user at the centre of the problem area. In addition, designers' tendencies to prototype early and iterate often allows for an agile approach in research. Such an approach would be particularly beneficial in the fast moving digital economy that thrives on start-ups and innovation, observable at the time of writing. This work seeks to replicate this mentality in its research.

Thirdly, the previous paragraph highlighted the necessary multi-disciplinarily of the problem space, meaning that we are dealing with a very complex and changing system with a multitude of factors and actors. More specifically, unlike automation at a workplace, interactions with the automation are far less likely to be at the core of users' activities in the domestic setting. Since automation takes a lot of control away from users, the interfaces that facilitate communication between the users and the automated systems need to take this into consideration. In addition, there are challenges associated with the ways people use their home space and matching the heating controls to this, as well as the various activities, social interactions, and thermal environments that all influence the users' decision-making process. Therefore, for any significant step towards a useful 'smart' home-automation solution to occur, it is important to consider the users and the true-to-life use context.

In order to address these gaps in knowledge, this research aims to investigate the role of user experience (UX) design for smart home heating systems in situ. The objectives of the research are to 1) take a holistic design approach to designing and implementing a spatiotemporal heating solution, which would allow to 2) investigate experiences of comfort, thermal comfort concepts for automated home heating, users' interactions and experiences of living with such a system in context, and the underlying utility of the system.

1.3 Contribution of this research

This research provides methodological, empirical and theoretical contributions to the automated home and home controls UX design domains as follows.

1.3.1 Methodological contributions

This research presents an agile prototyping solution to implementing an automated home heating solution in real world housing. The methodology, based on sensors, a computing unit, Wi-Fi-enabled plugs, and a smart-phone controller, is combined of off-the-shelf components and is highly customisable. The solution presents a methodology that could be adapted for several different home automation applications and allows systems or interfaces to be tested in real homes with relatively little cost and in an agile iterative manner.

1.3.2 Empirical contributions

This research has three empirical contributions. Firstly, a novel spatiotemporal heating algorithm that includes users' thermal preferences as variables is presented and its fitness-for-purpose assessed. Secondly, the potential for a spatiotemporal heating system to deliver energy saving is assessed. And thirdly, the users' thermal experience of different heating strategies including comfort maximization and discomfort minimisation are explored.

1.3.3 Theoretical contributions

The three main theoretical contributions of this research regard (1) understanding of human thermal comfort, (2) conceptualising the domestic design space for automated systems, and (3) design guidelines for UX and interface design and the role that intelligibility and visibility play in them.

1.4 Organization of thesis

This thesis follows a structure of parallel streams of activities illustrated in Figure 1-1.

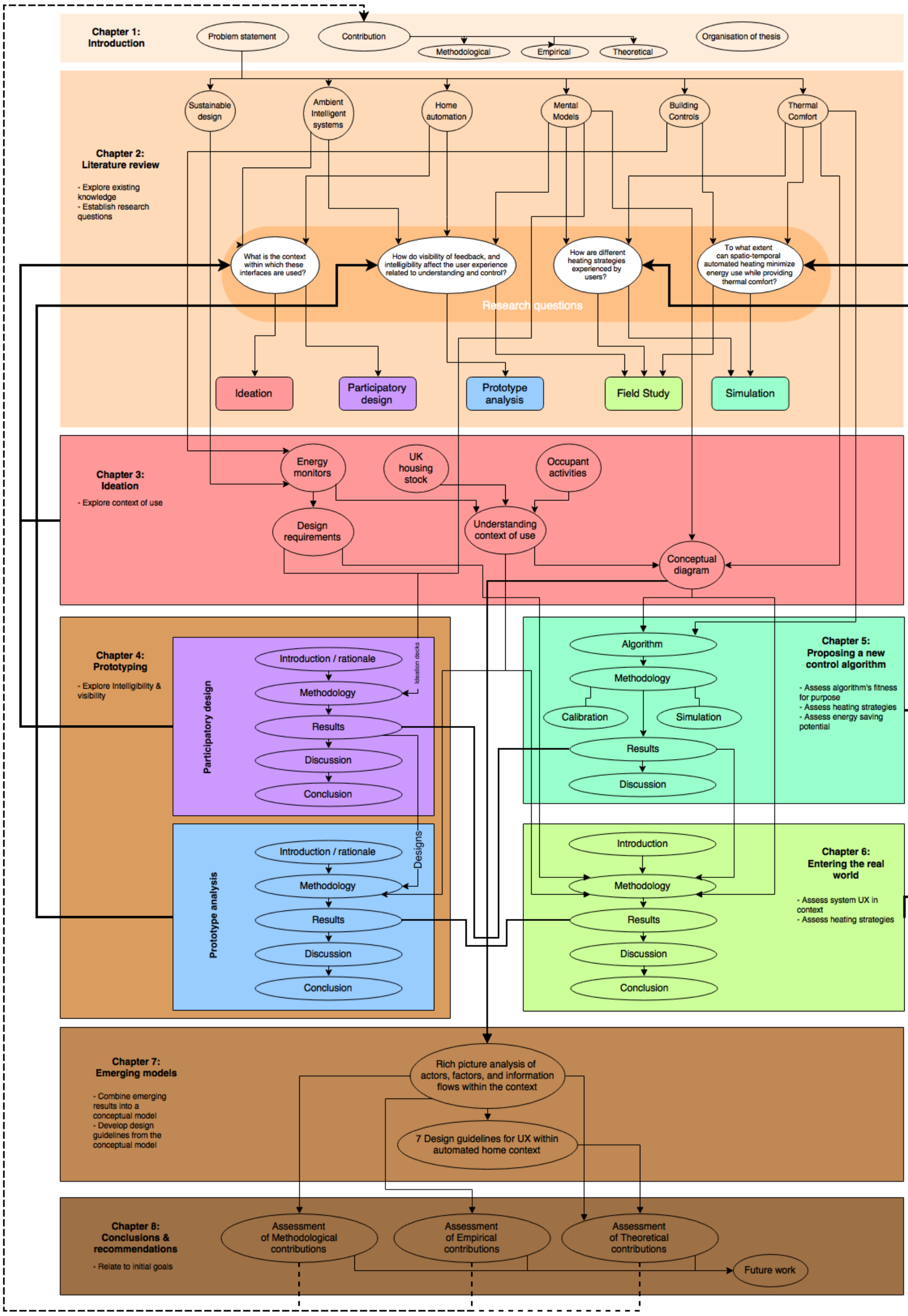


Figure 1-1 Thesis structure

Initially, existing literature from several domains will be explored and the research questions established. Subsequently, the application domain and context of use will be explored to establish the design space, following which the activities divided into two streams. The “applied” stream was focused on the design of spatiotemporal heating control algorithm, testing of the algorithm and application of the algorithm in a longitudinal field study; while the “design” stream dealt with exploration of the interface design elements and investigates the role of intelligibility and visibility through participatory design and prototype testing experiment.

2 LITERATURE REVIEW

2.1 Chapter overview

This chapter focuses on the existing knowledge that can be built upon. Firstly, the scope of the reviewed literature is considered, followed by reviews of relevant fields. Each literature field section begins with the wider knowledge within that field, before focusing on the most relevant findings and implications to this research. At the end of this chapter, research questions are established within the context of existing knowledge gaps and activities to answer these questions identified.

2.2 Literature boundaries

The literature reviewed in this research is extremely multidisciplinary and several fields can make plausible claims for relevance. However, boundaries need to be drawn as review of all relevant literature has the breadth to be an independent PhD research. Hence, the observed relevant literature has been divided into 4 categories: Contribution – the fields this research contributes to, Informing – relevant fields that inform this research, but are not directly contributed to, Mention – fields that have knowledge to contribute, but are not fully explored due to the chosen research perspective, and Awareness – fields on the periphery of this research and while a the researcher was aware of those, they were not explored. The categories are illustrated in Figure 2-1.

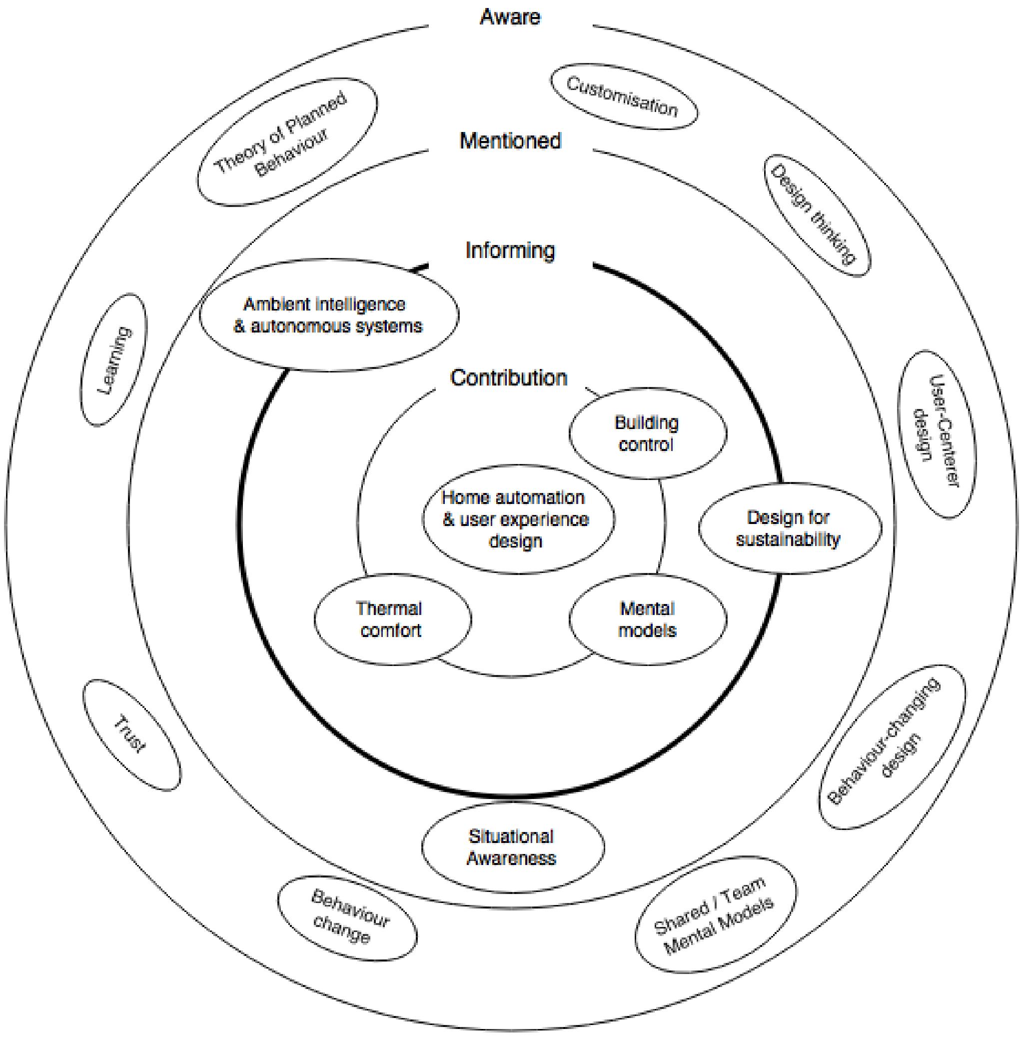


Figure 2-1 detailing the boundaries of relevant literature

2.2.1 Contribution

The body of work presented here aimed to contribute to three fields of literature to a varying extent: home automation, UX of building controls, and thermal comfort. There was a significant amount of overlap between home automation and building control areas but since the two research fields had a distinctly different focus, they were treated as separate. Home automation focused on the adoption of automation technologies into the home setting and Building controls was seen to be more concerned with the element of human control and consumption of utilities. The bulk of thermal comfort literature fell in the 'Informing' category, however there were specific contributions regarding the potential of different heating strategies for home automation and how these were thermally experienced by occupants.

2.2.2 Informing

Fields under this section included mental models and a large part of thermal comfort literature, which served to inform the specifics of the application domain and the interpretation of interactions in context. Others included ambient intelligence and design for sustainability for somewhat different reasons. Within the ambient intelligence literature, there has been interest in intelligibility of ubiquitous systems, which can lend much to the work at hand. Similarly, it has been pointed out above that research in the current field can benefit greatly from adopting a design approach. It has been seen in other fields of life that technology may exist in ready form, but was not accepted to wide-scale use until delivered in a product well designed for end-customers. Hence, it was accepted that the field of product design for sustainable living could inform design in the current domain.

2.2.3 Mentioned

The literature fields in this section were seen to have a large overlap with the informing literature and the literature in which this research aims to make a contribution in, but were not deemed paramount to the problem at hand. For example, as mentioned above, a huge part of the design for sustainability literature was not relevant and thus fell under this category. Similarly, while there were some parts of ambient intelligence literature that were extremely relevant, others were not.

2.2.4 Aware

These fields of literature were seen as peripheral to this research. It was accepted that a point of relevancy can easily be argued for many of these, for example theory of planned behaviour (Ajzen, 2007, 1991) or behaviour change (Verplanken and Faes, 1999), trust (Jiang et al., 2004; Lewandowsky et al., 2000; Rempel et al., 1985), or design thinking (Beckman and Barry, 2007;

Brown and Wyatt, 2010; Kimbell, 2010, 2009; Liedtka, 2011). It may also be argued that this whole research adopted a design thinking, or systems thinking approach, however, such notions were perceived as philosophical issues and while debate on those would be an intriguing affair, the more practical approach taken here renders such debate out of scope of this research. Instead, this work focuses on the practical nature of designing a system, deploying it, and exploring the user experiences it created, therefore, intricacies of more theoretical fields of knowledge are only utilised episodically in this research, and even then from a practical point of view.

2.3 Sustainable design

As mentioned in the previous chapter, this research takes a design approach to home heating, but prior to that, it is worthwhile considering why the approach is seen as an appropriate way to tackle the problems at hand.

In this research the term 'sustainability' is used in the context of sustainable design, which in turn is defined through sustainable development. The latter is most commonly defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Wced, 1987, p. 43). Indeed, as noted previously, our planet is facing a situation where those future needs are not catered for. From this definition, Elkington (1998) coined the term triple bottom line, referring to a concept of a triangular model compromising of people, planet, and profit, which can alternatively be referred to as social responsibility, environmental responsibility, and economic viability. While there has been much debate about the essence of both sustainability and the triple bottom line (Marshall and Toffel, 2005; Parker et al., 2009; Seghezzo, 2009; Tijmes and Luijf, 1995), the intricacies of these definitions are not paramount to this research, and the provided are seen as sufficient to move on to the definition of sustainable design. Moreover, sustainable design seems innately more focused on the practical rather than theoretical issues in making advancements towards a better life loosely based on these principals. For example, Ann Thorpe defines sustainable design as “theories and practices for design that cultivate ecological, economic, and cultural conditions that will support human well-being indefinitely.” (Thorpe, 2007, p. 13) Sustainable design originates from ‘green design’ (Madge, 1997), a popular term in the 80s best described through its lack of delivering real change; for example, an example of green design would be making the same product, but a new version that consumes less resources when used.

An improvement is eco-design, that includes the full life cycle of the product from the extraction of its raw materials, to use, to eventual discard and the impact of all those; i.e. making a product from alternative materials that are easier to source, easier to recycle, and consume less resource during use. Subsequently, sustainable design emerges as a further extension of that, including elements of societal context, ethics, systems perspective and so forth (Madge, 1997). An example of this would be the replacement of a product with a service, such as carpooling or communal cars in cities – concepts that replace everybody owning a low utility, high negative impact product with means to achieve the same desired outcome through alternative, highly efficient, and low impact means. This concept is recognised in the current research, as it could be argued that a transition in mentality occurs with intelligent homes. Sustainable design moves away from single-product-single-function solution towards solutions that comprehend the wider situation, understand desired outcomes, and alternative routes to pursuing them, while aiming to decrease any environmental impact that people’s lifestyles may have. In addition, sustainable design as discussed above is thus fundamentally dependent on human behaviour and the context of that behaviour, both of which have been proven extremely difficult to change. However, design by nature is a problem-solving discipline and the field of design thinking is full of examples introducing profound change in the way humans behave and achieve desired outcomes through behaviour-changing design.

Therefore, it is seen of high importance that design as a practice is placed at the very centre of providing solutions to the domain observed in this research.

2.4 Ambient intelligence systems

This section focuses on the intelligent systems around us. Since the emergence of the personal computer, the objects and products we own have become increasingly smarter. The definition of 'smart' varies and several have looked at objects that have been made 'smart' and what implications these have on the interaction users have with them (Aitenbichler et al., 2007; Buurman, 1997; Mühlhäuser, 2008). Since in the current case, the product is the environment; this section will focus on smart environments, briefly looking at the history before turning to the state of the art, and implications for this research.

2.4.1 Intelligent Environments

The concept of intelligent environments has been in development for around 20 decades and is often attributed to the work of Mark Weiser (Weiser, 1991). Weiser's vision of ubiquitous computing and a world where computers were embedded seamlessly into our environment and assisted humans through perfect understanding and anticipation of events; has later been enhanced by the concept of Ambient Intelligence (AmI). This concept was introduced by the European Comissions IST Advisory Group (ISTAG) and promoted focus on user-friendliness, efficient service support and user-empowerment (Ducatel et al., 2001). Several reviews have been published on Weiser's vision (Aarts and Grotenhuis, 2009; Rogers, 2006) and notable steps have been taken to provide the technology and computing capabilities for the realization of such environments (see Das and Cook, 2005; Das et al., 2002; Schmidt, 2005; Srivastava et al., 2001; Wagner and Hagras, 2010; Wooldridge and Jennings, 1995; Youngblood et al., 2005 for a selection of examples). Seamless web-based communications infrastructure, unobtrusive hardware, dynamic distributed device networks, dependability, security, and natural-feeling human interface were highlighted in the ISTAG report as key requirements for AmI applications (Ducatel et al., 2001). Three technology development paths required for intelligent environments have also been presented (Kaasinen and Norros, 2007; as seen in Kaasinen et al., 2012, p. 5) and seen in Table 2-1.

ICT Everywhere	**Advanced Interaction**	**Algorithmic intelligence**
Embedded information and communication technologies	Natural interaction	Context-awareness
Communication networks	High level concepts in interaction	Learning environment
Mobile technology	Environment evolving gradually both by design and use	Anticipating environment

Table 2-1 three technology development paths required for intelligent environments

As mentioned, technology has developed to a point where the realisation of such environments is well within the realm of possibility and thus, research has been carried out into application of AmI in assisted living (Aarts and Wichert, 2009; Gill, 2008; Kleinberger et al., 2007; Niemelä et al., 2007), security and safety (Aarts and Wichert, 2009; Jin Noh and Seong Kim, 2010; Lee and Yoon, 2009), health (Brown and Adams, 2007; Jin Noh and Seong Kim, 2010), ambient media (Kaasinen et al., 2009; Kulesza et al., 2012; Plomp et al., 2010), and housing (Albrechtslund, 2007; Jin Noh and Seong Kim, 2010; Koskela and Väänänen-Vainio-Mattila, 2004). Furthermore, several 'lab-homes' have been built to simulate and investigate the potential of smart homes (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). However, these suffer from a fundamental issue of not being a valid representation of a real dwellings; as Rodden & Benford (2003) suggested, intelligent homes are more likely to evolve from existing homes, rather than be a revolutionary step of new homes with intelligent technology embedded. With this in mind, it is safe to conclude that research into smart technologies embedded into an existing home is a much more meaningful approach over research into new homes created with the smart technology built into them.

2.4.2 Findings from Ambient Intelligence Research

The field of ambient intelligence is wide and accounting for all significant findings beyond the scope of this research. Rogers (1995) classified people based on their acceptance of new innovations, and while there existed a large segment of technophiles, it was pointed out that intelligent environments may never be accepted by some (Punie, 2003). It has been shown that even after living with intelligent environment technology for six months, people failed to accept or trust it (Koskela and Väänänen-Vainio-Mattila, 2004). A triangular model of user acceptance of these systems has been presented, culminating with a “Do It Yourself Intelligent Environment” where users have not only accepted the system, but are actively engaged with it through personification and modification (Figure 2-2 as seen in E Kaasinen et al., 2012).

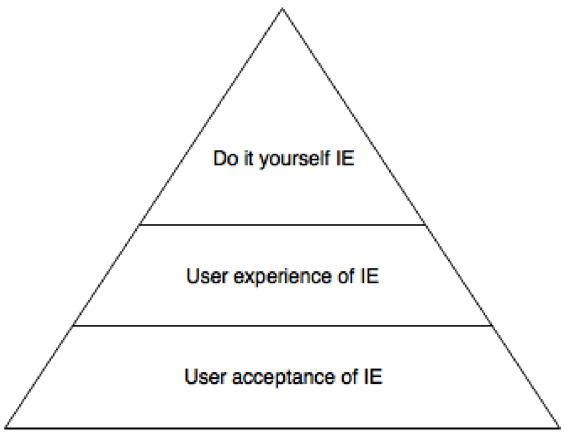


Figure 2-2 viewpoints of user expectations of intelligent environments (IE) as expressed by E Kaasinen et al., 2012

This viewpoint coincides with a suggested shift in ambient intelligence from maximum efficiency for the human user to more *meaningful* solutions (Aarts and Grotenhuis, 2009). Meaning, that people do not 'use' these systems, but co-inhabit the environment in which they exist (Kaasinen et al., 2012) and thus the systems need to deliver some 'benefit' (Shin, 2010) or 'value' (Kaasinen, 2009) to their users. The importance for these systems to fit into and support existing habits has also been discussed (Niemelä et al., 2007). Much experimental and case-study work has undergone into the element of control, including people's preference for increased control on account of effort (Misker et al., 2005); as well as willingness to sometimes give up control for specific benefits (Barkhuus and Dey, 2003). The importance of explanations in self-adaptive systems has been demonstrated and the essence of *why* questions broken down to *what* the system did, *how* the system satisfied its requirements and the *history* of adaptation events (Bencomo et al., 2012). The authors highlighted that this was a suitable approach for foreseen and foreseeable changes and acknowledged that ambient intelligence applications will often have to deal with unforeseeable changes (Bencomo et al., 2012). Kaasinen et al. (2012) observed multiple questionnaire and case studies (Hossain & Prybutok, 2008; Eija Kaasinen, 2009; Kim & Garrison, 2009; Shin, 2010) and concluded that several factors affected user acceptance of intelligence environments including usefulness, value, ease of use, sense of being in control, integration into practices, ease of taking into use, trust, social issues, cultural differences, and individual differences. The needs of considering people's expectations of intelligent environments has also been highlighted (Lee and Yoon, 2009).

2.4.3 Findings in current use context

One of the main issues with the systems described in this research is that they make their users feel that they did not have control over their environment. This has been shown to result from invisibility of the system, which meant the system was difficult to understand (Badia et al., 2009). Inability to understand the system's logic results in loss of trust in the system (Lim et al., 2009). To counter these effects, Bellotti & Edwards (2001) called for intelligibility and accountability in ambient systems. They defined and discussed the former as follows: "context-aware systems that seek to act upon what they infer about the context must be able to represent to their users what they know, how they know it, and what they are doing about it." (Bellotti and Edwards, 2001, p. 201) Self-explanation has been further explored, including development of 10 explanation types used by these systems (Lim and Dey, 2009); effectiveness of some of these explanations, notably 'why' and 'why not' explanations (Kulesza et al., 2009; Lim et al., 2009); development of a toolkit that automatically produces such explanations (Lim and Dey, 2010); visual depictions of correct predictions versus known failures (Talbot et al., 2009), and confidence of system making predictions (Kulesza et al., 2010; Mcnee et al., 2003). Enhanced intelligibility in the system, thus, increases people's understanding of the system's working, and has also been suggested to allow the user to tell the system how it should work (Kulesza et al., 2012, p. 10). Indeed, there exists a body of research on such debugging, in which debugging refers to explicitly correcting system's reasoning to match user's expectations (Amershi et al., 2010; Kapoor et al., 2010; Kulesza et al., 2010; Lim and Dey, 2010). This argument, therefore, shows the true value of intelligibility – with increased understanding, the interactions that users had with the system, become more meaningful and more aligned with the users' expectations. The users are able to co-operate with the system as a joint system; and they are able to maximise the system's functionality to the fullest.

Increasing intelligibility is not, however, straightforward as designing explanations for an ambient intelligent system could be a complex task (Bunt et al., 2007; Herlocker et al., 2000). For example, Bunt et al. (2012, p. 173) found that information about the system's functionality is only wished if it gives benefits such as enhanced utility of the system. The essence of enhanced utility is likely to vary from user to user and differences can be slight, yet pose a great threat to user experience of the interaction. For example, user satisfaction may be lowered by too much information if users are experienced with the product (Mcnee et al., 2003). These factors thus raise a plethora of questions such as when does a user become experienced, does the provision of information need to stop immediately when the user has become experienced, or what do users classify as “enhanced utility” of the system? Kaasinen et al. (2012, p. 2) have argued it is important to understand people’s expectations of intelligent environments. It can be suggested that those expectations could even affect the whole user experience. Users of ambient systems have expectations of the environment that originate from historical usage without the intelligent system in the environment. These expectations are a combination of large-scale expectations of what the system will ultimately deliver such as ‘increased comfort at home’; as well as small-scale expectations in terms of specifics that the system should be undertaking at that point in time to achieve comfort expectations. This highlights the second point in Bellotti & Edwards’ (2001) work – accountability. The authors discussed this element in terms of allowing users to take charge of their actions and choices. While intelligent systems reduce the user’s burden of choosing and carrying out tasks; they also ‘claim’ those tasks and the user may not see them as their own responsibility. With a successful alignment of expectations and system performance, this ownership of choice could be given back to the user alongside enhanced control capabilities.

Furthermore, as Vermeulen et al. (2009, p. 197) pointed out, ubicomp and ambient intelligence applications offer users little support regarding traditional user interface concerns such as feedback, control, and as mentioned, visibility. Traditionally, these elements have had a strong presence in explicit interactions with specific interfaces utilising input and output methods of buttons or screens. With ubiquitous computing, the interfaces and interaction disappear into the fabric of everyday life. If one considers time in the interaction with products, the process can be divided into pre-action, action and post-action. In traditional interfaces, feedback occurs in the latter two stages: during action (taking the form of clicks and haptic feedback to notify the user that button presses etc. have been successful) and post-action (the result of the action would notify the user of the successfulness of the undertaken action). It has been suggested that in the first stage, pre-action, another form of info transfer occurs – feedforward (Djajadiningrat et al., 2002). According to the authors, this "informs the user about what the result of his actions will be." (Djajadiningrat et al., 2002, p. 286) In the current context, this concept is deemed extremely valuable as it can replace feedback and thus eliminate the time delay between action and feedback. If this is the case, feedforward would not occur prior to action, but would more likely be occurring during action, giving the user an opportunity for trial-and-error-type experimentation with the eventual outcomes of their actions in the future. This in turn would enhance accountability as users have direct comparison between their informed decisions and outcomes. Without such feedforward, outcomes of user actions may even be falsely attributed to system functionality, causing loss of trust and rejection of the system, as discussed above.

Exploration of ambient intelligence devices seems to be a key issue in learning their functionality as people are currently used to this type of 'fiddling' with their products to uncover their capabilities and ways to manipulate them. Rehman et al. (2005) developed an augmented reality system that visualised a context-aware ubiquitous computing device. The authors concluded that the visualisation of the device's location was exceptionally useful for users to investigate and explore the system regarding its performance and whether it was fulfilling its goals, as well as facilitating the creation of context around the functionality that helped users answer 'what if' questions (Rehman et al., 2005). Building on this work, Vermeulen et al. (2009) presented another augmented reality system that overlaid the occupant's physical environment with a projected graphical interface to communicate system's functioning and reasoning. This application is of particular interest as, although the authors recognised several issues with mainstream use, this form of communication with the user is felt to enhance users' understanding of a system in situ. This author argues that interactions of such type are especially useful for large segments of the population such as the elderly and computer illiterate people to show specific functions of real-life objects. While a lot of attention has been paid to visibility of the system, it has also been noted that in some applications, transparency is not important when the system works or is perceived to work (Bunt et al., 2012). This suggests that the amount of visibility of the systems' inner workings varies greatly and a successful interface must facilitate user customisation of detail level.

As mentioned above and in the Mental Models section below, information gathered from devices by users facilitates the build-up of mental models. Research in ambient intelligence has shown contradicting results on the matter. Some suggest that relatively little change occurs in mental models over time (Tullio et al., 2007) whilst others have found users may change their mental models if the system communicates its functionality (Kulesza et al., 2010). The depth of the mental model formed by system explanation has also been discussed (Stumpf et al., 2007), however, any characteristic of a mental model is difficult to measure and thus caution must be exercised. Regardless, recent research has highlighted several interesting nuances of mental models in ambient systems regarding system-provided help and how this could lead to a better user experience. It has been shown that users with 'scaffolding' help in explaining the system build more accurate models of system functionality than users without help; and through receiving that help, people experience higher self-efficacy and less anxiety when tackling issues with the system (Kulesza et al., 2012). This shows that interfaces should assist the user in a non-demanding way when they are first introduced to the user's environment to simulate the ideal usage of user manuals. Furthermore, it has also been shown that this assistance allows people to feel more positive about their experiences with the system and; people who are most successful in aligning the system's thinking to their own experience greatest ‘improvements’ in their mental model (Kulesza et al., 2012). These findings suggest that support should not only be given at the start but throughout to facilitate the alignment of people’s thinking to the machine’s and reassure users their control over the system.

2.4.4 Implications to this research

From the previous paragraphs, it is concluded that:

- Research into ambient intelligence in people’s homes needs to be conducted to reflect ecological validity and steer away from lab-home applications
- Ambient intelligence interfaces need to display intelligibility for users to give meaning to interactions and facilitate user acceptance of devices
- Implementation of interface for increased intelligibility need to consider users’ expectations of the system and their environment
- Ubicomp ambient intelligence interfaces need to provide visibility of system actions and visibility of pre-action, action, and post-action
- User experiences need to encourage accountability and engage users with their energy behaviour

2.5 Thermal Comfort

The human body has a physiological need to maintain an almost constant internal temperature, irrespective of the amount of heat we produce within our bodies or what environment we are in. (Nicol et al., 2012, p. 10) Subsequently, it has developed measures to counter the effects of heat loss or excess heat gain. This means that the human body is in a constant dynamic relationship with its surrounding environment, be it outdoor or indoor, that is affected by time, climate, building form, social conditioning, economic and other factors (Nicol et al., 2012, p. 7). The relationship is complex as thermal sensation (effect of heat transfer mechanisms), is not the same as thermal comfort (emotion or perception of conditions) (Hensen, 1990). Subsequently, the rest of this section is divided to a discussion of heat exchange mechanisms and their measurement, human thermoregulation, a discussion of thermal comfort models, and a discussion of the implications of thermal comfort to this research.

2.5.1 Human thermoregulation & heat exchange

2.5.1.1 Heat transfer mechanisms and measurement of affecting factors

As mentioned above, human thermoregulation serves the purpose of maintaining a constant internal temperature. In other words, the human body works to counter the effects of heat exchange mechanisms that take place between the body and its surrounding environment. These mechanisms involve convection, conduction, radiation, and evaporation. All but evaporation could result in either heat loss or gain, depending on the environmental conditions (heat loss always occurs in evaporation due to endothermic reaction involved).

2.5.1.1.1 Convection

Heat transfer by convection has been defined as “the physical movement of a fluid past the body, which serves to carry away the heat.” (McIntyre, 1980, p. 32) Similarly, if the air temperature is higher than skin temperature, opposite reaction occurs. Clothing and activity levels affect the magnitude of convection greatly, however, it always occurs to a degree. Other influencing factors include differences in temperature between the body and air as well as air velocity.

2.5.1.1.2 Conduction

On a daily basis, conduction plays a small role in the heat exchange of human bodies. It refers to the direct transfer of heat from one body to another by contact. In our everyday lives, this is limited to heat loss through the soles of shoes, clothing surfaces, body contact when seated (Nicol et al., 2012) or other and in comparison to other mechanisms, has a small effect on our overall heat exchanges.

2.5.1.1.3 Radiation

McIntyre (1980, p. 7) explains that “all bodies above a temperature of absolute zero emit thermal radiation” as well as absorb it. Whilst these heat exchanges may not be as intensely experienced as through conduction when in contact with a cold/hot surface or as thermal radiation from the sun, they occur between humans and their surrounding environments at all times. It is known that several factors influence heat transfer via radiation such as the intervening medium, radiance, level of reflection at a surface, radiation geometry and others (see McIntyre, 1980). However, in research on thermal comfort, radiation is understood in terms of absorptivity and emissivity using the Stefan-Boltzmann equation. The equation states that the maximum power a body can emit is a function of temperature and calculates the radiant energy emitted (in W/m^2) using the Stefan Boltzmann constant and the absolute surface temperature (in kelvins) (McIntyre, 1973, p. 8). Bodies which emit radiance according to this equation are called black bodies and are deemed perfect emitters of radiation. In the computation of radiant heat exchanges, the form factor, or configuration factor is often used. This considers enclosures consisting of surfaces and allows us to calculate the direct heat exchanges from one surface to another. Intervening medium (usually air) is excluded as it is assumed to “have a refractive index of unity, and to play no part in the radiation exchange” (McIntyre, 1973, p. 12). We use this method to calculate heat exchanges from surface to surface, but in doing so, it is necessary to consider emissivity, which “describes how effective … [the surface] is at radiating energy compared with a black body.” (McIntyre, 1973, p. 25) However, we tend to discuss absorptivity rather than emissivity regarding the solar and near infra-red region as McIntyre discussed: “the actual emission at these wavelengths by a surface at normal ambient temperatures is negligible. In the visible and near infra-red wavelengths, the absorptivity of a surface is hard to predict; it varies with wavelength and with the detailed nature of the surface. A rough and ready guide to the solar absorptivity of a surface is its appearance: dark surfaces absorb well and light surfaces reflect well.” (McIntyre, 1973, p. 28) Subsequently, when discussing humans, variance in skin colour causes variance in absorptivity; and working values for the absorptivity of human body have been suggested (McIntyre, 1973, p. 29).

It has been demonstrated that in indoor environments the human body loses roughly equal amounts of heat through convection and radiation (McIntyre, 1980), which has led to the development of operative temperature as a concept. Operative temperature combines air temperature and mean radiant temperature into a single, weighted average (weights depending on the heat transfer coefficients by convection and by radiation at the clothed surface of the occupant) of the two to express their joint effect. (Nicol et al., 2012)

2.5.1.1.4 Evaporation

Water vaporisation is an endothermic process and thus requires extraction of energy in form of heat from the environment. In human thermoregulation, this process has been shown to consist of two separate and equally important parts: physiological regulation of sweating and the aforementioned physical process of sweat evaporation (McIntyre, 1980). “This cooling effect is very powerful ... [and] evaporative cooling becomes increasingly important as ambient operative temperatures rise through and above skin temperatures, from around 28°C through to 35°C, above which temperature the body relies solely on evaporation to cool itself.” (Nicol et al., 2012, p. 16) However, during the course of our everyday lives, less extreme forms of evaporation keep us comfortable such as insensible perspiration (evaporation of moisture from the skin surface without sweating (Nicol et al., 2012, p. 16)) and respiration loss (expiration of warmed and humidified air in the lungs and upper respiratory tract (McIntyre, 1980, p. 44))

2.5.1.1.5 Measurement

To measure heat transfers in an environment and the effects on humans, several variables need to be measured. Most commonly, these include Air temperature, Air velocity, Mean radiant temperature, Humidity, Clothing level and Human thermal parameters.

Air temperature

Air temperature is usually measured using a mercury-in-glass thermometer, a thermocouple, a thermistor or a platinum resistance thermometer and the differences between each can be seen in Table 2-2.

Property	**Thermocouple***	**Thermistor**	**Platinum resistance thermometer**	**Semiconductor junction****	**Mercury-in-glass**
Long-term stability	Variable	Ages	Stable	Stable	Stable
Signal for 1°C change	10-60µV	1% of resistance (linearized)	40 µV (at 1mA current)	2.3 mV	
Speed of response	Fast	Fast	Moderate	Moderate	Slow
Relative cost***	1	4	5	2	3
Mechanical stability	Moderate	Moderate	Moderate	Robust	Poor

Reproducibility	Moderate	Good	Very good	Poor	Very good
Linearity	Moderate	Linearized versions required	Good	Good	Good
Accuracy (typical)	±2°C	±1°C	±0.1°C	±1°C	±0.1°C (NPL calibrated)

Table 2-2 comparison of air temperature measuring devices (Parsons, 2003, p. 94)

* Cold junction or compensated circuit required

** High self-heating effect

*** Relative cost (1: cheap; 5: expensive)

Air velocity

Measurement of air velocity is quite difficult in comparison to the other parameters as air flows in terms of speed and direction are constantly changing. However, one way to measure air velocity is using a Kata thermometer in which a large bulb with alcohol is heated and exposed to the environment. Subsequently, the time it takes the alcohol to fall or rise over a 3°C range and air temperature are related to air velocity in an equation, described by mean temperature of Kata thermometer, air temperature, cooling time, Kata factor and thermometer variability constants (please see Parsons, 2003, p. 104 for the equation and full description). Other possible techniques include hot wire anemometers where cooling capacity of air along a hot wire is measured, providing good measure for computational analysis, but can be inaccurate in low air velocities (Parsons, 2003, p. 104).

Mean radiant temperature

As heat gains through radiation are rather complex, there are several devices used to measure different aspects of radiation (see Table 2-3)

Instrument	Measurement
Globe thermometer	Globe temperature. Calculate t_r using v and t_a
Heated globe thermometer	Power to maintain temperature
Shielded globe thermometer	Temperature of globe in a polyethylene envelope
Radiometer	Instrument that measures radiation
Net radiometer	Net radiation: direct, ground, sky
Pyranometer	Radiometer that measures short wave or visible radiation

Table 2-3 comparison of radiant temperature measurement devices (Parsons, 2003, p. 102)

Most commonly mean radiant temperature is of interest to researchers and thus a black globe thermometer is used. It consists of a thermometer with the bulb at the centre of a 150mm diameter copper globe with a matte black finish. From this, the radiant temperature can be calculated (see McIntyre, 1973 for a further discussion on calculation and influencing factors).

Humidity

Humidity affects sweat evaporation and is expressed through partial vapour pressure of water in air and relative humidity, which is a ratio of the former to saturated vapour pressure at the particular temperature. Humidity is measured using a whirling hygrometer see Figure 2-3.

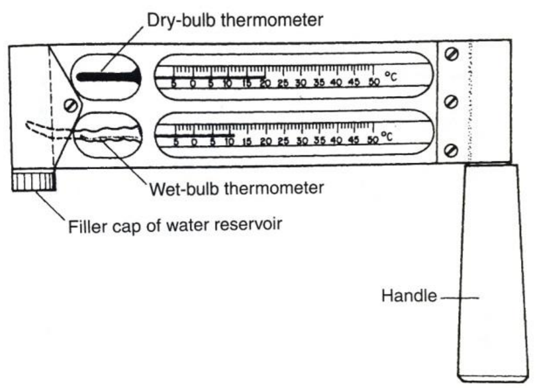


Figure 2-3 whirling hygrometer

The device is whirled, passing air through the thermometers' sensors and reducing the wet bulb temperature through evaporation. The difference in the dry and wet bulb thermometers then allows for relative humidity, partial vapour pressure and dew point to be calculated (for further discussion see McIntyre, 1973; or Parsons, 2003)

Clothing level

Clothing is an effective insulator for the human body and thus the effects of clothing need to be considered when calculating for thermal exchanges. To do this, thermal insulation qualities of materials can be measured. The Clo value is used as an expression of insulating quality of a piece of garment. From this, tables of Clo values of items or ensembles of clothing have been provided (notably ISO, 1995) and an example of such can be seen in Table 2-4 (data from [312]).

Clothing item	Clo value
T-shirt	0.09
Shorts	0.06
Normal trousers	0.25

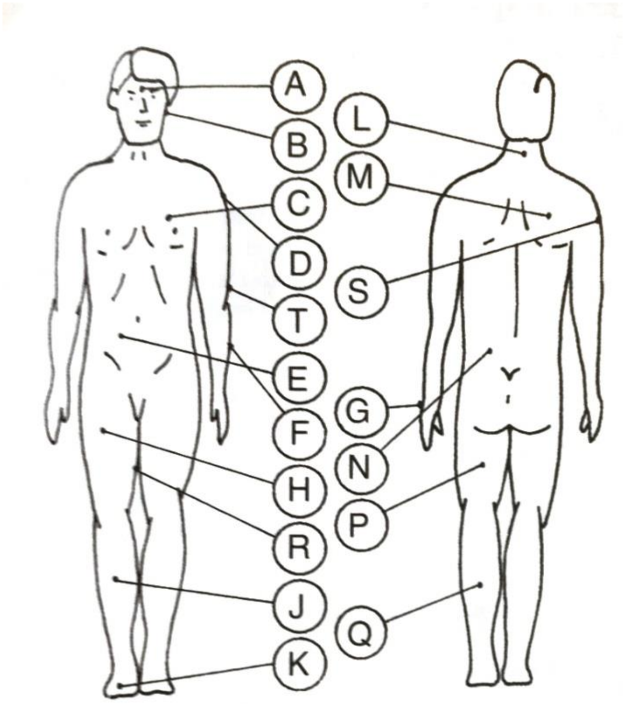
Light skirt (summer)	0.15
Thin sweater	0.20
Sweater	0.28
Jacket	0.35
Parka	0.70
Thick long socks	0.10
Nylon stockings	0.03
Shoes (thin soled)	0.04
Gloves	0.05

Table 2-4 example Clo values of some common clothing items

Therefore, to include effects of clothing in calculation, one needs to simply combine the Clo values of the observed occupant's attire.

Human thermal parameters

Measuring human thermal responses can be considered from physiological and psychological angles. To measure physiological response, most commonly, skin temperature can be measured, and this can be done from several places on the body see Figure 2-4 (adapted from Parsons, 2003, p. 113).



A) forehead	E) right abdomen	J) right shin	N) left paravertebral
B) left side of the face	F) left outer mid lower arm	K) right instep	P) left posterior thigh
C) left upper chest	G) left hand	L) neck	Q) left calf
D) left front shoulder	H) right anterior thigh	M) right scapula	R) right mid inner thigh

Figure 2-4 human body temperature measurement locations

Similarly, internal temperature can be measured in the form of tympanic, aural, forehead, oral, oesophageal, subclavian, intra-abdominal, rectal, vaginal, urine, or transcutaneous deep-body temperature (Parsons, 2003) using various thermometers.

Metabolic heat production can be seen as another physiological factor as our body constantly generates heat from glucose for cell activity. There are several methods for estimation of metabolic heat production, such as calorimetry, indirect calorimetry, collection and analysis of expired air, doubly-labelled water method, external work method, or use of tables and databases such as description of work performed or description of occupation (for a more detailed account see Parsons, 2003, pp. 131–155).

Psychological response

The most common method of measuring psychological response of humans to thermal environments is asking them with the use of a questionnaire. While highly subjective, the Bedford (1936) or ASHRAE (1966) 7-point scales have been extensively used and do provide a useful way to understanding thermal sensation that occupants have. Such scales ask the occupant to report their current thermal sensation as one of the provided options: hot, warm, slightly warm, neutral, slightly cool, cool, or cold. Parsons (2003) provides a further discussion on these as well as other methods of measuring psychological response such as behavioural and observational measures.

2.5.1.2 Human thermoregulation

The heat exchanges discussed above, sometimes referred to as the passive system of thermoregulation, change the skin temperatures of the human body and eventually would cause change in core temperature. The active thermoregulation system serves as reaction to signals from the skin to keep body temperatures constant. Warm or cold signals from temperature receptors in the skin serve as main information source for thermoregulation. These signals are processed in the hypothalamus, which then sends out signals to effectors in the body to induce vasoconstriction, shivering, sweating or vasodilation. This is illustrated in Figure 2-5 (as seen in McIntyre, 1980)

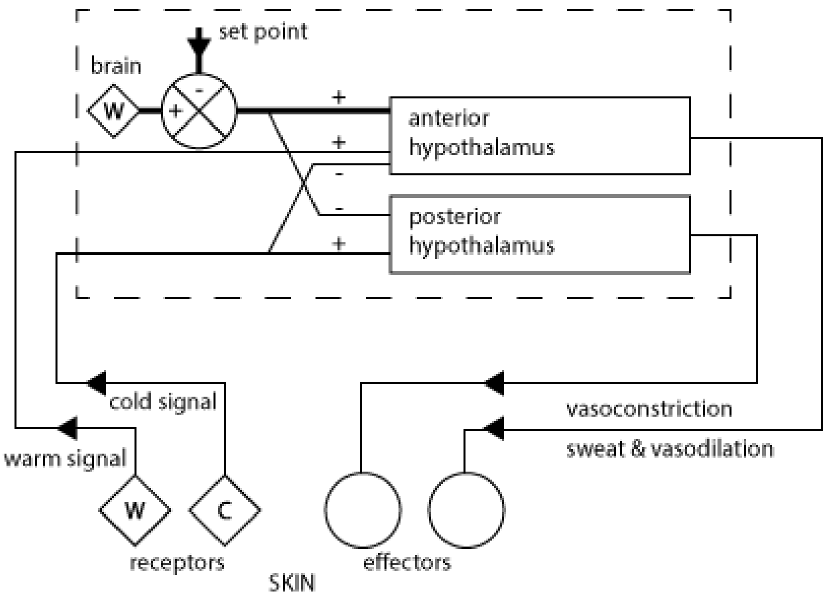


Figure 2-5 active thermoregulation model

There are two regions in the hypothalamus responsible for thermoregulatory control: the anterior and posterior nuclei, the former providing regulation when the body is hot and the latter when the body is cold (McIntyre, 1980). Hypothalamus has a set point temperature of 37°C and any change to above or below that can cause several intriguing consequences. For example, it was shown that the hypothalamus, when exceeding 37.1°C can command elevation in skin temperature to increase sweating or that initiation of sweating is not possible when the hypothalamus temperature is below 37°C (McIntyre, 1980). While the hypothalamus temperature set point is specific, the set point of the body core (usually also at 37°C) is dependent on metabolic rate (elevated set points can be experienced when performing intense exercise or when the body is in fever) but is independent of ambient temperature up until the point at which thermoregulation fails at high temperatures (McIntyre, 1980, p. 107). McIntyre explained that “metabolic heat production increases with both lowered skin temperature and lowered core temperature. Low skin temperatures have no effect if the core temperature is at or above the set point of 37.1°C” (McIntyre, 1980, p. 109). The author also discusses the relative inefficiency of the body to be able to maintain its temperature in cold environments as regardless of increased metabolic rate, the body slowly cools. In comparison, the body is highly effective in preventing overheating.

In conclusion, human thermoregulation comprises of the passive and active system and is the underlying physiological process concerned with maintaining our body temperature for survival.

2.5.2 Thermal Comfort Models

While there exists no consensus in the academic community on the classification of thermal comfort models under specific titles, it is the view of this researcher and some others, that four general bodies of work can be distinguished. These can be referred to the heat balance model, thermal adaptation concept, fully empirical adaptive model, and dynamic human thermoregulation model. Here, the basis of distinguishing between models is contribution and retrospective shortcomings of bodies of work – for example, work done under the title 'Heat balance' model contributed vastly to the field of thermal comfort, however, later we have found out that there are significant shortcomings, factors such as adaption that are not taken into consideration by authors in that classification; and can, therefore, be seen as a distinguishing feature.

2.5.2.1 Heat balance / Fanger's PMV model

Although Fanger in his work referred to the equation underlying this model as the 'comfort model', as Auliciems pointed out, this was in practice a heat balance model, which calculated for a zero heat storage situation, i.e. the human body generated as much energy as it released to its surroundings (Auliciems and Szokolay, 1997). From this it can be assumed that since this equilibrium is achieved, there exists a temperature or temperature range at which the human feels comfortable. In his experiments, Fanger exposed a large number of students to conditions varying in clothing levels (clo-value), activity levels, air temperature, mean radiant temperature, relative air velocity, and relative humidity in ambient air in a climatic chamber; and asked them to rate their thermal sensation on a 7-point scale (Fanger, 1970). The scale, although subjective, is a valid measurement as Miller previously recognised that the number of distinct sensations we can reliably distinguish is limited (Miller, 1956). On the other hand, it is worth mentioning at this point that it has later been shown that there are some fundamental semantic issues with such scale-based evaluation methodologies used in many of the studies discussed here. Humphreys and Hancock demonstrated that there exists a mismatch between the 'neutral' state on the ASHRAE (ASHRAE, 2003) scale (deemed a desirable goal for the built environment) and people's actual desired thermal state; for example people in cooler climates often desire to be in a thermal state warmer than 'neutral' and people in hotter climates in a state cooler than 'neutral' (Humphreys and Hancock, 2007). This suggests that a measurement of *sensation* (a scale with 0 or 'neutral' at the centre; assumed to be the best result) may not correlate to a measure of *comfort* and thus the scale does not necessarily reflect people's thermal preference. Regardless, those experiments allowed Fanger to calculate the predictive mean vote (PMV), which then allowed for the extension of the PMV index to predict the percentage of people dissatisfied (PPD) (Fanger, 1970). The latter serves as some form of a mapping between the sensation and comfort. From these results, Fanger’s model can then be used to calculate environmental conditions at which most people would feel comfortable, given clothing and activity levels of those people. This has become somewhat of a cornerstone of building design as the model has been widely used to determine indoor conditions for office buildings and adopted in the creation of international standards for building development notably the ISO 7730 (ISO, 2005). Fanger concluded that even at PMV index of zero, 5% of the people would still feel uncomfortable (Fanger, 1970). These findings have significant real world implications as the statement clearly indicates that there is not such a thing as 'ideal' conditions that apply to all. That in turn illustrates the point that thermal comfort is a personal and internal perception rather than physical conditions (however, this does not mean that the latter wouldn't influence the former).

Fanger’s model has also inspired other similar models, such as the two-node model that has influenced the development of ASHRAE standard 55-92 (ASHRAE, 2003). The two-node model is in essence very similar to Fanger's model. It was developed at the Pierce Foundation and calculates heat transfer from the core of the human body to the skin and from the skin to the surrounding environment (Gagge et al., 1971), a summary of which can be seen in Figure 2-6.

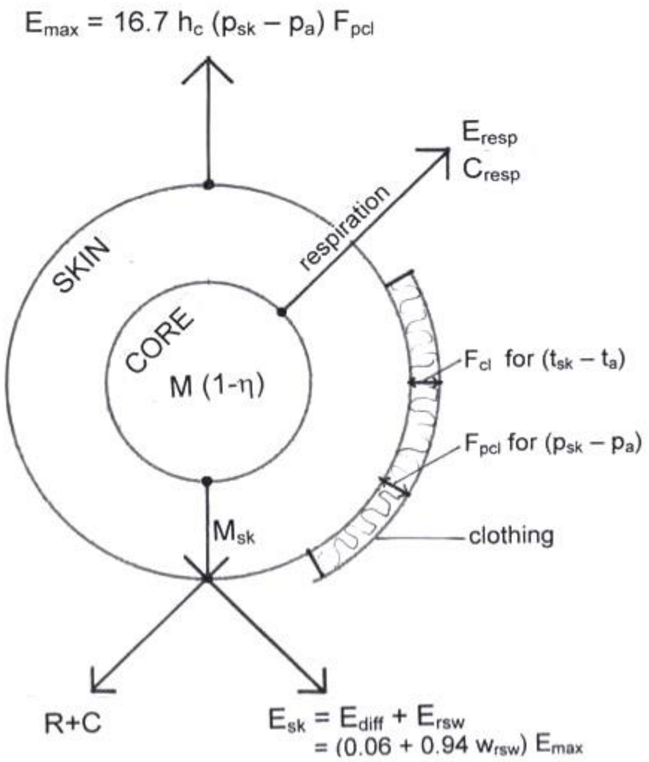


Figure 2-6 summary of the two-node model, as seen in (Auliciems and Szokolay, 1997)

This model captures the mechanisms of heat transfer mentioned above much in the same way as the PMV model.

Although wide use of the PMV model serves as some indication of its relevance or value, there has been much criticism of it. Several authors have pointed out the model's tendency to overestimate discomfort in warmer climates and conditions (de Dear and Brager, 2002; Karyono, 1996; Williamson et al., 1995), which has caused many authors to try and expand or improve the model, see Van Hoof (2008) for a further discussion. Two earlier studies also reveal the inability of PMV model to account for acclimatisation as a factor for thermal comfort (MacFarlane, 1958; Macpherson, 1962), while others have found no evidence for acclimatisation at all (Chung and Tong, 1990). However, the most significant criticism is that Fanger's model is a steady state model, meaning, it treated the human occupant as a passive receiver of thermal stimuli, rather than an active member of the environment with interaction capabilities (Brager and de Dear, 1998) and the feedback of those activities on thermal sensation; as well as, that it is only applicable to steady state environments. In other words, it assumes that the occupant is at equilibrium with his environment and that this relationship does not change. This means that the model cannot be applied to transient environments, where fluctuations in air temperature or other factors occur. However, such environments are common in most parts of the world where daily and seasonal changes in environments take place. This led to work on a different approach to thermal comfort.

2.5.2.2 Thermal Adaption Concept

The adaptive principle (originally seen in Oseland et al., 1998) states that if a change in the thermal environment occurs, such as to produce discomfort, people react in ways which tend to restore their comfort. This principle introduces the novel aspect of behaviour to thermal comfort research and is significant as it deflects from the steady state nature of PMV model, where no change in the relationship between occupant and environment was observed. In fact, several authors have shown through research in various seasonal and climate settings that in reality, people seem to feel comfortable in far more varied conditions than predicted by the PMV model (Busch, 1990; Chan et al., 1998; de Dear and Auliciems, 1985; de Dear and Fountain, 1994; de Dear and Schiller Brager, 2001; de Dear et al., 1991; Donnini et al., 1996; Schiller et al., 1988).

The thermal adaption concept was introduced by Nicol and Humphreys (1973) who used field surveys to suggest that sensations of hot and cold were part of a human's greater comfort control system. In other early research from the thermal adaption perspective, Humphreys (1976) reviewed 36 studies of measured indoor temperature and subjective measurements of comfort. The author concluded that people feel comfortable in a range of indoor temperatures spanning 13°C and attributed this result to people adapting to their surroundings (Humphreys, 1976). Auliciems (1969) proposed that outdoor temperature has an effect on indoor temperatures as well as occupant’s thermal expectations. Humphreys built on this principle and was able to prove a significant correlation between both free-running and HVAC buildings, and mean monthly outdoor temperatures (Humphreys, 1978, see Figure 2-7 (the validity of the graph was later confirmed in Humphreys et al., 2010) .

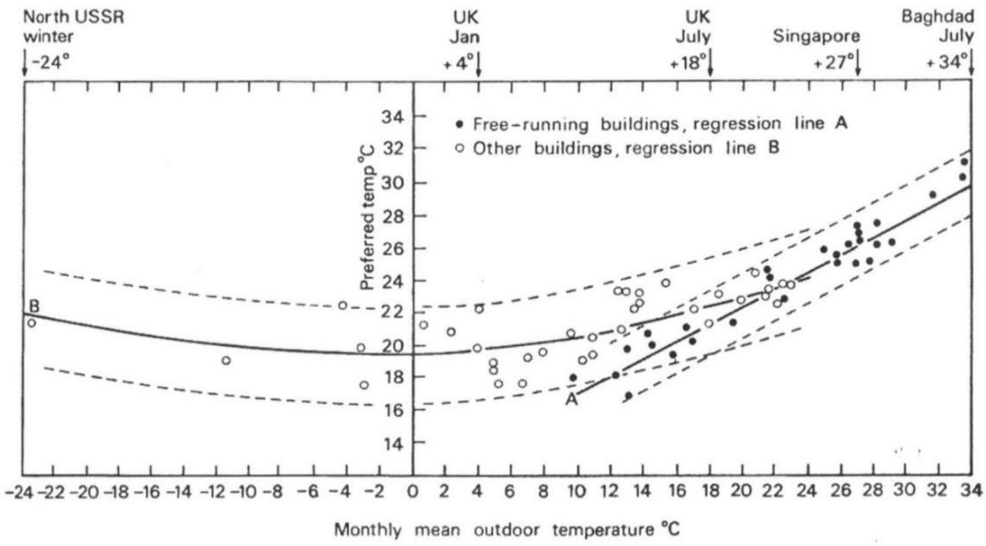


Figure 2-7 variation in indoor comfort temperature as a function of outdoor temperature and differences between free-running and other buildings (as seen in Nicol et al., 2012, p. 27)

Similarly, research has shown that if occupants have freedom over clothing choices, the clo values of their attires have a strong linear dependence on weather conditions outside (Fishman and Pimbert, 1982; Morgan and de Dear, 2003). The importance of clothing has also been the focus of others’ work and variance in neutral temperatures of Pakistani office workers of 15.7°C in winter and 26.4°C in summer have been reported (Humphreys, 1994; Nicol et al., 1994). Several authors (Baker and Standeven, 1996; Nicol and Raja, 1996) have noted that clothing decisions are not as much an hour-by-hour measure, but a predictive decision made at the beginning of the day, which was not to say posture changes or subtle alterations to clothing to either manipulate the insulating quality of attire or further exposure of body surface to outside conditions do not take place (Nicol and Raja, 1996). Haldi & Robinson (2008) later demonstrated that outdoor temperature is a better predictor of clothing level than indoor temperature, illustrating that clothing choices are a predictive strategy based on historic experience (weather conditions of the day compared to previous days); this issue will be revisited under those authors work in Fully Empirical Adaptive Model section. Similarly to these findings, Benton & Brager (1994) found that in comparison to other behavioural adaptation mechanisms, change of clothing, although seen as highly effective, was reported to be rarely used. The authors also noted that other actions such as taking a break or consuming hot or cold drinks are far more frequently used, however, caution must be exercised as those actions can also serve cultural, dehydration prevention or other purposes.

Similarly, research has been carried out into other actions that occupants can perform to increase comfort such as manipulating doors (Baker and Standeven, 1996, 1994; Indraganti, 2010; Raja et al., 2001), windows (Baker and Standeven, 1996, 1994; Brager et al., 2004; Fabi et al., 2012; Indraganti, 2010; Raja et al., 2001), window shading devices (Raja et al., 2001), fans (Baker and Standeven, 1996, 1994; Indraganti, 2010; Raja et al., 2001), or even furniture (Baker and Standeven, 1996, 1994; Indraganti, 2010)(more on this under Fully Empirical Adaptive Model). Baker & Standeven (1996) suggested that the mere presence of an opportunity has the potential to extend the occupants' comfort zone (range of conditions at which a person feels comfortable) if the opportunity is exercised. (Illustrated in Figure 2-8)

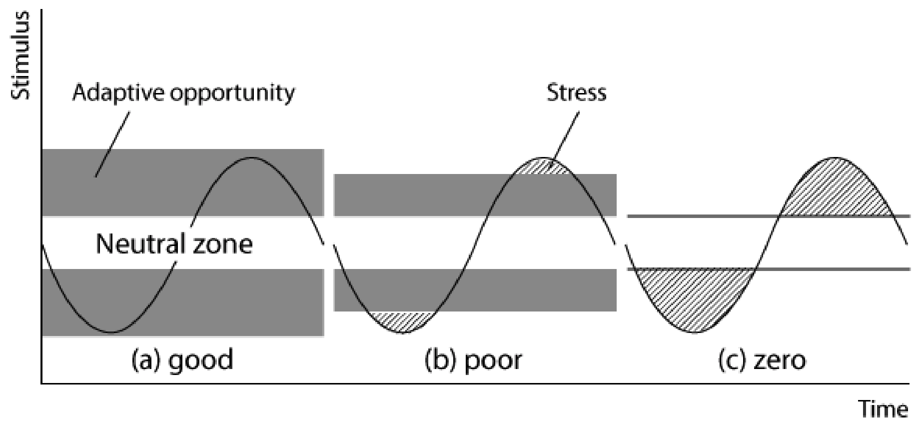


Figure 2-8 comfort zone is extended beyond the neutral zone by adaptive opportunity

In Williams' (1995) study occupants reported higher satisfaction when perceived themselves in control of the environment. This argument was further supported by findings of temperature alterations of a few degrees in air-conditioned buildings with little occupant control causing thermal dissatisfaction amongst occupants (Elder and Tibbott, 1981; Gagge and Nevins, 1976). Similarly, studies on differences between air-conditioned and naturally ventilated buildings using occupant comfort votes revealed that higher tolerance for fluctuations and high temperatures in naturally ventilated buildings where people had higher control (Black and Milroy, 1966; Fishman and Pimbert, 1982; Rowe et al., 1995)

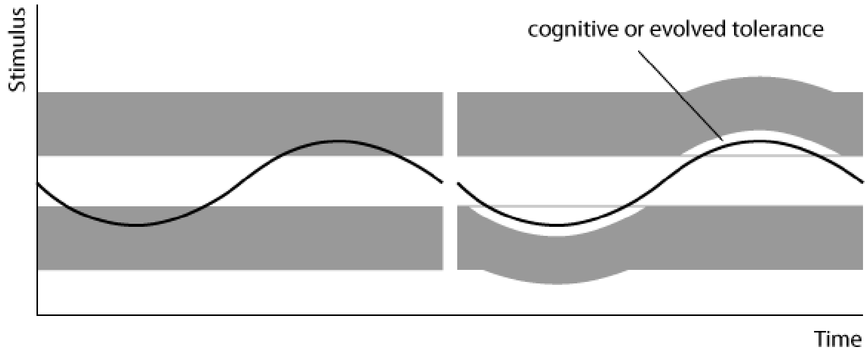


Figure 2-9 knowledge of the cause of the stimulus may increase tolerance

Furthermore, as seen in Figure 2-8 the authors also suggested that knowledge of the causes of discomforting stimulus further contributed to this, through the creation of "cognitive or evolved tolerance" (Baker and Standeven, 1996,

p. 181). The concept of adaptive opportunities described in that research has been widely accepted and expanded upon. Brager & de Dear (1998) refer to these changes as psychological adaptation, which refers "to an altered perception of, or a response to, the thermal environment, resulting from one's thermal experiences and expectations." (Brager and de Dear, 1998, p. 90)

In conclusion, much of the work done on the concept of thermal adaptation is based on field studies that can be classified into 3 classes based on their rigor in measurement and compliance with ASHRAE Standard 55 and ISO 7730 (see Brager and de Dear, 1998, p. 88 for a more comprehensive outline of the 3 classes). In these studies votes of thermal comfort are compared to recordings of indoor and/or outdoor temperatures of those locations and people are assumed to have freedom of adaption in their environment. Such adaptations can be classified as "regulating the rate of internal heat generation, regulating the rate of body heat loss, regulating the thermal environment, selecting a different thermal environment …" (Nicol et al., 2012, p. 30). However, this work, although a step in the right direction, merely serves as a descriptive reflection that established a linear regression of occupants' neutral temperature and indoor/outdoor temperature for the observed population at the observed time in the observed climate. It does not assist in predicting thermal comfort conditions for a specific population of a specific building in a specific climate, unless all parameters are close to identical with those observed. Furthermore, all adaptation actions are handled implicitly, i.e. the regressions do not allow for prediction of the probability at which certain actions will be performed; predict what impact these actions had on neutral temperature of occupants; or resolve for the unknowable or individual differences. In other words, this work is reflective of the past, rather than predictive of the future, thus offering little for real-world implementation.

2.5.2.3 Fully Empirical Adaptive Model

It was because of these shortcomings that subsequent work focused on developing models to understand and predict the nature of the adaptive actions. The goal of this was to 'open the black box' of the adaptive model and be able to predict the likelihood of actions taking place as well as the effect these actions have on thermal comfort.

Early models linked current window angle to outdoor temperature and previous window angle (Fritsch et al., 1990), use of windows, lights, blinds, heaters and fans to outdoor temperature (Nicol, 2001) or window state to corresponding occupancy and outdoor temperature (Herkel et al., 2008). Figure 2-10 illustrates the thinking behind one of these early models.

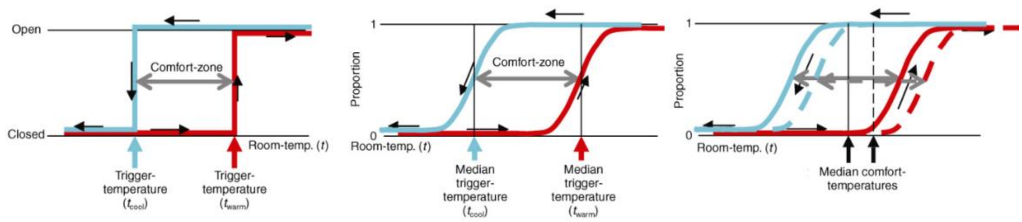


Figure 2-10 window opening and closing behaviour of a perfectly consistent person (left), interpersonal variance (middle), and introduction of a fan (right)

However, those models suffer from a much more significant error in tying adaptive action to outdoor temperature, because coupling indoor conditions with performance of actions has been shown to be more appropriate (Nicol and Humphreys, 2004; Robinson, 2006). Furthermore, Nicol and Humphrey’s model (2004) has been somewhat discredited by subsequent work for reasons of inaccuracy in performance when compared to actual observed behaviour (Haldi, 2010) as well as inability to predict the duration of window opening (Bourgeois, 2005). This led to refinement of the model (2007) where the authors attempted to simultaneously consider indoor and outdoor temperature with regard to window opening behaviour. Yun & Steemers (2008) developed a model that accounts for occupants’ interactions with window controls as a function of (1) indoor temperature, (2) previous window state, and (3) time of day effects. From data acquired from field studies, the authors observed that there was high average frequency (61%) of transition from window state closed to open at the first arrival of the occupant into the office environment; and subsequent changes from open to closed and closed to open during the presence of the occupant were very low (3% and 2% respectively) (Yun and Steemers, 2008, pp. 1473–1474). Building on this, the authors' model comprises of separate sub-models for the start (occupant arrives in the office), intermittent hours (presence during working hours) and end of occupation (leaving at the end of the working day); with each sub-model predicting the "probability of changing a window state from open to closed or from closed to open as a function of indoor temperature and the previous window state." (Yun and Steemers, 2008, p. 1482) The authors also concluded that individuals respond differently to thermal stimulus and thus them performing adaptive actions also varies greatly. However useful, the model has some drawbacks, namely that it is (1) based on a dataset recorded in summertime only, which also means that in wintertime, there could be several (2) other strong stimuli such as rain or wind that affect window-opening behaviour.

Haldi & Robinson (2008) used logistic regression techniques applied to data from a longitudinal field survey in Switzerland where environmental factors were recorded along with the performing of both environmental (windows, doors, blinds & fans) and personal (clothing, activity & consumption of drinks) adaptive actions by office occupants, as well as their comfort ratings. Their model predicts probability of occupants' actions as a function of both indoor and outdoor temperature, and the authors highlighted that "in the order of decreasing sensitivity (…) fans, blinds, doors, clothing, consumption of cold drinks and windows are well described by internal temperature, and in all cases better so than with outdoor temperature" (Haldi and Robinson, 2008, p. 2175). Furthermore, another significant contribution was the authors' quantification of the effects of each action, reflecting an offset of 0.33±0.06

(windows) to 1.94±0.13 (fans) in the occupants' neutral temperatures when the actions were exercised, illustrated in Table 2-5.

Control in use	Without action (°C)	With action (°C)	Offset (°C)
Windows	24.22 ± 00.4	25.10 ± 0.06	0.88 ± 0.06
Blinds	24.45 ± 0.03	25.50 ± 0.08	1.05 ± 0.08
Fans	24.55 ± 0.03	26.49 ± 0.13	1.94 ± 0.13
Doors	24.43 ± 0.04	24.92 ± 0.06	0.49 ± 0.06
Drinks	24.57 ± 0.04	24.88 ± 0.07	0.31 ± 0.07
Clothing	24.49 ± 0.04	24.82 ± 0.06	0.33 ± 0.06

Table 2-5 empirical contribution of adaptive action to thermal neutral temperature

The combined effect and associated phenomena (some actions undermining others and thus reducing combined effect) were also discussed; and the authors termed the neutral temperature offset effect as *empirical adaptive increments* (Haldi and Robinson, 2008). Other implications of this work involve explanation of inability of thermal stimuli alone to infer performing of an action and the importance of additional variables, as is illustrated in the case of windows by Figure 2-11.

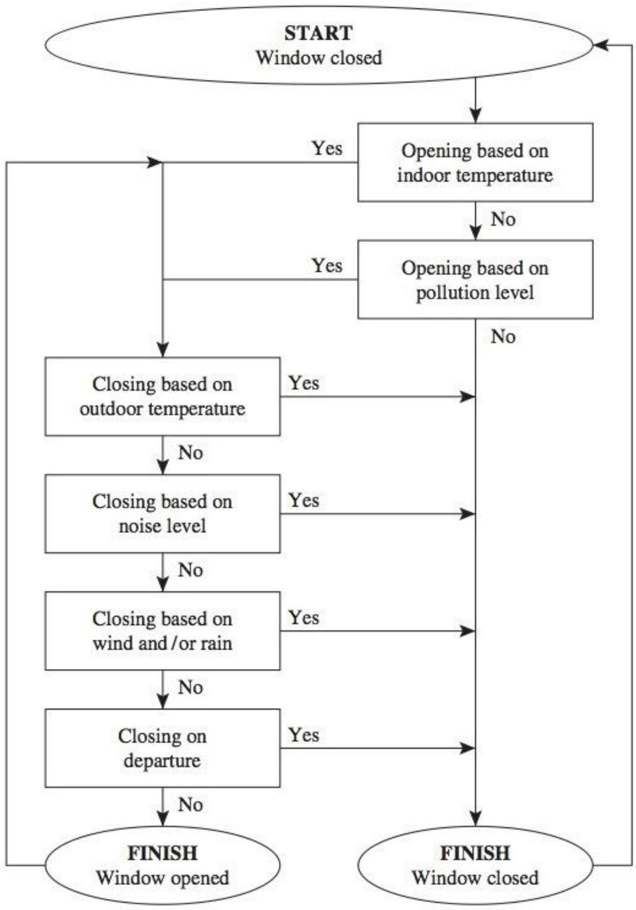


Figure 2-11 scheme for the treatment of actions on windows

Subsequent work by the same authors has since produced a predictive model of actions on windows depending on indoor & outdoor temperature, occurrence of rain, occupant presence, and duration of occupant absence (Haldi and Robinson, 2009; Haldi, 2010); and a predictive model of actions on shading devices depending on occupancy states and outdoor luminance, with the capability to predict occupant actions as well as choice of shaded fraction (what portion of window is shaded) (Haldi and Robinson, 2010a; Haldi, 2010). The models assume availability of climate data, existing prediction of occupancy, and coupling of the thermal model with a daylight model on the case of blinds. The authors then presented a probabilistic model of thermal comfort and demonstrated its inter-relatedness with their predictive models through the concepts of action inertia and adaption-corrected temperature (Haldi and Robinson, 2010b), illustrated in Figure 2-12.

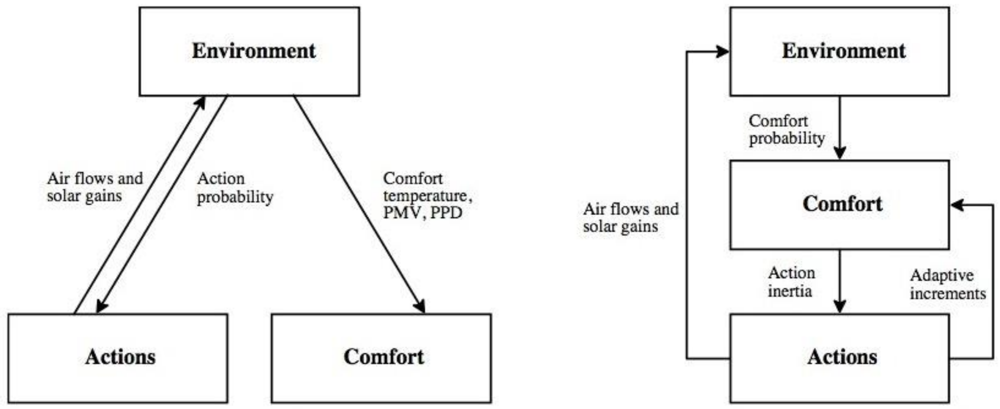


Figure 2-12 differences in previous (left) and suggested (right) perspectives to understand the interactions between the environment, occupant comfort and adaptive actions (as seen in Haldi and Robinson, 2010b)

The authors defined the former as an offset between increasing discomfort probability and increasing action probability, i.e. discomfort causes actions and the elapsed time before the action is taken could be referred to as the action inertia (Haldi and Robinson, 2010b); while the latter referred to the empirical adaptive increments discussed above. This model allows for the prediction of building and occupant specific neutral temperature, thermal sensation probability distribution, and comfort probability distribution; as well as has the potential to predict thermal sensation and comfort probability distributions accounting for building and occupant-specific neutral temperatures, and relationships between other environmental stimuli (Haldi and Robinson, 2010b).

This model and similar work (Bahadur Rijal et al., 2012) are of great interest to the thermal comfort community as they provide extremely useful real life implications in terms predicting occupant comfort with regard to specific buildings and specific occupant behaviours as well as measure the feedback of these actions to thermal comfort in quantifiable terms.

2.5.2.4 Dynamic Human Thermoregulation Model

Work described in the previous section highlights the approach of statistic modelling that increased our knowledge of adaptive actions and their feedback, and started to solve for the stochastic nature of people in their everyday lives, which provided a solid step towards a better understanding of thermal comfort in everyday life. However, future research should focus on uniting statistical modelling with physical modelling in a multi-nested simulation approach. Such an approach would dynamically resolve for human thermoregulatory processes (as discussed above) and thermal sensation using a geometric model of a human being. This geometric model could be nested within a computational fluid dynamics model that resolves for airflows; and is in turn nested within a dynamic simulation program that provides boundary conditions to the models within. As the geometric model of the human body resolves for thermal sensation, the outputs of that could be combined with a probabilistic model to predict the likelihoods of adaptive actions being undertaken and resolve for the response of those actions to the occupant's thermal sensation.

Work on such models has already begun with the Fiala thermoregulation model (Cropper et al., 2008) being a good example: according to the essence of human thermoregulation as discussed above, the model divides thermoregulation into (a) the controlled passive system; (b) controlling active system, seen in Figure 2-13.

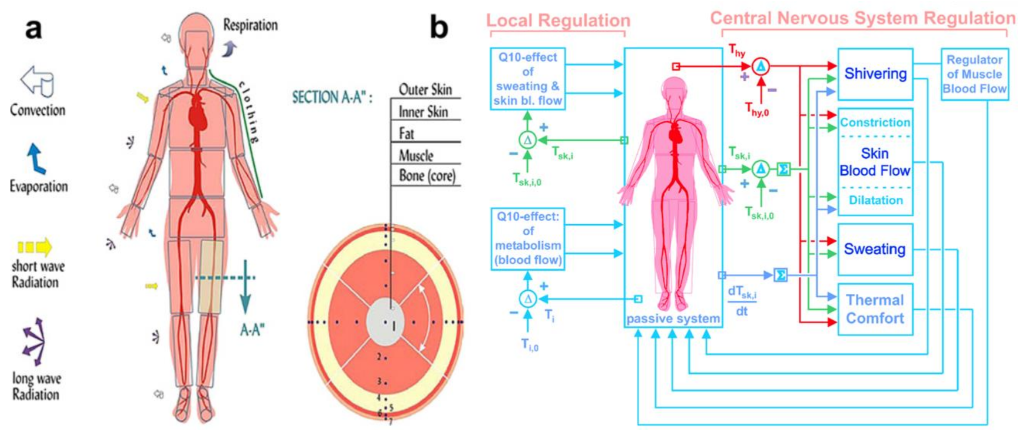


Figure 2-13 schematic diagrams of the IESD-Fiala model: (a) Passive system (b) Active system

The controlled system (a) simulates heat exchanges within the body (the authors divide the body into 20 spherical and cylindrical parts and each part is further divided into anterior, posterior and inferior sectors (Fiala et al., 2010); as well as between the body surface and the surrounding environment; taking into account the local variations of heat transfer mechanisms (convection, radiation, evaporation), moisture collection on skin surface and clothing levels in all their non-uniformities (unlike the standard clo value assumptions) (Fiala and Lomas, 1999). The active system, on the other hand, resolves for physiological factors including shivering, sweating and blood flow control (Fiala et al., 2010). While this work is a step in the right direction in terms of providing the geometrical model for simulating human thermoregulation, there is still a lot of work to be done on such models. Later work by the same authors incorporated a computational fluid dynamics model to the thermoregulation model (Cropper et al., 2010), and there have also been similar models proposed, including notably the UC Berkeley model (Huizenga et al., 2001), hybrid model developed in Aachen (Streblow et al., 2008) based on the work of Tanabe et al. (2002) and Stolwijk (1971), as well as the VTT Human Thermal Model (Holopainen and Tuomaala, 2010). These models, once developed to a state described at the beginning of this section, would render a powerful tool to model specific conditions for specific populations of specific buildings with accuracy, taking into account real life variable and physical elements. This would be of extraordinary use to fields of architecture, building design, and building control design among many others. The key conclusions or features of the work matching the 4 classifications of thermal comfort models can be seen in Table 2-6.

2.5.2.5 Summarising the highlights of different thermal comfort models

Thermal Comfort Model	**Key Implications**
Fanger / PMV	Environmental characteristics influence humans in a measurable way – effects of certain elements can be altered to create suitable conditions for people

	No universal fix for comfort, people are different, thermal comfort is an internal perception rather than a set of physical conditions
Thermal Adaption Concept	People's perception of control and knowledge of discomforting factors increase their tolerance towards uncomfortable conditions and alters their perception of comfort
Fully Empirical Adaptive Model	Thermal adaptions have a measurable effect on thermal comfort and there is a quantifiable feedback loop via those actions to thermal comfort. We are able to use this to predict comfort and actions for specific populations of specific buildings
Dynamic Human Thermoregulation Model	Currently researched state of the art in thermal comfort modelling, aiming to achieve a powerful model to predict comfort for multiple application domains

Table 2-6 key highlights of different thermal comfort models

2.5.3 Implications for this research

This research does not intend to contribute to the thermal comfort models body of work, however, it draws form the existing knowledge in this field in a number of ways:

- Primarily, thermal comfort models and explorations of adaption actions provide a way to interpret the potential interactions that users in home settings take with the interface and the heating system and the factors causing these interactions

- The accumulated understanding of people's experience of thermal comfort and behaviour within a space provides an interesting starting point to address people's experience of comfort in the home setting, and the implications this has to the required amounts of energy to maintain comfort in an environment where they perceive to have control (adaptive actions) over the space
- Building controls need to facilitate individual control specific to that household and their comfort needs, as defined by those occupants in that particular building.
- The control strategy needs to take into consideration the stochastic nature of home owners as well as the complexity of their environment including possible adaptive actions and the effects of these actions. The interface for building controls had to facilitate knowledge of factors causing changes and allow the user to feel in control of the environment.
- Understanding of the variance in occupants' experience of comfort both between and within individuals provides intriguing opportunities for energy saving through heating controls that effectively target this variance.

2.6 Mental Models

This research uses mental models as an explanatory tool to understand communication between the heating controls and users. Jones et al. (2011, p. 5) illustrate this approach by discussing work in system dynamics field: "Researchers … use the mental model construct in a pragmatic sense: as a tool to better understand complex, dynamic systems to ultimately improve their design and usability (Doyle and Ford, 1998; Moray, 2004)." Home heating controls are used in a relaxed, individual and non-goal-orientated environment. The interpretation of the devices occurs without supervision and the effectiveness of operation is determined by users themselves. In this context, mental models are seen as an appropriate paradigm for trying to enhance sense making in users. Following from this, the mental models literature chosen also focuses on the role of designers in assisting in the creation of mental models. Regardless, to facilitate better understanding of the term, it is worth observing the mental model concept in its wider usage. Subsequently, the rest of this section is divided as follows: a discussion of mental model definitions and use in different fields; properties of mental models; a suitable approach to mental models in current domain; limitations of mental models research; and implications to this research.

2.6.1 Mental Models: Use and definitions

Mental models concept has been described in several disciplines, with its origins often being attributed to the field of psychology and the work of Craik (1943), or alternatively to the introduction of schemas by Bartlett (1932). Subsequently the fields of natural resource management (Jones et al., 2011), cognitive psychology, system dynamics, psychology, human-machine and human-computer interaction, risk perception, and communication have made use of the concept (Doyle and Ford, 1998). The variety of disciplines have used the notion for a multitude of purposes including scripts for understanding routine activities (Bower and Morrow, 1990; Schank and Abelson, 1977), situation models for understanding text (Van Dijk and Kintsch, 1983), causal scenarios or stories to aid in making causal attributions or judging likelihood (Kahneman and Tversky, 1982; Read, 1987; Tversky and Kahneman, 1973), scenarios to enable judgmental forecasting (Jungermann and Thüring, 1987), schemas for perceiving and remembering information about people (Fiske and Taylor, 1991), imagery that allows objects not physically present to be scanned and mentally manipulated (Kosslyn, 1990), and problem representations to help structure and manipulate information during problem solving (Greeno, 1977), as discussed by Doyle & Ford (1998).The authors also explain that while it is possible to draw some sort of boundaries around the field of mental models research, the task is made more difficult by the variety of terms that are used by academics: mental picture (Alexander, 1964), mental representation (Pennington, 1987), folk theory (McCloskey, 1983a), naive problem representation (Larkin, 1983), intuitive theory (McCloskey, 1983b), implicit theory (Neisser, 1987), knowledge map (Howard, 1989), idealised cognitive model (Lakoff, 1999), conceptual model (Young, 1983), internal model (Veldhuyzen and Stassen, 1977), cognitive structure (Shavelson, 1972) and knowledge structure (Means and Voss, 1985). Quite naturally, this extensive use has rendered a plethora of definitions of mental models (see Table 2-7 for a summary) and has created a situation where the term could mean “all things to all people” (Wilson and Rutherford, 1989, p. 630) and be too vague for any tangible benefit.

Definition	**Reference**
“[Mental models are] intuitive generalizations from observations of real world events”	(Meadows et al., 1974, pp. 4–5)
“Mental models ... contain the ideas, opinions, assumptions, etc. with respect to a policy problem and related issues”	(Vennix, 1990, p. 16)
“”Mental Models” are deeply ingrained assumptions generalizations, or even pictures or images that influence how we understand the world and how we take action. Very often, we are not consciously aware of our mental models or the effects they have on our behaviour”	(Senge, 1990, p. 8)

"It is useful to think of mental models as a dynamic pattern of connections compromising a core network of "familiar" facts and concepts, and a vast matrix of potential connections that are stimulated by thinking and the flow of conversation"	(Morecroft, 1992, p. 7)
...mental models are multifaceted, including distinguishable sub-models focused on ends (goals), means (strategies, tactics, policy levers) and connections between them (the means/ends model).	(Richardson et al., 1994 as seen in Doyle & Ford, 1998)
"In systems dynamics, the term mental model stresses the implicit causal maps of a system we hold, our beliefs about the network of causes and effects that describe how a system operates, the boundary of the model (the exogenous variables) and the time horizon we consider relevant – our framing or articulation of a problem."	(Sterman, 1994, p. 294)
"Mental models are some sort of psychological construction with an intended representational content. Mental models ... are usually expressed by a set of sentences in ordinary language, describing both the interactions among the elements within the system and their external influences"	(Vázquez et al., 1996, p. 25)

"A mental model can be defined as a representation of a body of knowledge – either a long-term or short-term that meets the following conditions: 1. Its structure corresponds to the structure of the situation that it represents. 2. It can consist of elements corresponding only to perceptible entities, in which case it may be realized as an image, perceptual or imaginary. 3. Unlike other proposed forms of representation, it does not contain variables ... In place of a variable ... a model employs tokens."	(Johnson-Laird, 1989, p. 488)
[knowledge about] "how a device works in terms of its internal structures and processes"	(Kieras and Bovair, 1984, p. 255)
"Organized structures consisting of objects and their relationships"	(Staggers and Norcio, 1993, p. 590)
"abstract concepts that ... represent a person's knowledge of a decision problem"	(Coury et al., 1992, p. 673)
"Mental models are the mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states."	(Rouse and Morris, 1986, p. 351)

"by a mental model we mean a person's understanding of the environment. It can represent different states of the problem and the causal relationships among states."	(Shih and Alessi, 1994, p. 157)
"mental model of a dynamic system is a relatively enduring and accessible, but limited, internal conceptual representation of an external system whose structure maintains the perceived structure of that system."	(Doyle and Ford, 1998, p. 17)
"people at work hold in their minds a representation of the systems with which they are working, and upon which they draw to assist their understanding and operation of those systems"	(Wilson, 2006, p. 800)

Table 2-7 comparison of mental models definitions

At this stage, Doyle and Ford's (1998) definition (see above) is adopted to provide a common starting point, due to the authors extensive research of previous work on the definition of the term as well as the alignment of the discussion of the term's components ('relatively enduring', 'limited', 'conceptual', 'external system' etc.) that reflect this author's view of the factors at play regarding the current domain (for a further description on the components of the discussion, see (Doyle and Ford, 1998)). However, since the existence of mental models within the observed situation between users of home heating controls and the system they control is assumed to be slightly different in certain aspects, mainly as that interaction is more likely to display a Human-Computer Interaction (HCI) or human factors approach to mental models; other definitions may be used to address specific phenomena that are deemed relevant to this research field.

2.6.2 Properties of Mental Models

It can be seen that views on the properties of mental models are extremely diverse and contradictory in terms of many aspects such as stability, complexity, form, specificity, and multiplicity of structures. Forrester (1961) suggested that mental models are unstable and fleeting, while years later a contrasting view of stability and ingrained nature has prevailed (Senge, 1990). On a similar tone, there is on-going discussion on whether mental models reside in working memory (Johnson-Laird, 1983; Vosniadou, 1994; Wilson and Rutherford, 1989), long-term memory (Bainbridge, 1992; Craik, 1943; Moray, 2004) or both (Nersessian, 2002). This introduces a distinction issue between mental models and schemas, defined by Jones et al. (2011, p. 3) as "long-term knowledge structures which people use to interpret and make predictions about the world around them" (Note the similarity with Rouse and Morris, 1986 definition above). Fortunately, several authors have put forward differences between the two (see Table 2-8 (as seen in Jones et al., 2011)).

Author	**Basis of differentiation**	**Schemata**	**Mental Model**
(Rutherford and Wilson, 2004, p. 312)	Static vs. dynamic structure	"…A procedural data structure in memory"	Use procedural data "in a computationally dynamic manner"
(Holland et al., 1986, p. 13)	Representational flexibility	Inflexible knowledge structures stored in long-term memory provide "predictive knowledge for	Flexible knowledge structure that combines multiple schemata to represent or

		highly regular and routine situations"	simulate an unfamiliar situation
(Brewer, 1987, p. 189)	Generic vs. specific knowledge	"…Precompiled generic knowledge structures."	"Specific knowledge structures that are constructed to represent a new situation through the use of generic knowledge of space, time, causality, and human intentionality"

Table 2-8 differences between mental models and schemas

Coinciding with some of the explanations provided in Table 2-7, it has been shown that when people are faced with an unfamiliar domain, they tend to rely on knowledge of a familiar domain and make sense of the system based on analogies from the familiar domain (Collins and Gentner, 1987; Rickheit and Sichelschmidt, 1999).

Extending from this argument, early work into mental models suggested that people have abstractions of all experiences in the world (Meadows et al., 1974) while later work has shown that while this may be the case, a mental model is a subset of these abstractions that is used to address a specific problem (Coury et al., 1992; Shih and Alessi, 1994; Sterman, 1994; Vennix, 1990). Similarly to the level of inclusion, complexity is another widely debated aspect, ranging from views of simple to extremely complex forms of mental models (Meadows et al., 1974; Senge, 1990; Vázquez et al., 1996), as well as whether a mental model is a single type of cognitive structure (Morecroft, 1992) or a set of different structures (Richardson et al., 1994). Forrester (1971) and Senge (1990) agreed that these models are essentially images of or schematics, while contrasting views have perceived images as epiphenomenal to mental models (Wilson and Rutherford, 1989), meaning that they can be regarded as particular views of the mental model rather than an independent representation on their own; and others favour the view that they are beliefs or concepts (Morecroft, 1992; Sterman, 1989) and do not involve images at all. Several authors have concluded that mental models are inaccessible by the person who has constructed them and that they are outside conscious awareness (Rouse and Morris, 1986; Van Heusden, 1980; Whitfield and Jackson, 1982).

2.6.3 Mental Models in Current Context

In the current context, attention is paid to the theory or conceptualisation of mental models from ergonomics, proposed by Norman (1983, 1986) and Young (1983). This is because it involves the designer as part of the mental model development – a central theme in this research, and highlighted the interaction of user and system via mental models on a level basic enough for real-world application, while facilitating observation through the prism of more complex discussion into essence of mental models seen above. The conceptualisation can be seen in Figure 2-14, in which “the design model is the designer's conceptual model. The user's model is the mental model developed through interaction with the system.

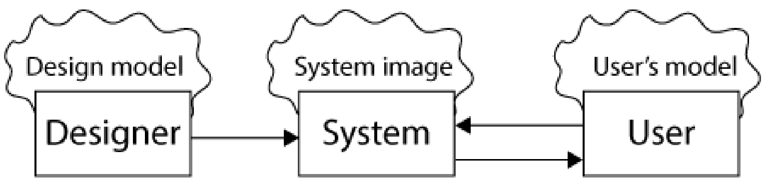


Figure 2-14 conceptual model of designer affecting user's mental model through system image

The system image results from the physical structure that has been built (including documentation, instructions and labels). The designer expects the user's model to be identical to the design model. But the designer doesn't talk directly with the user - all communication takes place through the system image. If the system image does not make the design model clear and consistent, then the user will end up with the wrong mental model." ((Norman, 1986)(as seen in Norman, 1988, p. 190)) Wilson & Rutherford proposed for the model to include the designer's conceptual model of the user's mental model and further annotated the elements (Wilson and Rutherford, 1989) (see Figure 2-15).

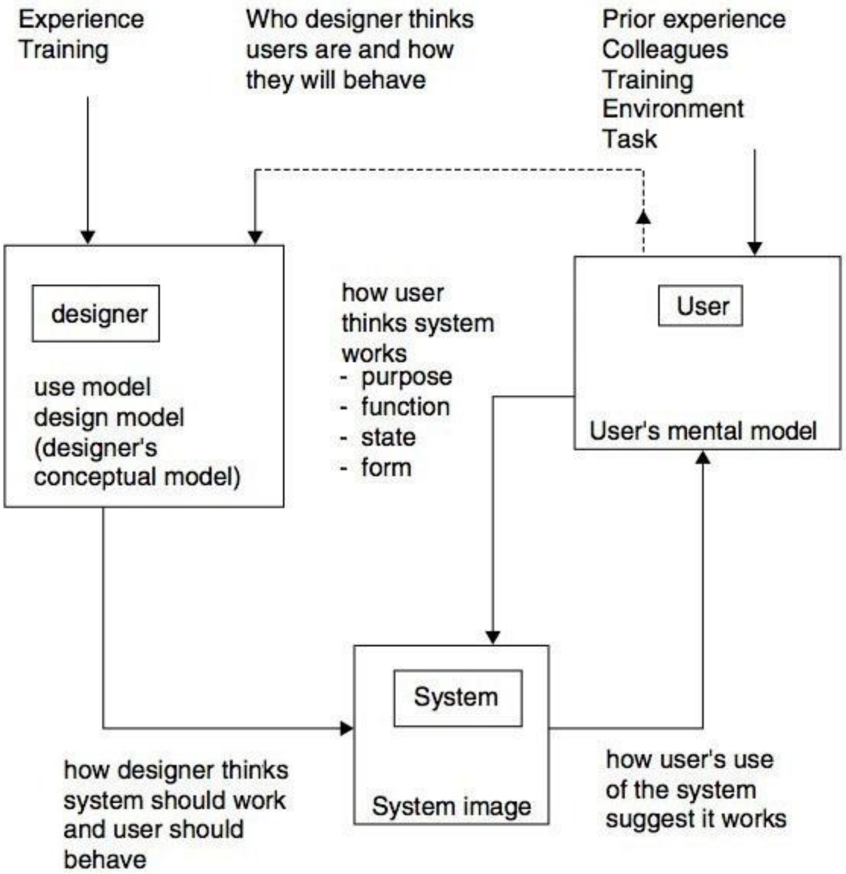


Figure 2-15 conceptual model of mental models in design

The authors explained: "we use the term designer's conceptual model for the designer's representation of the user. The term user's conceptual model may be employed to mean the user's representation of the system, defined in terms as structured or loose as desired. We would reserve user's mental model to refer to descriptions of the user's internal representations which are informed by theories from psychology" (Wilson and Rutherford, 1989, p. 631). In this diagram, there is a lot of transfer of knowledge and mental models from one actor to another and great importance lies with ensuring correct aspects of the model are learnt. This importance originated from the fact that "the mental model of a device is formed largely by interpreting its perceived actions and its visible structure. I call the visible part of the device the system image. When the system image is incoherent or inappropriate, ... then the user cannot easily use the device. If it is incomplete or contradictory, there will be trouble." (Norman, 1988, p. 17) Although there exists a slight issue in Norman's (1988) text regarding use of terms 'conceptual model' and 'mental model' (the author discusses the former to be a predecessor of the latter, although in light of the discussion of definitions above and the essence Norman saw in 'conceptual model', the two are taken interchangeably by this author when regarding this diagram) the value of them to using a device is quite evident: "a good conceptual model allows us to predict the effects of our actions. Without a good model we operate by rote, blindly; we do operations as we were told to do them; we can't fully appreciate why, what effects to expect, or what to do if things go wrong." (Norman, 1988, p. 13) This view has found support elsewhere, with a mental model being seen as a computational structure (Rutherford and Wilson, 2004) and described by Jones et al. (2011, p. 4): "A mental model… …[can] be run like a computer simulation allowing an individual to explore and test different possibilities mentally before acting." The notion follows the footsteps of Rouse & Morris' (1986) definition of a mental model above; and from this it is evident that in order for a person to have meaningful comprehension of a system and its functionality, an accurate mental model has to be constructed.

Norman suggested that designers can ensure the formation of a good conceptual model by using the right (1) affordances, making important things (2) visible, using correct (3) mappings and provide (4) feedback where needed. (Norman, 1988)

(1) "The term affordance refers to the perceived and actual properties of the thing, primarily those fundamental properties that

determine just how the thing could possibly be used" i.e. "Plates are for pushing. Knobs are for turning. Slots are for inserting things into. Balls are for throwing or bouncing. When affordances are taken advantage of, the user knows what to do just by looking: no picture, label, or instruction is required." (Norman, 1988, p. 9)

(2) By visibility, the author referred to both physical and mental visibility. For example, this can refer to both the presence of a label that indicates the function that a button performs and that the button is not hidden behind a cover etc.; or that the capabilities of a button are apparent, the author brings an example of the handles of scissors, which make it visible that when they are moved, the blades will open and close. (Norman, 1988)

(3) The term 'mapping' referred to "the relationship between two things, in this case between the controls and their movements and the results in the real world." (Norman, 1988, p. 23) Examples of this can be light switches on the wall which often tend to be poorly mapped, resulting in confusion as to which switch controls which light; or car steering wheel - when turned clockwise, the top of the steering wheel goes right as do the wheels; and the other way round. Good mappings, the author discusses, include physical analogies and cultural standards that lead to immediate understanding; consider a rising a control to increase something or diminishing level to indicate lessing. (Norman, 1988, p. 23)

(4) Norman defined feedback as "sending back to the user information about what action has actually been done, [and] what result has been accomplished" (Norman, 1988, p. 27)

However, it is quite evident that in the chosen domain, devices struggle with regard to many of these factors, namely visibility. As the users of heating controls interact with the control panel, the actual visibility of mechanics that they influenced are extremely low. They rely on the info provided by labels on the device, on buttons, etc. and user manuals, which are seen as extremely cumbersome and technical to read by many and can thus be seen to contribute relatively little if a wider population is observed. Secondly, as the device controls heating, there are relatively low levels of feedback due to the lag between performed actions and observed outcomes, limiting the efficiency and speed of trial-and-error learning of the device. Affordances, in this case, refer merely to the buttons or other control mechanisms deployed on the actual device and are therefore dependent, to a large part, on the specific design of a device. Mappings are seen as of tremendous importance in this field. For example, if more appropriate mappings would be used, the probability of developing the misconception of a heating system as a valve rather than a switch, could be avoided.

It was pointed out by Wilson & Rutherford more than two decades ago that "the increasing "black box" nature of systems, the power and complexity of control, and the wealth of output information mean that in large part the mental models that operators develop are in hands of designers" (Wilson and Rutherford, 1989, p. 627). It can be assumed, that at the time, the authors were referring to the emergence of the personal computer and the associated changes to human interaction with machines. The statement increases in validity over time as modern day advancements in artificial intelligence and ubiquitous computing increase the capabilities of systems while decreasing visibility and control available to humans. According to Weiser's (1991) vision of ubiquitous computing, the computer vanishes into the background and performs its actions seamlessly in the environment, making observation of affordances, visible actions, mappings or feedback of actions rather difficult. Because of this, there is no easy way to build up a mental model, if one doesn't exist, as the computer has no means of explicitly representing its behaviour. From this it can be hypothesised that initially, the role of a ubiquitous computing interface is to assist in mental model forming, while later it can diminish to a more seamless info transfer to an existing mental model.

As devices and computing capabilities are increasingly more complex, it is important that people experience a 'level playing ground' with machines. It has been shown that people tend to form inaccurate, over simplified and incomplete mental models of mechanical devices (Borgman, 1986; Moray, 1987; Williams et al., 1983). Given the hidden nature of ubiquitous computing devices, this is an extremely likely scenario in the current case as many users have no means to deduct the capabilities of a quasi-autonomous home system and if that is the case, false models are likely to be formed.

Furthermore, it has also been demonstrated that familiarity and extent of time using a system greatly affects the way people use mental models (Galotti et al., 1986). The authors concluded that expert users tend to rely more on abstract rules while novice users rely more on mental models. This has significant implications as it demonstrates the importance of mental models regarding introduction of complex systems to novice users who rely on the interface to deliver understanding and control over the system, suggesting that more assistance should be offered by the system in early stages of use. Moreover, as discussed above, the lack of trial-and-error learning and the overdependence on documentation and labels to explain the way the designer has conceived the system to work, learning the operation of the device has been made rather difficult for the novice user. This author suggests a closer coupling of the 'system image' (as of here forth, 'system image' as discussed by Norman (1986) will be used interchangeably with 'interface') with the user during the learning of the system would provide more meaningful understanding of the system. For this, it is thought best to adopt a tutorial-based approach often seen in video games, where the system itself taught the user by assisting the operation the user wishes to perform, the first time they performed it.

It has also been suggested that people have several mental models about the same system (Clement, 1983; De Kleer and Brown, 1983; McCloskey, 1983a; Williams et al., 1983). This has further issues when taking into consideration the element of multi-occupancy: there will be more than one person interacting with the heating controls in a house. However, while this author is aware of the extensive work that has been done in the field of team mental models research (please see Mohammed et al., 2010 for an extensive review), it is perceived that this is not particularly relevant in the current case for two main reasons. Firstly, the multiple people present in the house are not seen as a team regarding their interactions with the device – while accepted that all of them wish to feel comfortable, this is not seen as a dominant goal that required continuous activity involving the device by users to be achieved. Secondly, due to the first reason, the interactions performed with the device are seen as episodic and disjointed between users, i.e. if one user changes heating controls, the next user does not need to have the same mental model in order to be able to observe the system and make changes suitable to their needs. Thus, the critical factor here is seen as differences between perceptions of comfort, rather than differences between mental models. Regardless, with the several people involved and each of them, possibly, forming several mental models of the system, it is important that the interface remained somewhat constant. Meaning, none of the possible interpretations included the chance of creating misconceptions, such as the valve/switch case. In a case-study into heating systems of six participants, Revell & Stanton (Revell and Stanton, 2013) highlighted that users' mental models differ greatly from the actual functioning of their heating system. The authors concluded that entire control devices (thermostats, programmers) were omitted from mental models, users worked around parts of systems (some reverted to electric heaters when heating system failed to deliver comfort), and operated them significantly differently, that the equipment was meant to be used (bypassing thermostat and operating heat delivery at the boiler) (Revell and Stanton, 2013). The authors highlighted that users' mental models could not be classified according to existing literature and indicated that when a user was asked to "translate heating goals (e.g. comfort, reduced consumption) in terms of the options available on the home heating system …

the ease of this translation is likely to effect optimal operation" (Revell and Stanton, 2013, p. 14). This highlights a clear focus on ensuring users are able to communicate their goals and expectations to the automated heating system, which needs to make sense of them and adapt itself to deliver these goals, while explaining how it does so.

Wilson & Rutherford (1989) discussed their previous work in (Wilson and Rutherford, 1987), and suggested that displays (seen in this case as an interface) must be compatible with user's internal representations of the system; and that displays allow or determine that certain mental models be built up. To illustrate the previous point, Thimbleby (1984, p. 171) suggested that "the designer is obliged to ensure the users have or construct an appropriate user model", however, with the multitude of target users and the inability to measure mental models (discussed below), it is perceived by this author, beneficial to design interfaces that avoid determining certain mental model development, but provide means for users to develop their own mental models, which match their needs and use of the system. The obvious counterargument to such an approach is that an interface cannot be created without applying some existing mental model that the designer has, regardless, difference is made between building-blocks of an interface with correct mappings and an interface as a whole. By extension, it is therefore suggested that users of home controls should be able to 'build' their own interfaces that empower them to use the system how they want, when they want, and through the interactions that they want. In other words, if we accept the premise that an interface is essentially a series of interactions between users and a system, then this author suggests that the goal shouldn't be to design the interactions (interfaces) but a framework that allows itself to be populated with interactions by the user. This reduces the role of "Who designer thinks users are and how they behave" in Figure 2-15 and shortens the link between interface and user.

2.6.4 Limitations regarding this research

Both recent and early work (Chapanis, 1959; Wilson, 2006) on mental models warns to use the concept with caution, highlighting the main limitation of the concept to practical work – that mental models are extremely difficult to measure and efforts to do so may themselves change the mental model merely by asking people about them. Furthermore, as Wilson & Rutherford (1989, p. 630) point out: “A mental model cannot be a first-order design tool for the reason that although the general idea is applied to the data, the specific form of the presumed mental model has to be inferred by using other research/design tools and criteria.”

2.6.5 Implications to this research

- Designers can ensure the formation of a good conceptual model by using the right (1) affordances, making important things (2) visible, using correct (3) mappings and provide (4) feedback where needed
- The disappearing nature of ubiquitous systems means there exists no explicit way to demonstrate the ‘inner workings’ of the system, which hinders mental model formation, crucially in the learning phase where novice users are relying on some mental model to establish an understanding of the system.
- Initially the role of a ubiquitous computing system interface is to facilitate mental model formation before regressing into the seamless operation more similar to Weiser’s (1991) vision
- The interface must not attempt to recreate the designer’s mental model in the user, but focus on the validity of individual mappings and cues in the representation so that the user can build up their own mental model

- Users can form several mental models about the same system and multiple users add to this issue as conflicts between mental models and knowledge can occur
- Mental models provide a way of explaining people's behavior when they are presented with a novel technology, in this case, ambient intelligence home controls.
- Wilson and Rutherford's (1989) diagram provides a good starting point for explaining the interactions between the system and the user and the role of the interface in communicating "system image" to the user.

2.7 Building controls

The body of research presented in this section illustrates the current prevailing situation where simple design agendas are ignore or addressed inadequately, resulting in unnecessary inability of homeowners to use their homes to the full extent of their efficiency. To illustrate the most basic points of this argument, a recent study by Combe et al. (2010) revealed that a simple thermostat controller excluded 9.3% of UK population based on usability issues such as vision, hearing, thinking, dexterity, reach and stretch, or locomotion requirements. Unfortunately, poor product design choices are not the full extent of the issue, several studies have listed control as a significant problem in homes (Hackett and McBride, 2001; Lutzenhiser, 1992; Ubbelohde et al., 2003). In order to shed light into these shortcomings and learn from them for application into this research, the rest of this section will be divided as follows: a discussion of building controls and information delivery systems in wider context; home controls use issues; lessons from building controls in intelligent homes; and implications to this research.

2.7.1 Building controls & information displays in wider context

Research has shown that theoretical consumption of energy in houses does not line up with actual consumption (Audenaert et al., 2011) and while governmental documentation, spurring from the work of Utley and Shorrock (2006), claimed increasing temperatures in homes are responsible for falling short of the predicted energy savings others have shown that this is not the case and required temperature has stayed at the same levels for decades while efficiency of building fabric has increased (Shipworth, 2011). Thus, logic dictates that other factors are responsible for unmet expectations of carbon savings. With the emergence of various energy saving technologies and the stability of thermal comfort levels, it can be assumed the proposed technologies are not working as intended. Indeed, Tuohy and Murphy (2012) presented a summary of several advanced buildings (mainly office and governmental buildings) that were underperforming in comparison to their expected levels. This poor performance was attributed to invisibility of actual performance, poorly designed controls, building managers' and occupants' inability to understand the building's functionality, and lack of user control as primary causes. These factors merit consideration in finer detail.

There already exists a large knowledge base of research into devices displaying performance and resource consumption information. Such devices are often aliased as "energy monitors" or "building custodian devices" and they act to enhance user control by increasing user's knowledge of their energy usage. A short cross-section of such devices observed in this research can be seen in Table 2-9.

Device name	**Authors**	**Energy aspect tackled**	**Type of interface**
Carbon Culture	(Lockton et al., 2011)	Electricity, Gas	Web
Stepgreen	(Mankoff et al., 2007)	Carbon footprint	Web

The PowerHouse	(Bang et al., 2007)	Electricity	Web
Wattsup	(Foster et al., 2010)	Electricity	Web
Wattbot	(Petersen et al., 2009)	Electricity	Web/Plug-in & Display
UbiGreen	(Froehlich et al., 2009)	Transportation	Plug-in & Display
GeoSmart	(Hargreaves et al., 2010)	Electricity	Plug-in & Display
BeAware	(Björkskog et al., 2010b)	Electricity	Plug-in & Display
Greeny Energy Meter	(Wever et al., 2008)	Electricity	Plug-in & Display/Ambient
EnergyLife	(Björkskog et al., 2010a)	Electricity	Plug-in & Display/ Ambient
PowerAgent	(Bang et al., 2007)	Electricity, Water	Plug-in & Display/ Ambient
Flo	(Shrubsole et al., 2011)	Electricity	Plug-in & Display/ Ambient
Coralog	(Kim et al., 2010)	Electricity	Plug-in & Display/ Ambient
ECD	(Yun, 2009)	Electricity	Plug-in & Display/ Ambient

Infotropism	(Holstius et al., 2004)	Landfill waste	Ambient
Waterbot	(Arroyo et al., 2005)	Water	Ambient
Jetsam	(Paulos and Jenkins, 2006)	Landfill waste	Ambient
Imprint	(Pousman et al., 2008)	Printing	Ambient
WattLite	(Jönsson et al., 2010)	Electricity	Ambient
Power Aware Cord	(Gustafsson and Gyllenswärd, 2005)	Electricity	Ambient
Raymatic	(Yun and Gross, 2011)	Thermal Energy	Ambient
Nuage Vert	(Evans et al., 2009)	Electricity	Ambient
7000 Oaks & Counting	(Holmes, 2007)	Carbon Footprint	Ambient
Futureproofed power meter	(Jeremijenko, 2001)	Electricity	Ambient

Energy AWARE Clock	(Broms et al., 2010)	Electricity	Ambient
Powersocket	(Heller and Borchers, 2011)	Electricity	Ambient

Table 2-9 summary of energy monitoring devices

While the topic of energy usage monitoring devices is not paramount to this research, it is maintained that the field does hold value in terms of designing an interface that is effective in enhancing engagement with the energy conservation aspect of domestic heating. For this purpose, these devices are analysed in the ideation chapter (Chapter 3) below. Returning to the discussion of these devices in the context of home control devices, it has been revealed that the initial savings using such devices is not sustained over long periods of time (van Dam et al., 2010). Similarly, it has been shown that proposed technologies are not accepted or used as intended (Crosbie and Baker, 2010). Some have suggested the poor performance of UK's 'zero-carbon' housing is significantly influenced by user behavior through heating ventilation, understanding, and control they have over their home (Stevenson and Rijal, 2010). To understand these shortcomings better, it is important to consider the use and misuse of current home controls.

2.7.2 Current home controls use

Research has shown that people are happy to use minor modifications to improve the energy performance of their homes such as LED lights or programmable thermostats (PT) (Chetty et al., 2008), however, it is vital that technologies aimed to reduce energy consumption are used correctly (Crosbie and Baker, 2010). This does not seem to be the case as Liao et al. (2005) discovered that inadequately fitted controls on boilers and heat emitters cause overheating in UK houses and suggested that the overall interaction of the heating system needs to be considered in design of control devices.

Stevenson, Carmona-Andreu & Hancock (2012) highlighted that these problems extend to other appliances such as heating and water controls, mechanical ventilation controls, electrical equipment controls, kitchen appliances, water services controls, and other. The issues discussed included interfaces that failed to show vital information about system state, placement of interfaces that prohibited their use, wrong settings installed by installers, users' false conceptualizations about what a system did, among others (Stevenson et al., 2012). The authors classified these barriers as (1) habits, referring to people's override of the system or unawareness of wrong settings or context in which the controls were used; (2) guidance, referring to poor performance by demonstrators during handover of the property or the fact that "the guidance literature on these controls was overly technical and did not facilitate easy learning through bespoke graphical illustrations of equipment situated in the home" (Stevenson et al., 2012, p. 6); and (3) learning, which referred to the necessary know-how for engagement with technology in all stakeholders (Stevenson et al., 2012).

In order to understand the inability to reach users more context-specifically, attention should be drawn to heating controls. Several pieces of research have been conducted in America into regular and programmable thermostat use and usability (Meier, 2012; Meier et al., 2011, 2010; Peffer et al., 2011). It is easy to see why this is a case of great interest as programmable thermostats provide the technology to potentially conserve significant amounts of energy (Maheshwari et al., 2001); are widely used and demanded by US legislation (as discussed in Peffer, Pritoni, Meier, Aragon & Perry 2011) but fail to be correctly used by occupants (Freudenthal and Mook, 2003; Meier et al., 2011). There are a number of reasons why this is the case. Meier et al. compiled such complaints and unexpected beliefs from numerous studies conducted in the U.S. and Europe, classifying them as Energy Misconceptions, Thermostat Misconceptions, Programmable Thermostat Complaints/Issues, Thermostat Instruction Manual Complaints/Issues and Barriers to Using PTs in Table 2-10.

Energy Misconceptions	References
Heating all the time is more efficient than turning heat off	(Norman, 2002; Rathouse and Young, 2004)
People have no knowledge of the annual/daily running cost	(Rathouse and Young, 2004)
People ignore the temperature set in their own thermostats	(Rathouse and Young, 2004)
People have little knowledge of how the HVAC system works	(Diamond, 1996; Karjalainen, 2008; Rathouse and Young, 2004)
People ignore the environmental impact of overheating	(Rathouse and Young, 2004)
Thermostat Misconceptions	**References**
Thermostat is simply an on/off switch	(Rathouse and Young, 2004)
Thermostat is a dimmer switch for heat (valve theory)	(Karjalainen, 2008; Kempton, 1986; Rathouse and Young, 2004)
Turning down the thermostat does not reduce energy consumption (or not substantially)	(Nevius and Pigg, 2000; Rathouse and Young, 2004)
Boiler thermostat is used to change the temperature in the room (as if it is a room thermostat)	(Rathouse and Young, 2004)

People are afraid of using PTs (unknown terrible consequences)	(Diamond, 1984a, 1984b; Karjalainen, 2008; Nevius and Pigg, 2000; Rathouse and Young, 2004)
Programmable Thermostat Complaints/Issues	**References**
PTs are too complicated to use	(Boait and Rylatt, 2010; Chetty et al., 2008; Consumer Reports, 2007; Critchley et al., 2007; Diamond, 1996, 1984a, 1984b; Freudenthal and Mook, 2003; Fujii and Lutzenhiser, 1992; Karjalainen, 2008; Lindén et al., 2006; Moore and Dartnall, 1982; Nevius and Pigg, 2000; Rathouse and Young, 2004; Vastamäki et al., 2005)
Buttons/fonts are too small	(Consumer Reports, 2007; Dale and Crawshaw, 1983; Diamond, 1984a, 1984b; Rathouse and Young, 2004)
Abbreviations and terminology are hard-to-understand; light and symbols are confusing	(Dale and Crawshaw, 1983; Diamond, 1984a, 1984b; Karjalainen, 2008; Lutzenhiser, 1992; Moore and Dartnall, 1982)

The positioning of interface elements is illogical	(Dale and Crawshaw, 1983; Diamond, 1984a, 1984b; Moore and Dartnall, 1982)
PTs are positioned in an inaccessible location	(Karjalainen, 2008; Rathouse and Young, 2004)
Setting the thermostat is troublesome	(Freudenthal and Mook, 2003; Lindén et al., 2006; Nevius and Pigg, 2000; Rathouse and Young, 2004)
It is difficult to set time and date	(Consumer Reports, 2007)
PTs give poor feedback on programming	(Karjalainen, 2008; Moore and Dartnall, 1982)
PTs are not attractive to use	(Parker et al., 2008)
Thermostat Instruction Manual Complaints/Issues	**References**
Too technical – only for plumbers	(Freudenthal and Mook, 2003; Rathouse and Young, 2004)
Not enough pictures and diagrams	(Rathouse and Young, 2004)
Too wordy, time consuming, too detailed, better focus on basics, not procedural (step by step instructions)	(Rathouse and Young, 2004)
Better if attached to the control (easy to lose)	(Rathouse and Young, 2004)
Barriers to Using PTs	**References**

Payback and increased convenience are not worth the cost	(Nevius and Pigg, 2000)
Presence of alternative heating/cooling devices not controlled by PTs, (for example wood stoves)	(Nevius and Pigg, 2000; Rathouse and Young, 2004)
Age dependent problems with programming	(Freudenthal and Mook, 2003; Sauer et al., 2009)
Unpredictable time at home makes programs useless	(Nevius and Pigg, 2000; Rathouse and Young, 2004)
Incorrect mental models about good indoor temperature	(Karjalainen, 2008; Vastamäki et al., 2005)
Thermal feedback is delayed (thermal inertia) and desired thermal comfort is delayed	(Rathouse and Young, 2004; Vastamäki et al., 2005)
Conflicts among people in the household with different thermal needs and operating practices	(McCalley and Midden, 2004; Parker et al., 1996; Rathouse and Young, 2004)
Aesthetics of the device	(Gupta et al., 2009)
People want to retain control	(Kempton et al., 1992)
Special HVAC systems (Evaporative cooling, Heat Pumps) work differently than normal systems and require a different operating mode, user practice and thermostat setting	(Bouchelle et al., 2000; Diamond, 1996)

High priority for heating in people's expenditures	(Rathouse and Young, 2004)

Table 2-10 literature demonstrating energy misconceptions, thermostat misconceptions, programmable thermostat complaints/issues, thermostat instruction manual complaints/issues, and barriers to using programmable thermostats

Automation possesses capabilities to overcome many of these by presenting users with meta-information in an indirect, but concise way. Users could communicate in this easily understandable meta-information to the automation, which would allow the automation to translate meta-information to specific technical commands and provide easily understandable feedback. Firstly, however, it is worth considering what has been revealed about building controls in such environments.

2.7.3 "Smart homes" heating controls

Subsequently, attention is drawn to 'smart' heating controls. For a wider discussion on the term, please refer to Ambient intelligence systems section. It is clear from the research presented there, that developments in computing research are at a stage where building an environment that manages home heating through sensory input is achievable, however, as Chetty et al. (2008, p. 243) point out: "the question of what to include for a resource consumption management display and control system remains open."

Firstly, let us consider the role humans play in 'smart' homes. In a probe study into values associated with smart homes, energy saving was found to be the least related value to technology; while most valued items were associated with feelings of comfort, sentiment and relaxation (Haines et al., 2006). Furthermore, Jaffari and Matthews (2009, p. 9) speculate that if automation chooses for the human to take environmentally friendly action, the consequences, on top of reduced autonomy for the humans, may include diminished understanding of the impacts people's actions have on the environment (accountability). Such disengagement from the system

(Borgmann, 1995) would not only encourage “creative ways of working around the system rather than straightforward, energy-efficient compliance with it” (Jaffari and Matthews, 2009, p. 9), but would also diminish the potential energy effectiveness of the building. It has been suggested that ‘green’ buildings rely on “both the building systems and inhabitants interact[ing] and adapt[ing] in response to changing external conditions and needs” (Cole et al., 2008, p. 333) to perform to their potential. This in turn means that a successful controls implementation would consider end user behaviours and values (Crosbie and Baker, 2010). From this we can conclude that even with homes that have advanced capabilities, humans still play a crucial role.

When designing these systems, it is often assumed that people act in a typical manner – perform typical actions in typical locations at typical times (Crabtree et al., 2002; Rogers et al., 2011). However, research in thermal comfort has shown that people are extremely stochastic and when systems (such as air conditioning or heating units) are in control of the environment, users are far less forgiving as expectations are higher (Brager and de Dear, 1998; Leaman and Bordass, 2001; Paciuk, 1989). This means that when these mismatches occur, the user would act ‘untypically’ and “often suddenly customise[s], struggle[s] or work[s] around the (often rigid and inflexible) controls and systems provided” (Ackerman, 2000, p. 187). This would further be increased by the level of manual control humans have learnt to possess (Stevenson and Rijal, 2010, p. 561). Depriving users of this control would not only cause people to rebel against the system, but as already mentioned above, also “take away human responsibility for and awareness of their immediate surrounds.” (Jaffari and Matthews, 2009, p. 6) The importance of human override is therefore evident and the degree to which this should be allowed or encouraged without impairing system functionality has been also been highlighted in research (Stevenson and Rijal, 2010, p. 561). However, over-ride is perhaps a more critical issue than most would care to admit as it defines greatly the extent of humans being in control of the machine; or the machine being in control of the humans. Paradigms of such nature have been considered in the field of product design or design for sustainability (Bhamra et al., 2011; Elias et al., 2007; Jelsma and Knot, 2002; Lilley, 2009; Lilley et al., 2006, 2005; Rodriguez and Boks, 2005; Tang and Bhamra, 2009, 2008) and it has been concluded that even slight alterations in functional design can drastically change the element of power within the relationship.

It has been demonstrated that building occupants feel more comfortable when they perceive themselves to have control over their surroundings (Black and Milroy, 1966; Elder and Tibbott, 1981; Fishman and Pimbert, 1982; Gagge and Nevins, 1976; Williams, 1995), as well as the reduction of this perception with the increase in the number of people sharing the space (Leaman and Bordass, 1993). Paciuk distinguished between available control (adaptive opportunity), exercised control (behavioural adjustment) and perceived control (expectation) and found the latter to be the strongest predictor if thermal comfort and satisfaction of the three (Paciuk, 1989), and this correlation has recently been confirmed (Boerstra et al., 2013). Stevenson & Rijal (2010) highlighted the importance of introducing occupants to the subtle complexities of their homes to ensure 'interactive adaptivity' between the home and its inhabitants is properly executed. The term interactive adaptivity could be understood through "the affordances provided in the building design for the occupants to manage and control their environment more actively as well as the capabilities of occupants to do so." (Stevenson and Rijal, 2010, p. 550) However, with the invisibility issue in these systems, this interaction between the inhabitant and the building would be likely to suffer.

When perceived control and available control are discussed, it is worth considering the timeliness and physical location of control interfaces that deliver these factors to the user. Ubiquitous computing devices are purposefully designed to operate in the fabric of our environments, with deliberately little to no interaction with the end user; and while this can be beneficial in disburdening the user, it has also been suggested to be disengaging (Borgmann, 1995). Furthermore, this could even be seen as a weakness of the technology, because occupants who are used to have high levels of manual control over the devices in their homes, are now forced to manipulate their familiar environment through new interaction techniques (Van de Sluis et al., 2001). Some have suggested that “because these utility systems have faded into the background of householders’ lives, … developing systems that encourage householders to reflect on and re-engage with these aspects of the home’s infrastructure is a research agenda that Ubicomp is well poised to fulfill” (Chetty et al., 2008, pp. 242–243). However, in a world where users are constantly being engaged through notifications from devices, it is worth considering the way people use information in their homes. Haines et al. (2006, p. 358) concluded that “people do not display and share information in one single place or using one single technique; people often leave impromptu notes and messages left in context-specific locations around the home. A single, all-encompassing user interface cannot adequately support this type of behaviour.” In comparison, some authors suggested that certain areas such as fridge doors do often serve as information centres (Chetty et al., 2008, p. 244). Therefore, it is not only a question of what controls are presented to the user, but also where these are presented.

Finally, two elements should be considered: household dynamics and learning how to operate controls. Firstly, the element of control gets an added dimension in most homes as there are more than one occupant. Multi-occupancy has been shown to increase confusion in the performance of the system through conflicting preferences (Chetty et al., 2008) or knowledge of settings based on these preferences (Koskela and Väänänen-Vainio-Mattila, 2004). Secondly, research into home controls has pointed out the complexity of user manuals and instructions, which would be likely to worsen with the extended functionality of intelligent home controls. Easy and effective information presentation also limits the disengaging aspect of invisibility factor, as illustrated by Stevenson et al. (2012, p. 7): “Rather than requiring twenty pages of guidance, a boiler programmer should reveal its functionality in a straightforward way to the user. A positive user engagement will also lead the user to value the controls as objects in their own right which are to be maintained, repaired if possible, and appreciated…"

2.7.4 Implications to research

From the literature observed above, the following implications have been outlined:

- Barriers to successful usage can be classified as (1) habits, (2) guidance, and (3) learning.
- Several misconceptions of use in terms of energy, thermostats, programmable thermostats, instruction manuals and barriers to use can be observed.
- Automation provides opportunities to overcome misconceptions and barriers to successful use as users can be presented with less technical meta-information leaving the automation to handle operation of controls based on meta-information.
- When mismatches between system delivery and users' high expectations occur, users act unpredictably to over-ride the system. This should be allowed and gained from, rather than seen as a break-down.
- Perceived control affects comfort greatly and the control interface must demonstrate transparency and clarity in order to enhance this in the user.
- The physical location of information, multi-occupancy, and clarity in instructions must be taken into consideration when implementing any control interface.

Stevenson & Leaman (2010) express well the general perspective that implementation of building controls should take: "A successful approach will allow inhabitants to feel empowered, rather than guilty, although reality checks provided by individual footprint and carbon taxes may be essential to demonstrate and reinforce the consequences of their actions."

2.8 Home automation

In the previous section and the introduction chapter above, it was described how automation possesses the potential to increase the efficiency of home heating systems and thus limit the energy requirements of the building. Automation can be defined as technology introduced to perform tasks previously fulfilled by human operators (Parasuraman and Riley, 1997) and the rest of this section focuses on the general automation regarding automation, automation in the home setting, and home heating-specific body of work.

2.8.1 Automation in the wider context

Since the industrialisation of production, machines have been employed to do human's work. However, it soon emerged that automation was not as straight-forward as one might think. In one of the most influential texts in automation, Bainbridge (1983) highlighted several ironies of automation such as reduced understanding in the operator, reduced efficiency in difficult tasks, and higher risk of failure in novel situations. Regardless, the perceived benefits of automation such as reduced inefficiency, human workload and human error (Bainbridge, 1983; Hollnagel, 2001) outweigh the potential shortcomings in a successful implementation. Several different ways to implement automation can be conceived and models have been developed to explain the level of automation in a system and the implications this could have on the user and the user-system interaction (Billings, 1991; Endsley and Kiris, 1995; Endsley, 1999; Parasuraman et al., 2000). Level of automation refers to a dimension on which at one end the user had full control of the system's actions and on the other the system was fully autonomous in its operations. It has been suggested that higher levels of automation can reduce user's trust in the system and the preparedness to assume action if the system fails (Hollnagel, 2001). Focus should therefore be placed on trust and how systems can utilise automation without reducing user's trust in them. On the other hand, high levels of trust have been shown to increase user's likelihood of using the automated system (de Vries et al., 2003; Moray et al., 2000). It has been suggested that trust in a system originates from the user's ability to understand it (Lee, 1991). Additionally, the types of errors the automation made have also been found to influence use (Jiang et al., 2004). Moray et al. (2000) showed that users with higher self-confidence than trust in the system preferred manual control over automated control. With this in mind, it is useful to observe the more specific automation literature in the home setting.

2.8.2 Home automation

Focus is now drawn to a more domain-specific field of home automation. It is speculated that several differences occur in the domain due to the drastic change in user behavior between a work and home setting. It has been revealed that people see automation as time saving and making household tasks easier (Haines et al., 2006), as well as a highly desired interaction technique (Koskela and Väänänen-Vainio-Mattila, 2004). However, if we re-consider Moray et al.'s (2000) findings regarding self-confidence and trust, an interesting dynamic can be observed. Because of the home domain, users are much likelier to take ownership of the items in their home and can be assumed to have much higher levels of self-confidence, even though, these may be misplaced as seen above from Revell & Stanton (2012). Therefore, contrary to the perceived utility stated above (Haines et al., 2006), users are be suspected to be less forgiving in a home setting and more likely to desire manual control, hindering the automation's ability to perform to maximum efficiency.

Variation in levels of automation has also been observed in the home setting. It has been noted that users have high expectations on how to control automation and whether they want full automation, pattern control, instant control, or a mixture (Koskela and Väänänen-Vainio-Mattila, 2004). The first refers to a fully autonomous system; the second a string of automated occurrences that are planned by the user; and the last refers to a control strategy similar to standard ‘do this now’ commands. Large number of research studies have focused on the technical implementation of smart-home systems due to the plethora of “real-world” problems that need addressing such as hardware, connectivity, or interfacing between a multitude of differing devices, as well as security and privacy issues of these systems (Gill et al., 2009; Gomez and Paradells, 2010; Yang et al., 2015 to name a few).

With regard to interface design for home automation or control systems, several studies have investigated the use of voice-controlled ambient interfaces including technological attainability of voice recognition understanding different voices (Al Shu’eili et al., 2011) and an early example of the system implemented internet, GSM network, and voice recognition to demonstrate the possibilities of real-time monitoring and remote control of a house (Yuksekkaya et al., 2006). Others adopted a computer or browser-based approach with either displays in home or on user’s own devices, for example the Follow-me graphical user interface exploring the technological implementation of a browser-based interface that could be accessed from any browser-enabled display in the house (Dooley et al., 2011). Differences in user demographics have been demonstrated through proposal and assessment of two contrasting touchscreen display-based interface concepts with one specifically aimed at elderly occupants and resulting in design guidelines for the Chinese home context (You et al., 2008). Others developed custom interfaces including a token-based interaction concept where users would interact through a TV remote control-style device and the user-cantered design process behind the device (Van de Sluis et al., 2001). It has also been demonstrated through a projection-based prototype that an ambient interaction altering the manner in which the user sees their environment, illustrating invisible links between visible elements in the users’ environment can help users understand the ambient automation in their home (Vermeulen et al., 2009).

This research aligns with the commercially predominant approach relying heavily on smartphone applications (Ecobee, 2015; Nest, 2012; Smartthings, 2015), which are seen as a suitable choice due to the technological flexibility of these devices, their communicative capabilities, popularity at the time of writing, and a wide-spread adoption by users that has rendered the devices never more than an arm's length from the user.

2.8.3 Home heating automation

In order to best understand home heating automation solutions and the direction in which the adoption of these devices is headed at the time of writing, it is important to begin by considering available commercial products. The most popular and widely publicised solution to date has been the Nest learning thermostat (Nest, 2012) which learned user's manual alterations of the thermostat to learn behaviours. Nest users could utilise set-back temperatures to lower temperatures during night time and occupant absences, remote control via smartphones, and cues for lowering temperatures, thus promoting energy-efficient behaviours. The German provider Tado (2015) uses users' GPS location to cool the house when users were away, optimises heating behaviour to building construction, and allows users remote overview or manual over-ride via a smartphone application. The Ecobee (Ecobee, 2015) also uses motion sensors to monitor presence and turn heating off when users are away and facilitates manual override via a smartphone app, as well as several integrations with other home automation products including voice control. These systems are readily available to consumers, but it is important to understand the potential of the technology and social implications of these systems.

In order to do so, knowledge obtained by deploying similar systems in home setting needs to be considered. As mentioned in the home automation section above, much of the research conducted in the field has focused on the exploration of the technology. Existing work in automated home heating control algorithms has included several different approaches to introduce energy saving. An early example applied a neural network to predict occupancy probability that most matched observed pattern using the past few hours, the previous three days, and same weekday data from the past four weeks (Mozer et al., 1997). The authors concluded that their controller was able to operate around changing life patterns and suggested that cost saving was possible. Others used GPS positioning data from occupants' phones as trigger for a set-back mode and their simulations demonstrated savings up to 7% could be obtained by integrating drive-home time as a trigger for re-heating the house to user-selected settings (2009). Subsequent work highlighted that a probabilistic presence schedule derived from GPS data outperformed user-reported presence schedules and driving home duration alone (Krumm and Brush, 2011) indicating that an automated system could deliver better results for limiting heater switch-on time than a human-programmed thermostat. However, neither of these studies applied these schedules to a simulated or situated heating system, thus not reflecting the complexities in managing a thermal environment to match user expectations.

By utilising a control algorithm that acted reactively after presence was detected, rather than proactively predicting presence and catering for future occupancy, it was demonstrated that occupants' ability to forgive the algorithms delays in this "miss time" could be utilised to reduce heating and cooling durations, resulting in potential heating and cooling demand reduction up to 15% above US recommended EnergyStar setback schedule (8am – 6pm) (Gao and Whitehouse, 2009). This model used a user-selected set-point temperature and applied it based on their presence. While an interesting approach, the energy saving was delivered at the cost of occupant comfort, a trade-off that would not be possible for all users. Another control algorithm used motion sensor and magnetic door sensor data to (1) monitor occupants' presence to switch the HVAC (Heating Ventilation and Air

Conditioning) system off during night-time and absences, (2) utilised previous presence data to predict presences and choose between a proactive and reactive approach to heating, and (3) utilised a 'deep setback' in which the temperature house was allowed to decay without a lower set-back temperature (an extremely low safety set-back temperature of 10°C for heating and 40°C for cooling were employed to prevent damage to the building) (Lu et al., 2010). A static set-point of 70°F (21°C) was used and the authors concluded a potential delivery of 28% energy reduction was possible and highlighted that deeper set-backs have a larger impact on energy saving than longer setbacks are (Lu et al., 2010). However, similarly to the previous example, this study can be criticised for not including a dynamic set-point temperature, or any variation in it to assess the controller's efficiency for different users with different thermal preferences.

In a more comprehensive approach, Scott et al. (2011) gave their algorithm control over a single-stage gas-fired heating system algorithm in 5 households in the UK (2) and the US (3). One of the five participating households tested a spatiotemporal control algorithm, whilst the remaining four were controlled as a uniform thermal environment throughout the house; both responding to predicted occupancy. User presence was detected using RFID tags (using electromagnetic fields to automatically identify and track tags attached to objects) and the algorithm's performance was measured against a 7-day programmable thermostat schedule. The utilised algorithm pre-heated living spaces in expectance of future presences, applying a user-defined set-point when the space was occupied during the day and a sleep set-point during the night. When the space was unoccupied their algorithm predicted the next occupied period by representing space occupancy as a binary vector for each day, where each element represented occupancy in a 15- minute interval. A partial occupancy vector from midnight up to the current time was kept and used to predict future occupancy by finding similar days from the past. The algorithm then computed the Hamming distance between the current partial day and the corresponding parts of all the past occupancy vectors (the

Hamming distance simply counts the corresponding number of unequal binary vector elements), and picked the 5 nearest past days for making the prediction as a mean of those five days (Scott et al., 2011, pp. 284–285). When the algorithm was deployed, the results demonstrated an 18% decrease in gas usage for per-room control and 8% reduction for a uniform solution suggesting a spatiotemporal heating solution offers more energy saving over the same control mechanism deployed in uniform across rooms. While the proposed algorithm was a step in the right direction, it failed to close the thermal comfort feedback loop and dynamically account for users' thermal preferences. By that it is meant that it merely applied a user-defined set-point temperature and did not treat this set-point as a variable that can be part of the thermal comfort dialogue.

2.8.4 Implications for current research

As seen from above, the existing knowledge of home heating automation has some gaps that this research is positioned to fill.

- Firstly, exploration of user experiences of these systems in live deployments have thus far been far and few between. Therefore, the exploration of user experience of deployed systems is currently lacking and our understanding of the environment including the alterations that the introduction of automation causes insufficient.

- Secondly, work on heating control algorithms has focused on the algorithm and not the user experience of it, which, as highlighted by the section on broader implications of automation in the home, has an immense effect on its success. This, therefore, indicates a need to take a holistic approach to home automated heating control algorithm design.

- Thirdly, state of the art in automated home heating control algorithm, due to a lack of the holistic view encompassing thermal comfort, lacks the inclusion of thermal comfort experience as a variable.

2.9 Study questions

From the vast quantity of existing knowledge above, it has become evident that the user experience of automated home heating controls is a complex matter and there are a variety of factors influencing it. It has been demonstrated that there exists a gap in knowledge regarding automated home heating systems research focusing on the human element and the user experience that is observed in the wild.

This research aims to fill that gap by exploring the user experience of quasi-autonomous home heating systems, and how this could be enhanced by user interface qualities.

This rest of this section reflects on the implications of each subject field for this research and establishes specific gaps in research and the study questions to fill these gaps.

Firstly, the sustainable design section highlighted the usefulness of design as a problem-solving discipline that facilitates understanding and catering for complex problems with multiple constraints. This establishes the overall research theme and perspective. Secondly, thermal comfort literature revealed the complexity involved in the human experience of thermal comfort ranging from adaptive actions, stochastic nature of home occupants, as well as the physical environment of the home in terms of dwelling type and characteristics. Building control literature highlighted that those factors are mixed with barriers to successful operation of heating control devices, and that users must feel empowered rather than constrained by these devices. However, before these issues can be addressed with design solutions, a design brief (however elusive or concise) must be obtained. For this, it is necessary to better understand the qualities of the environment that is being designed for. From this we come to the first study question:

Q1 - What is the context within which these interfaces are used?

Furthermore, previous research into automated home heating has highlighted energy saving potential, but lacked the element of closing the occupant acceptance loop of proposed interventions. These interventions often involve a control mechanism that could jeopardise thermal comfort, a concept that has proved to be a dynamic and elaborate experience, rather than a passive equilibrium. Thus, we must understand the energy saving potential of such automated controllers from a human thermal comfort experience perspective, giving rise to question 2:

Q2 - To what extent can spatiotemporal automated heating minimise energy use while providing thermal comfort?

In addition, thermal comfort literature highlighted variance in thermal comfort sensation both between and within occupants. Coupled with the variety of demonstrated automation control algorithms, the previous question can be elaborated to investigate whether a control algorithm could use an alternate heating strategy to increase energy saving without compromising the thermal comfort experience of the user:

Q3 - How are different heating strategies experienced by users?

Finally, mental models research has highlighted the complexity of users creating an understanding of a new system and how it works. Coupled with the variety of usability and user experience issues shown in the building controls section, we arrive at a problem where even the most advanced home automation could be rendered useless by human override. The challenge is elevated by findings from ambient intelligence system research that highlight the disappearance of these systems and interfaces into the fabric of our lives, rendering a situation where understanding of the systems is significantly hindered. Reduced understanding in turn reduces user’s trust and confidence in the automation reducing its ability to function to maximum efficiency. Potential solutions have been suggested in ambient intelligence research, but these have not been explored in the home heating automation domain with sufficient focus, nor in situ. Therefore, we are left with question 4:

Q4 – How do visibility of feedback, and intelligibility affect the user experience related to understanding and control?

These questions will dictate the activities of this research in the following chapters.

2.10 Research methodology

It was demonstrated above how home heating systems operated in a highly complex environment influenced by social, technological, and environmental factors. The user experience of such systems is therefore dependent on a successful solution to problems from all these fields. Research aiming to understand the user experiences must consider the mentioned fields and must therefore be highly multi-disciplinary in nature. Subsequently, this research adopts a mixed-methods approach. Furthermore, as demonstrated above, this author suggests that a design perspective would be most likely to result in a successful implementation due to the innate problem-solving nature and user-focus of the design practice. However, a design practice requires a design brief, which has been established above with the research questions, and design constraints. The latter were the environment where usage occurs and these require further exploration. To such end, this research will initially embark on an ideation activity observing the environment that user experiences are designed for. This would provide answers regarding study question 1 (Q1) the context within which these interfaces were used. In addition, the results of this activity in combination with the knowledge gained in Chapter 2 will be used to provide a model, which will be used as the lens through which subsequent activities would be undertaken and assessed.

Designing user experiences would be counter-intuitive if users' attitudes, opinions and preferences are not considered. Therefore this research will subsequently direct attention to user-involvement in early-stage design process through participatory design practice aiming to understand the users' values and provide design prototypes to then build upon. Proposing a user interface and thereafter assessing its effectiveness in delivering a user experience rich in control, intelligibility, and understanding would tell us little beyond the success of that design. Indeed, this approach would provide marginal knowledge about how such user experiences in domestic settings can be designed. Consequently, this research proposes the use of several interfaces designed with the intent of use as technology probes to extract user attitudes towards interface qualities and explore their roles in creating a successful user experience.

In addition, it has been suggested above that only an ecologically valid assessment of user experiences and behaviours could result in an understanding that enhances the ability to design 'meaningful' interfaces and interactions. With this in mind, a quasi-autonomous spatiotemporal heating system will be designed and deployed in real homes in a semi-longitudinal field study. Prior to the deployment, the control algorithm will be tested in a simulation to establish its fitness-for-purpose. These two activities will jointly answer study questions Q2 and Q3 - to what extent can spatiotemporal automated heating minimize energy use while providing thermal comfort; and how are different heating strategies experienced by users.

Finally, the results of the ideation, technology probe experiment, and field study will be combined in a rich-picture analysis to interpret the complex environment and how successful user experiences for it could be designed. This analysis will provide a thorough answer to study question Q4 - How do visibility of feedback, and intelligibility affect the user experience involving understanding and control?

3 IDEATION

3.1 Chapter overview

This chapter focuses on initial ideation activities. The aim of the activity is to establish an understanding of the complex architectural, technical, and social context within which automated home heating systems are used and to develop a conceptual model of it. To this end, the chapter summarises what was learned about the environment from Chapter 2 - Literature review, explores important aspects through data visualisation, and proposes and explains a conceptual model.

3.2 Introduction

Knowledge obtained in Chapter 2 - Literature review, primarily in sections regarding thermal comfort, building controls, home heating systems could be expressed in the form of a diagram in Figure 3-1.

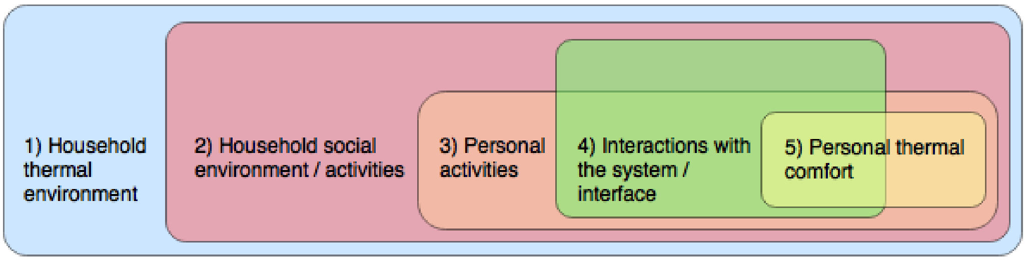


Figure 3-1 conceptual model of wider system environment and context of use

From Figure 3-1 it can be observed that the interactions with the heating system (4 on Figure 3-1) form a small part of the environment in which they occurred. The environment consists of the physical and thermal environment of the building itself (1 on Figure 3-1), affected by the thermal characteristics of the building and external factors like seasonality and climate. Within the household thermal environment lays the social environment consisting of the interactions between household members (2 on Figure 3-1). The occupants perform a plethora of actions and activities around the house, of which interactions with the heating system or other actions to maintain thermal comfort form a small part. Each household member then has their own personal activities (3 on Figure 3-1), within which interaction with the heating system (4 on Figure 3-1) and personal comfort (5 on Figure 3-1) can be observed. Personal activities regarding personal thermal comfort are performed to maintain an equilibrium between personal thermal comfort and household thermal environment. These may or may not include altering the heating system through interactions with the interface. In addition, a case could be made for personal thermal comfort also existing outside personal activities, however, for the purposes of this research, only the conscious aspect of thermal comfort is considered. By this it is meant that while humans continually experience some level of thermal comfort, this author worked off a principle that they were consciously or actively attending to it when the user experienced some form of discomfort. Secondly, it is also worth noting that interactions with the system / interface also extend beyond personal activities into household social environment / activities. This is due to the fact that in a multi-occupant household, several users have access to heating controls and could thus affect the system functionality, unknowingly to other occupants.

Subsequently, the rest of this chapter focuses on understanding the real-world context of the diagram presented in Figure 3-1, including the needs of occupants regarding the use of space and the spaces' ability to provide suitable thermal environments (points 1-2 on Figure 3-1), exploring the activities that these people perform to understand the procedural environment (points 2-3 on Figure 3-1), as well as the potential interactions with energy-intervention devices that these people may have (point 4 on Figure 3-1) and how these might affect their thermal comfort. For this the chapter is divided into three activities: 1) construction of a housing and household typology, 2) analysis of domestic activities, and 3) analysis of existing energy interventions. This understanding will then be synthesised into a conceptual model of the environment that is designed for, which will be used to explain and inform later activities within this PhD.

3.3 Methodology

Several methods from the Human-Computer Interaction (HCI) field could have been employed to establishing the context of use. Typically such knowledge is obtained through stakeholders identification, context of use analysis, survey of existing users, field study/user observation, diary keeping, or task analysis (as discussed in Maguire, 2001). However, the limitations of these methods rendered most of them inappropriate for the desired outcome or limited as the only employed method. Stakeholder identification’s strengths in assuring the needs of everybody involved are met was seen crucial in delivering a pleasant UX, but a this needed to be done at scale to fully understand who the stakeholders in observing the UK housing stock were. Context-of-use analysis, relying on stakeholders explaining he context, in other words, meeting with each main user group, was not deemed feasible at large scale and too exclusive, if only applied to a subset of the population. Similarly, surveying existing users is typically recognised as a feasible method for gathering data from a large number of users, however, it was still deemed too limited in scope and too time consuming as the aim of the exercise was to generate a context of use for the whole broad population. Field / user observation and diary keeping methods were recognised for their appropriateness when environmental context has significant effect on usability, record user behaviour, and gain a picture of how behaviours can be supported by the interface, however, these again were seen too resource intensive and extremely limited regarding the sample size to deliver a holistic view.

Subsequently, a data visualisation and triangulation approach was adopted. By this it is meant that existing datasets containing information regarding stakeholder identification (occupant data in UK house-stock), behaviour through existing diary studies, and other methods was reviewed, combined and synthesized into a model. This type of data triangulation of multiple large datasets explored in visual format with existing scientific knowledge from literature review, allows for higher validity in the presented model.

Exploring large these datasets relied heavily on the method of data visualisation. Data visualisation has been suggested to provide a method to describe and communicate a subject matter (Snyder, 2014) with the earliest examples dating back to the Crimean war and the work of Florence Nightingale (http://understandinguncertainty.org/, 2008) in illustrating the causes of death in support of her campaign for sanitation. Furthermore, the idea of telling stories with data had become popular in the period of this research and the term “infographic” entered common phraseology. Several journalists and authors told these stories through collections of data visualisations (McCandless, 2010). The storytelling aspect of this methodology was deemed necessary at this stage of the research. The complex context explored by this author was described by large datasets of differing and often conflicting information. Indeed, a whole PhD could be spent analysing this complex environment and deriving models to provide frameworks on which practical work could be founded. However, since this research is practical and pragmatic in nature, it was deemed most appropriate to opt for an analysis methodology that allowed to tell a whole story without needing a time-consuming, in-depth analysis of the data. Data visualisations have been suggested to be a key tool in exploration of information and generating understanding of a complex or abstract situation (Evanko, 2010). Good data-visualisation practice has been preached by several authors regarding focus on data (Tufte, 2001), minimalism in design (already emerged in pre-war Vienna through the work of Otto Neurath and Gerd Arntz (Arntz, 2015)), and visualisation creation practice (Yau, 2012). In contrast, others have pointed out the often misleading nature of graphics (Cairo, 2015), notably people’s tendency to attribute greater truth to more compelling graphics or *cartohypnosis* (Boggs, 1949, 1947) and the opposite of downplaying the value of data represented poorly (Kurosu and Kashimura, 1995; Sillence et al., 2004;

Thorndike, 1920). However, these pitfalls are not seen as catastrophic to the research project due to the manner in which the tool was used – not in order to solidify an argument, but to construct a picture – and its purpose of aiding design. By that it is meant that the constructed picture, along with its gaps and inaccuracies, leaves room for interpretation that facilitated creativity for the design stages of the research.

3.3.1 Housing typology – Creation & data manipulation

The data gathering for the housing typology was performed by retrieved datasets using keyword searches on the Google and Google Scholar search engines targeting questions regarding the observed environment outlined above. These searches included terms “UK”, “housing”, “population”, “dwelling type”, “energy performance”, “occupant”, “breakdown”, etc. and returned several datasets, of which the English Housing Survey (Department for Communities and Local Government, 2012) was selected to provide much of the data. The typology was created as a tiered pie chart with tiers added outside increasing the size of the graph. English Housing Survey (Department for Communities and Local Government, 2012) data was placed at the centre and used to indicate the percentage of each dwelling type - detached house, semi-detached house, terraced house, converted flat, purpose-build low-rise flat, and purpose-build high-rise flat.

Data for subsequent tiers was manipulated to reflect a percentage expression totalling 100% for dwellings of that type. E.g. original data expressed the social characteristic as a whole and type of house was the variable i.e. out of all Small Families XX% lives in detached houses, YY% in semi-detached houses and so forth. Absolute numbers for different kinds of people living in each house type were added and percentages then calculated to then provide the following expression: out of all people living in detached houses XX% is small families, YY% is large families, etc.

Tiers outside dwelling type (in respective order) reflected heating system type (central heating, room heating, storage heating) (Department for Communities and Local Government, 2012), energy efficiency expressed as SAP rating bands (from A to G with A being best and G being worst) (Palmer et al., 2011), and household type (1 - one adult aged 16-59, 2 – two adults aged 16-59, 3 – small family/lone parent, 4 – large family, 5 – large adult household, 6 – two adults, one/both aged 60 or over, 7 – one adult aged 60 or over) (Department for Communities and Local Government, 2012). The final tier was different as it utilised a bar chart wrapped around the pie chart and represented tons of carbon emitted annually per dwelling of that type on an axis from 0-9.

No specific questions were asked of the data at the beginning of this process, but rather it was used to allow issues of interest around architectural and sociological energy-related to emerge.

3.3.2 Activities – Creation & data manipulation

Data regarding the occupants' activities was obtained from the 2005 UK Time Use Survey (Oxford, 2015), as other work utilising this dataset was underway in the research group (Jaboob et al., n.d.). UK dataset (Gershuny et al., 2011) contained data from 6500 households and 11700 individuals who completed questionnaires at 10 minutes intervals, describing their chronological activities from a choice of 69 categories (Fisher et al., 2012), for one calendar day starting and ending at 4:00 am. The data was wrapped so that final entry (03:50) preceded the first entry (04:00) and the starting and ending times were adjusted to midnight. The observed activities were condensed to only include activities taking place at home and aggregated these into a set of nine meta activities, with activities taking place outside of the home being aggregated into the activity *out* of the home, seen in Table 3-1.

Activity number	**Activity name**
1	Sleeping
2	Passive
3	Audio-Visual
4	IT
5	Cooking
6	Cleaning
7	Washing
8	Metabolic
9	Appliance
10	Out

Table 3-1 list of the observed 10 activities

Most of the activities in Table 3-1 are self-explanatory, but others require some explanation – *Passive* refers to occasions when an individual was awake, but not physically active, *Metabolic* refers to a person being awake and physically active, *Cleaning* involved using non-washing-related cleaning appliances (e.g. vacuuming), while *Washing* referred to personal hygiene (e.g. washing, bathing and showering) and *Appliance* refers to the use of washing appliances (e.g. dishwashers and washing machines). The dataset was cleaned to focus on the emerged 3 archetypes from the housing stock analysis (Housing typology section below) and subsequently, the transition probabilities were calculated as the ratio of the total number of transitions from the observed activity state to another activity state, to the total number of transitions from the observed state to any state, including itself.

Transitions were combined, focusing on the activity that was transited to and ignoring the origin activity. This allowed for a single glance area chart to be created that highlighted times during the day when certain activities were likely to take place.

3.3.3 Energy interventions - Creation & data manipulation

The data for assessing existing energy saving devices was obtained from the literature review undertaken in Chapter 2(2.7.1 Building controls & information devices). Two particular papers (Froehlich et al., 2010; Pierce, 2012) were used to find other relevant work, leading to many of the devices featured. The energy monitors were picked using an unstructured selection process, due to the fact that a systematic analysis of all devices was not seen as a goal in this research in itself, but rather it was deemed important to find a reasonable amount of interesting and differing devices and uncover trends from the conclusions that the authors of these artefacts drew. The journals used in the literature could generally be classified to be revolve around the design and human-computer interaction themes including CHI conference proceedings, Interaction Magazine, Behaviour, Energy and Climate Change Conference proceedings, UBICOMM conference proceedings, DIS conference proceedings, Energy Policy journal, ACM conference proceedings, Journal of Sustainable Engineering & more. Resulting data can be seen below in Table 3-2, which is a partial copy of Table 2-9 in Chapter 2.

Device name	**Authors**	**Device name**	**Authors**
Carbon Culture	(Lockton et al., 2011)	ECD	(Yun, 2009)

Stepgreen	(Mankoff et al., 2007)	Infotropism	(Holstius et al., 2004)
The PowerHouse	(Bang et al., 2007)	Waterbot	(Arroyo et al., 2005)
Wattsup	(Foster et al., 2010)	Jetsam	(Paulos and Jenkins, 2006)
Wattbot	(Petersen et al., 2009)	Imprint	(Pousman et al., 2008)
UbiGreen	(Froehlich et al., 2009)	WattLite	(Jönsson et al., 2010)
GeoSmart	(Hargreaves et al., 2010)	Power Aware Cord	(Gustafsson and Gyllenswärd, 2005)
BeAware	(Björkskog et al., 2010b)	Raymatic	(Yun and Gross, 2011)
Greeny Energy Meter	(Wever et al., 2008)	Nuage Vert	(Evans et al., 2009)
EnergyLife	(Björkskog et al., 2010a)	7000 Oaks & Counting	(Holmes, 2007)
PowerAgent	(Bang et al., 2007)	Futureproofed power meter	(Jeremijenko, 2001)
Flo	(Shrubsole et al., 2011)	Energy AWARE Clock	(Broms et al., 2010)

Coralog	(Kim et al., 2010)	Powersocket	(Heller and Borchers, 2011)

Table 3-2 summary of data used for energy intervention devices infographic creation

An open coding approach was combined with an axial coding technique (Robson, 2002, p. 490) to group author-reported findings of energy intervention device research into themes. Themes were then arranged according to perceived relevance to the domain of this research. Themes with a negative connotations were placed below a centre line and themes with a positive connotation above it. For example, a positive connotation would be that the device included and educational element, while a negative connotation would be causing usage stress. Subsequently, design criteria was synthesised from these themes.

3.4 Results

The results of this activity were the compiled data visualisations and the implications of these to this research study. Implications refers to the narrative that is read from the infographic and what it told about the use context of quasi-autonomous home heating systems.

3.4.1 Housing typology

The compiled housing and household typology data visualisation can be seen in Figure 3-2. This graphic allowed for an overview of the buildings in England, occupants within those buildings, and their carbon footprint to be gained, ensuring that the energy intervention was targeted to deliver highest impact.

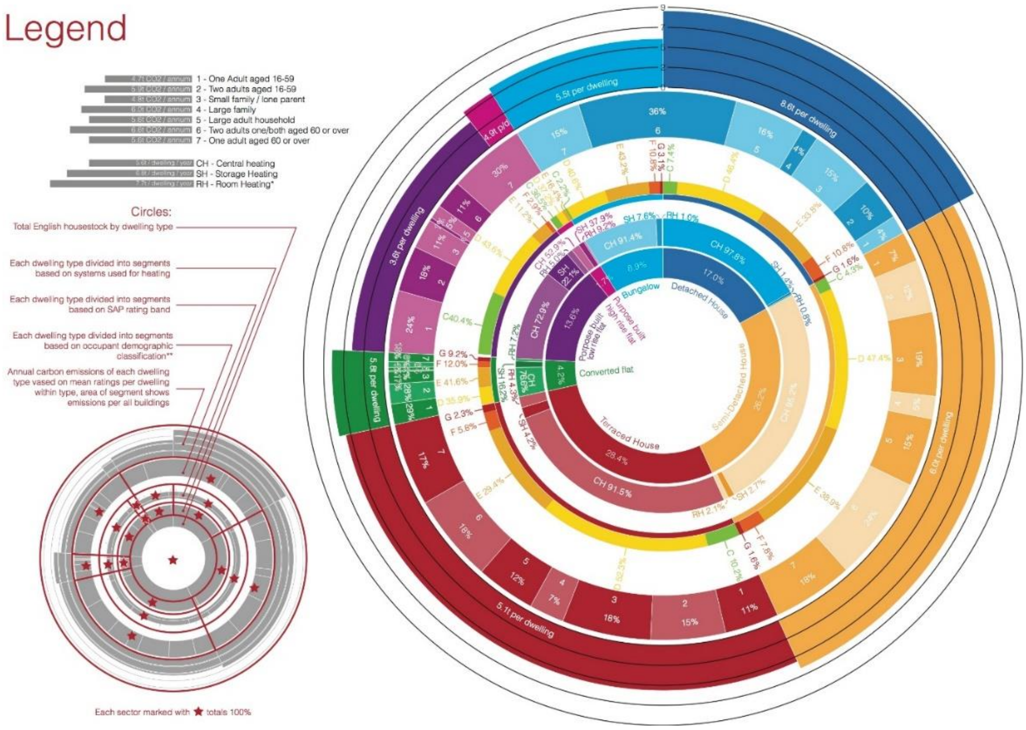


Figure 3-2 English house and household infographic

This infographic facilitated constructing a snapshot of the kind of dwellings present in the UK and their abundance in relation to one another. Furthermore, it proportionally characterised the dwellings and established links between dwelling and occupant types. This snapshot was used to observe the wider context of use and isolate areas of interest.

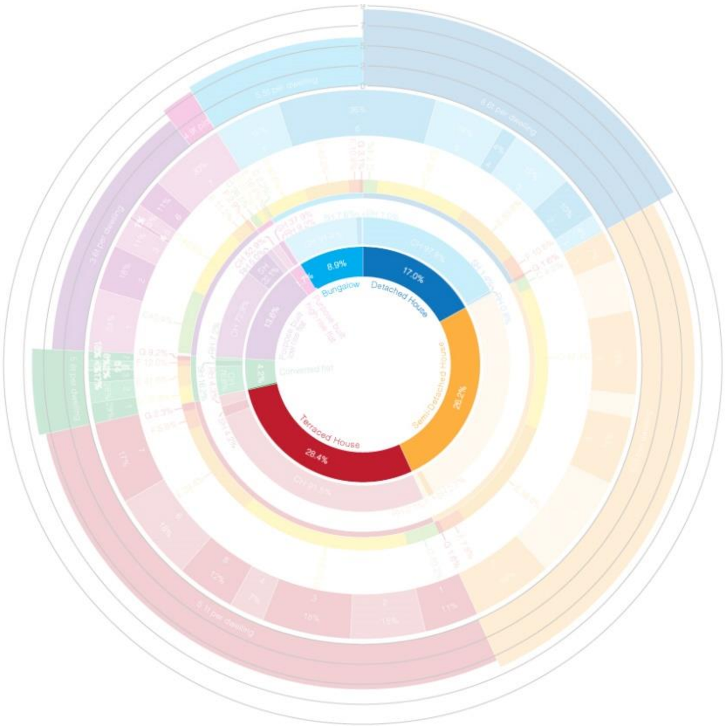


Figure 3-3 dwelling types of interest

Four types of dwellings emerged from Figure 3-3 as dwellings of interest: detached houses, semi-detached houses, terraced houses, and bungalows. This was due to these four out of the total seven accounting for 80.5% (Figure 3-3) of the total house stock. Furthermore as bungalows, defined in the Oxford dictionary as “a low house having only one storey or, in some cases, upper rooms set in the roof, typically with dormer windows” (Oxford University Press, 2012), and detached houses are perceived to be extremely similar in essence and in thermal qualities, four fifths of all English houses could be targeted by focusing on 3 architectural types. Furthermore, the outer tier in Figure 3-4 suggested that these dwelling types contributed the majority of English residential dwelling carbon emissions – 85.8% of total house stock emissions (highlighted in linear form in

Figure 3-4), combined of bungalows 8.4%, detached houses 25.4%, semi-detached houses 27.0% and terraced houses 25.0% (Department for Communities and Local Government, 2012). This implies that these houses either use vast amounts of energy, are extremely inefficient in their use, or both. In either one of those cases, the environmental impact of those dwellings should be focused on and curtailed.

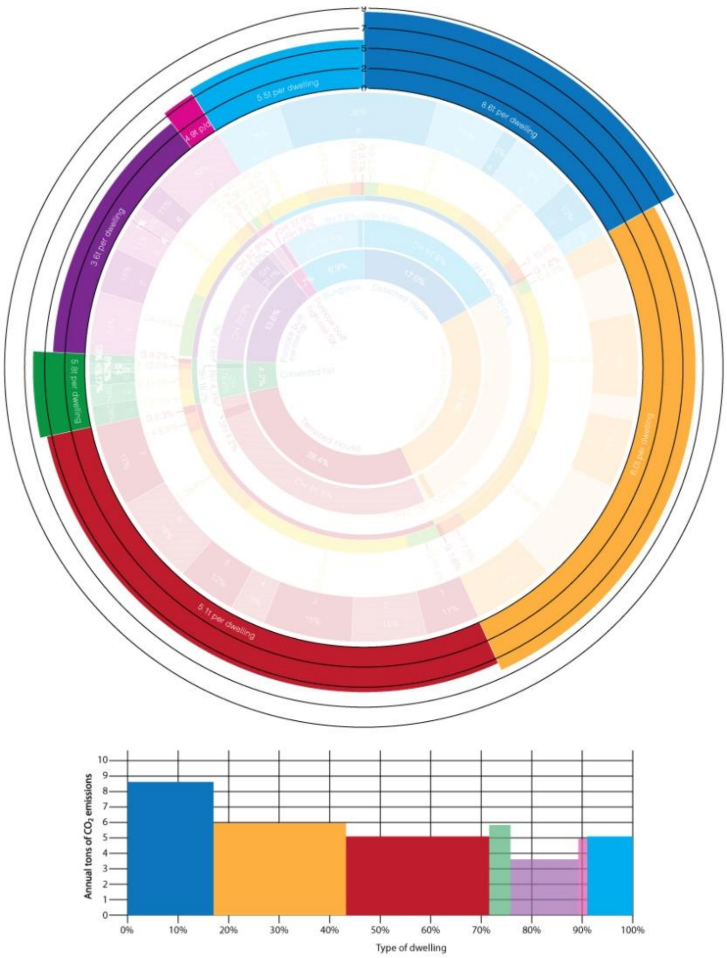


Figure 3-4 annual carbon emissions by house type

As the spatiotemporal automated heating control that this research focuses on could in theory be on could in theory be applied to any heating type, the research can be claimed to apply to all buildings to apply to all buildings in the UK. However, there are several nuances to discuss. Firstly, a convincing discuss. Firstly, a convincing case can be made that focus should be on those heating systems that are heating systems that are least efficient (storage and room heating (Department for Communities and (Department for Communities and Local Government, 2012)), however, those heating system types heating system types form a minority of the UK housing stock, which primarily uses central heating uses central heating systems. Central heating systems contribute least to annual carbon emissions per annual carbon emissions per dwelling and are widely popular – 91.4% of bungalows, 97.8% of

bungalows, 97.8% of detached houses, 95.2% of semi-detached houses and 91.5% of terraced houses use the heating system type (

Figure 3-5). Since these dwelling types are the largest polluters, it can be concluded that while the heating systems in the dwellings are efficient, either the occupants' operation of them is not, or the buildings envelope displayed poor thermal performance. By focusing on spatiotemporal heating solution that fits gas or electricity powered central heating systems (87.2% and 5.4% respectively), 92.6% (Figure 3-5) of all heating systems can be targeted.

Figure 3-5 target dwellings by heating system type (CH - central heating, RH - room heating, SH - storage heating)

Figure 3-6 illustrates the breakdown of different demographic types living in each dwelling type. It was suggested that three grouped categories could be formed – "Elderly" (made up of types 6 & 7 – Two adults, one or both aged 60 or over & One adult aged 60 or over, respectively), "Families" (made up of types 3 & 4 – Small family / Lone parent & Large family, respectively), and "Professionals" (made up of types 1 & 2 – One adult aged 16-59 & Two adults aged 16-59, respectively) are focused on (highlighted in

Figure 3-6).

Figure 3-6 proposed target population

This was suggested for a number of reasons:

1) Combining demographic types into these three categories and addressing their needs allows this research to address 68.8% of the total observed (all dwelling types) population without needing excessive diversification. This allows for a suitable balance between a “one size fits all” and “fully tailored” approaches to be found.

2) The chosen categories are formed of types that display similar characteristics in terms of assumed lifestyles and thermal behaviours. For example, in the “Elderly” group it can be assumed that regardless of whether there is one or more occupants, all will have a relatively low activity level lifestyle and have higher room temperature needs than those of one or more younger people.

3) Types 6, 4 and 2 (“two adults, one/both aged 60 or over”, “large family”, “two adults aged 16-59”) had, respectively, the highest annual carbon emissions across dwelling types. This means that there must be lifestyle

characteristics associated with these types that are responsible for high consumption levels. Furthermore, as the main difference between types in categories is scale (number of people), it can be assumed that the lifestyle needs of types 1,3 & 7 (“one adult aged 16-59”, “small family/lone parent”, “one adult aged 60 or over”) are extremely similar to those in 2,4 & 6, respectively. Thus, creating categories in the manner above allows targeting the highest emission lifestyles.

4) The categories are extremely interesting in terms of interface design as the people in each type vary greatly between categories; i.e. the needs of the “Elderly” vary greatly from the assumed “Professionals” category. This has extremely interesting practical design implications and it may occur that in later stages of this research, focus may shift to only one or two of the three categories.

5) At first it was proposed to name the “professionals” category “young professionals” to reflect the fast, tech-savvy and often perceived as desirable lifestyle of these individuals. However, as the categories 1 & 2 in the Household Typology are defined as “One adult aged 16-59” and “Two adults aged 16-59” respectively, age is not a factor when distinguishing between these categories and the “Small family” & “Large family” categories. Furthermore, as evidence from the UK population statistics (Office for National Statistics, 2011) and birth statistics (Office for National Statistics, 2012) show, there is no significant trends in the distribution of population to justify the targeting people in their 20s. In addition, all live births to women in the 20-29 age group makes up 46.5% of all live births (Office for National Statistics, 2012), which means that transition from groups 1 or 2 to groups 3 or 4 (“small family/lone parent”, “large family”) is extremely likely to happen in that age range. This means that groups 1 & 2 should not be broken up by the age factor. However, age distribution in the population should be taken into account when determining sample compositions future in the research.

The housing typology in Figure 3-2, therefore, suggests, that by focusing on most common heating system type in the least efficient, but most populous dwelling types, occupied by merely three household archetypes would allow for 64.2% of the entire English housing stock to be designed for. This data visualisation has enabled to establish an understanding of the UK housing stock, demonstrated the need to address energy consumption in large spaces & isolated three target occupant categories that form 68.8% of the UK population.

3.4.2 Activities

The activities data visualisation in Figure 3-7 illustrates the representation of the behavioural context in which the aforementioned three archetypes of people would use heating controls (see Appendix 2 - Full scale activities infographic for more detail). This allowed for the behaviours within the home space to be understood.

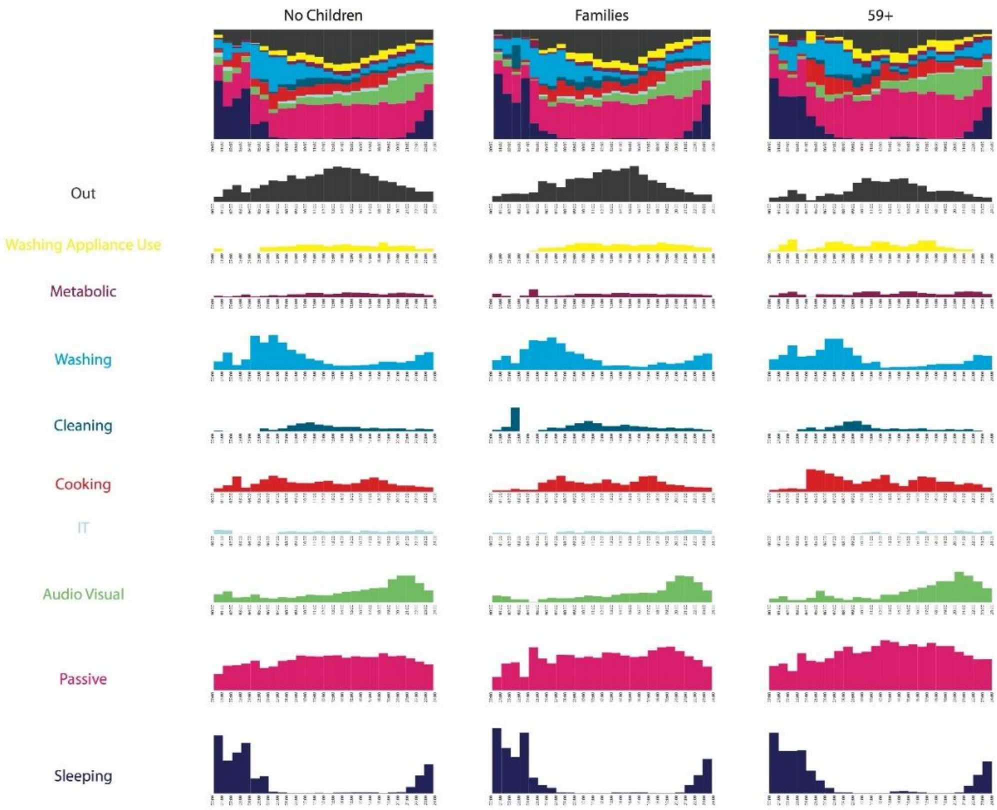


Figure 3-7 illustrating total probabilities of transiting into any of 10 activities across 24 hours for all 3 archetypes

At the top of each column in Figure 3-7 a combined view can be seen. This details the probability of any activity starting in that hour across a 24-hour span. Below, each activity is observed individually to see the probabilities of that activity being started in that hour across a 24-hour span.

Figure 3-7 showed that across the day, the general life pattern was rather similar between the archetypes with sleeping being the predominant activity in the early hours of the day. Subsequently, people transited into their morning routine activities of washing, cooking and cleaning after their breakfast. Following that the no-children archetype was very likely to go out to work while the 59+ and families were less likely to and could instead perform various active or sedentary activities at home. Towards the early evening, activities revolved around eating and entertainment of various activity levels before retiring for the night. Differences between archetypes included a more erratic and active early hours of the morning and a more sedentary middle of the day for the 59+ group in comparison to the other two. Figure 3-7 displayed a cross-population view of a 24-hour span "in the life of", however, this lacked the ability to provide individual quirks and elements of importance that would give a richer design agenda when creating an interface.

From this, it was evident that broadly speaking, all three archetypes displayed a similar life pattern, however, slight variation during the day could be observed. These slight differences highlighted the need for variation, but should be investigated in more detail to establish a higher degree of empathy for design activities through participatory design. Regardless, the results from this exercise have provided a reasonable understanding of what these people do during the day to construct a conceptual model of use context.

3.4.3 Energy interventions

The analysis of existing energy intervention device research – artefacts designed with the purpose of altering people's consumption of resource or consumption behaviours – can be seen in the infographic presented in Figure 3-8 (for more detail see Appendix 3 - Full scale energy monitors infographic). This facilitated an understanding of the potential reactions that users may have to an energy intervention and provided design requirements in order to facilitate acceptance of the intervention.

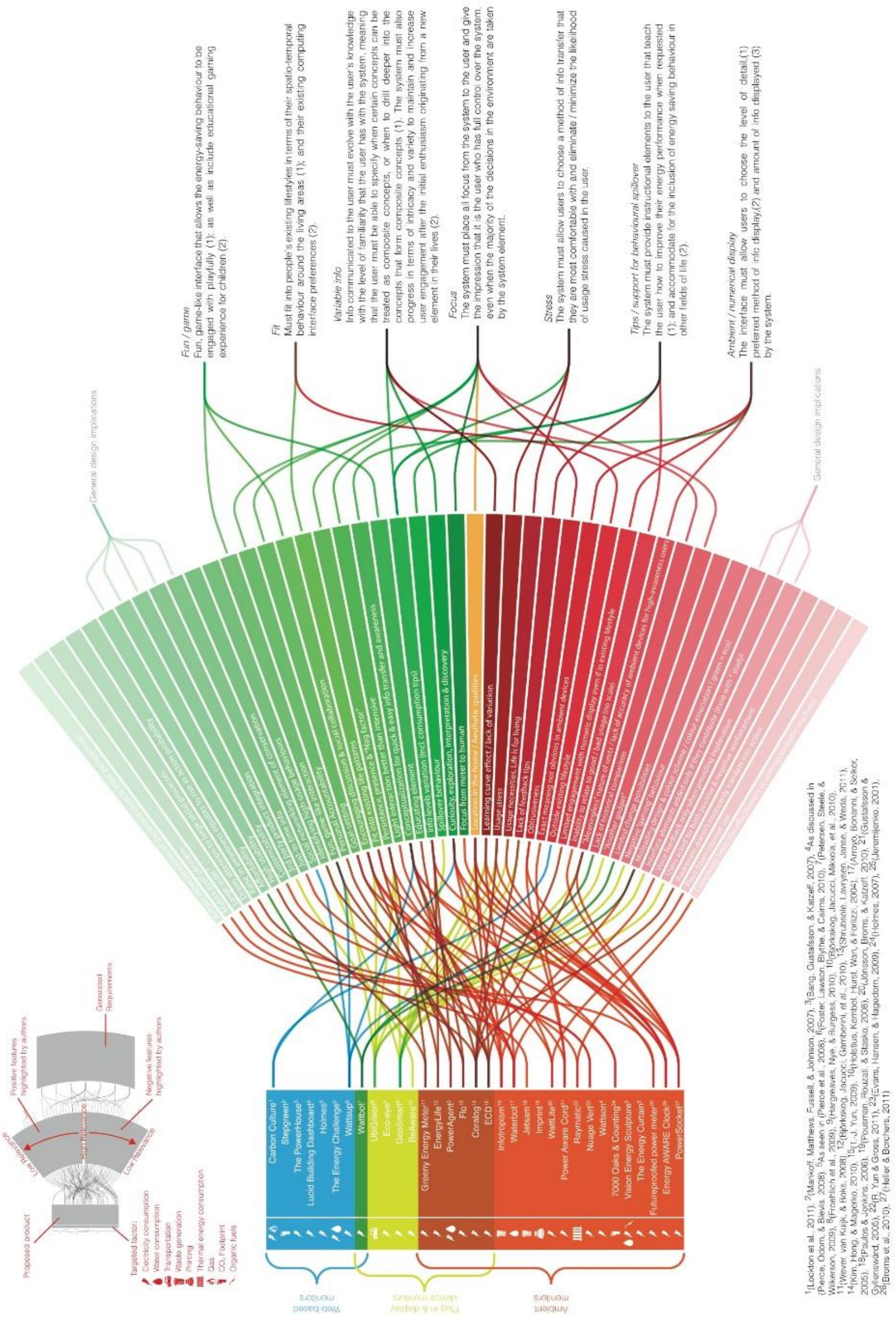


Figure 3-8 energy monitors infographic

The first two columns of infographic in Figure 3-8 reflected the process of synthesising design requirements for home heating control interface design. The first column (highlighted in Figure 3-9) details the observed designs and their characteristics, with icons indicating the resource the artefact was designed to conserve. The artefacts were divided into three groups based on the form the interface took (website, mobile/smartphone interface, or ambient interface), highlighted by colour.

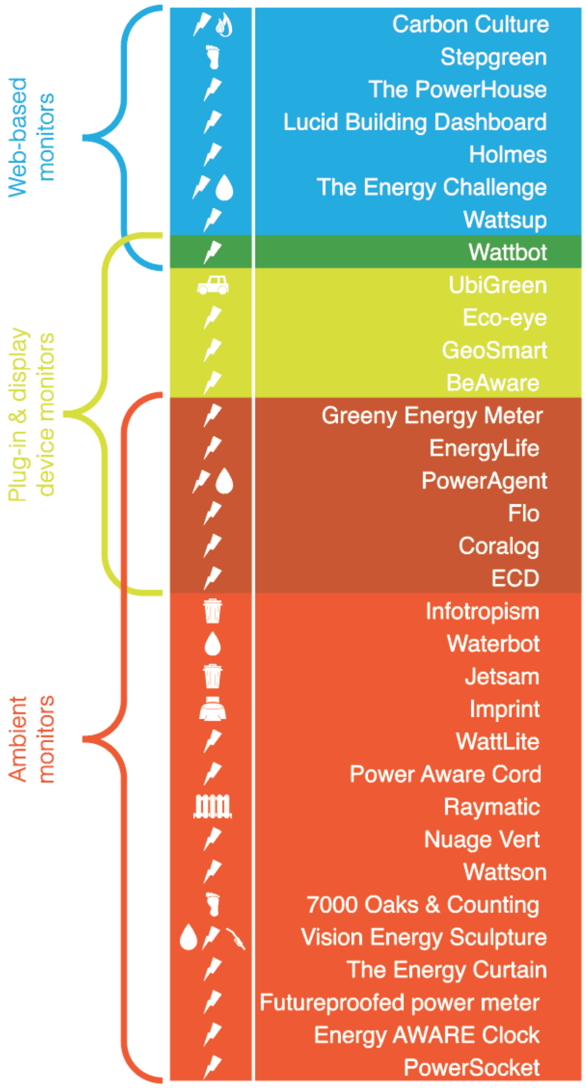


Figure 3-9 column one extracted from Figure 3-8

The second, curved column, detailed the findings or conclusions of each artefact's author, linked to the artefact from which they originate and arranged by relevance to current domain.

The synthesised design requirements (as seen in third column of Figure 3-8) were as follows:

- Fun / game – it was preferred to have (1) a fun, game-like interface that allowed the energy-saving behaviour to be engaged with playfully; as well as (2) include educational gaming experience for children.

- Fit – the designed interface needed to fit into people's existing lifestyles in terms of (1) their spatiotemporal behaviour around the living areas; and (2) their existing computing interface preferences.

- Variable info – the information communicated to the user needed to (1) evolve with the user's knowledge and the level of familiarity that the user has with the system, meaning that the user needed to be able to specify when certain concepts can be treated as composite concepts, or when they wished to drill deeper into the concepts that form composite concepts. The system also needed to (2) progress in terms of intricacy and variety to maintain and increase user engagement after the initial enthusiasm originating from a new element in their lives.

- Focus – the system needed to place all focus from the system to the user and give the impression that it was the user who has full control over the system, even when the majority of the decisions in the environment were taken by the system.

- Stress – the system needed to allow users to choose a method of info transfer that they were most comfortable with and eliminate / minimise the likelihood of usage stress caused in the user.

- Tips / support for behavioural spill-over – the system needed to provide (1) instructional elements to the user that taught the user how to improve their energy performance when requested; and (2) accommodate for the inclusion of energy saving behaviour in other fields of life.

- Ambient / numerical display – the interface needed to allow users to choose the (1) level of detail, (2) preferred method of info display, and (3) amount of info displayed by the system.

These requirements would hereafter be utilised in subsequent experiments, where they were used as prompts in the form of ideation decks in participatory design sessions, and as guidelines when designing interfaces for field study equipment, or probe interfaces in a Wizard-of-Oz study. 33 energy intervention devices were explored, the finding of their creators analysed, and design requirements regarding the interactions that address specific issues in the user's behaviours in response to interventions synthesised.

3.5 Discussion

The selected methodology of data visualisation facilitated interpretation of the data in a personal way meaning that each person viewing the aforementioned 3 infographics could potentially reach their own conclusions. This was seen as a positive aspect in the context of this research as this section focused on exploring the target environment with the purpose of establishing a design agenda and exploring the design space. However, as the visualisations were based on data, it was possible to draw grounded conclusion regarding the portion of the population that any proposed autonomous home heating system would target. Furthermore, interpreting the data visualisations allowed this researcher to understand the spatial, behavioural and energy intervention-related context that latter influenced the design of tested prototypes, as well as interpretation of data from field deployment. In addition, the infographics led to the formation of a cognitive ergonomics conceptual model of the use context that can be seen in Figure 3-10 and will be explained below.

3.5.1 Conceptual model

The cognitive ergonomics model was based on the diagram presented by Wilson & Rutherford (1989) as it included all the elements perceived relevant to the context and their interactions. The diagram was populated with knowledge obtained from the literature review carried out in Chapter 2 and from the data visualisation activities carried out above.

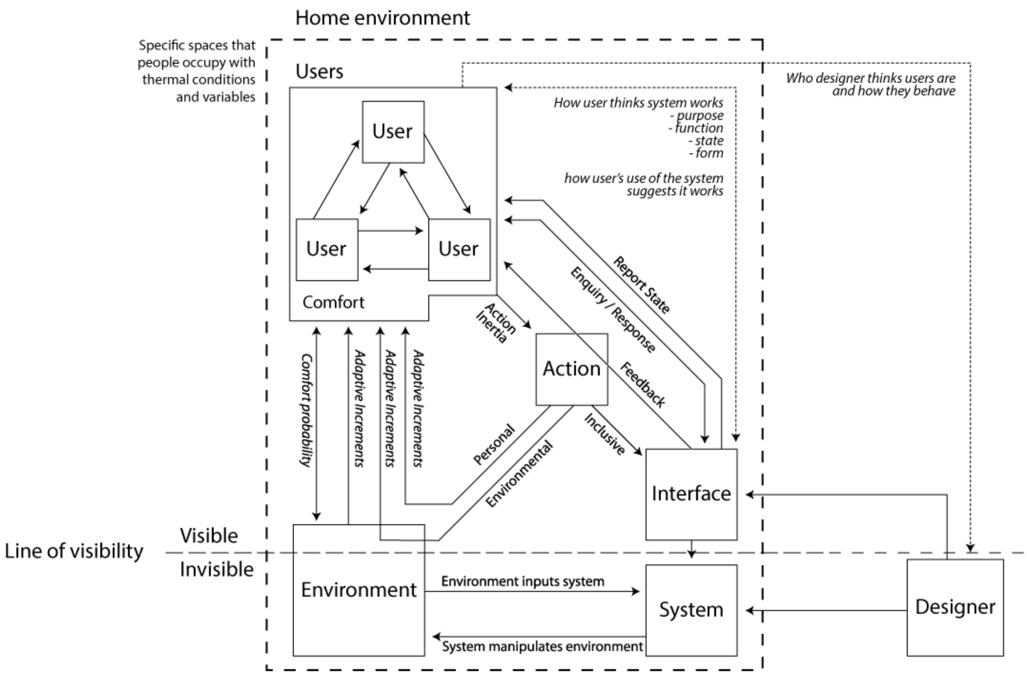


Figure 3-10 proposed conceptual model of the home heating system use context

Similarly to Figure 3-1, the model encompasses elements at play within the home environment, however, the designer's role in designing for the element was added. Home environment refers to the thermal environment within the building that users occupy. The environmental conditions (ECon) within this environment are the physical conditions outside and within the building that are experienced by the user through sensors in their skin and are affected by outdoor temperature, building envelope, indoor relative humidity, indoor air velocity, indoor ambient air temperature, indoor solar gains, and others. This environment is also represented as an actor at the bottom left corner of the model. Within the environment, "Users" exists, which denotes the occupants and their social interactions as described in point 2 in Figure 3-1. Depending of the household composition, as observed in the house and household typology in Figure 3-2, "Users" can consist of one or more users. Each user has their own comfort expectations (CEx). These are their thermal comfort perceptions coupled with thermal preferences, and are influenced by various factors including personal preference, financial opportunities, energy usage attitudes, current and previous activity, knowledge of previous, current, and future outdoor weather conditions, knowledge of past, current, and future indoor conditions, as well as their understanding of how the system works.

Within the home environment a line of visibility exists. This separates elements explicitly visible to the user from those hidden. For example, the heating system interface is explicitly visible and accessible to the user, but the functionality of the heating system itself occurs in the heating infrastructure hidden from the user. Similarly, due to the delay in feedback the heating system's manipulations of the environment occur invisibly. Some part of the environment exist above the line of visibility, meaning the user receives input from the environment via skin receptors, however, since this is merely a snapshot of current conditions, rather than a full understanding of past and future changes, the majority of the environment is placed below the line of visibility. The user's understanding of how the system worked and snapshot observations of the system create an understanding of system state (SS) for the user. This refers to the user's understanding of what the system is doing and why it is doing it. This is affected by information from the interface about system state, understanding of the system (mental model that corresponds to real system structure), and extraneous variables such as attitude towards technology, etc. The user also has expectations of the system (ExS), this refers to what the user thinks is needed to take place in order for comfort expectations to be met (for example it needs to get warmer). This is affected by their understanding of heat transfer mechanisms, comfort expectations, understanding of the system, and understanding of adaptive actions at their disposal.

The conceptual model also highlights several potential actions that users might take based on matches or mismatches occurring between the four elements highlighted in the previous paragraphs. These have been highlighted in Table 3-3.

Mismatch name	**Mismatch formula**	**Mismatch description**
A – All OK	ECon = CEx and SS = ExS	The surrounding conditions are comfortable to the user and the system is maintaining those conditions
B – Uncomfortabl e but succeeding	ECon ≠ CEx and SS = ExS	The user does not feel comfortable but the system is doing what is necessary for these conditions to be achieved
C – Comfortable and yet failing	ECon = CEx and SS ≠ ExS	The user feels comfortable, but the system is not doing what it should be doing either in their immediate surroundings or elsewhere in the house
D – Everything is wrong	ECon ≠ CEx and SS ≠ ExS	The user experiences thermal discomfort and the system is not doing what is perceived necessary by the user to restore comfort

Table 3-3 description of possible expectation mismatches within the proposed conceptual model

The actions that are likely to take place as a result of the mismatches are highlighted in Figure 3-11

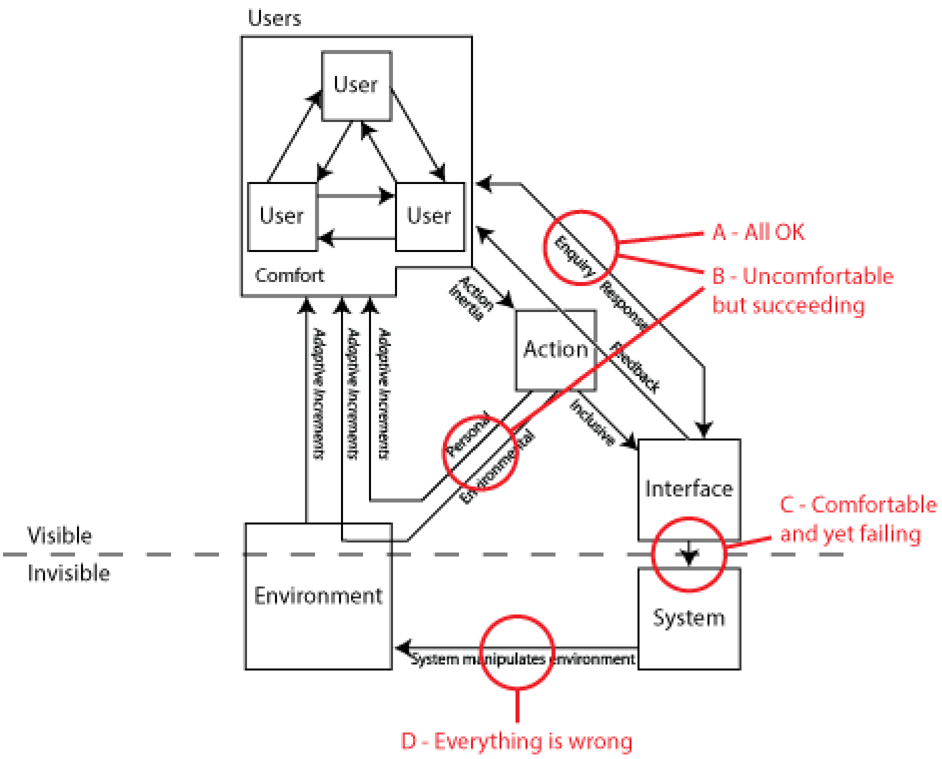


Figure 3-11 actions caused by mismatches in Table 3-3

In the case of mismatch A – All OK in Figure 3-11, it is likely that no action is taken or that the user performs an enquiry / response interaction with the interface to ensure current functionality is continued. Mismatch B – Uncomfortable but succeeding (B in Figure 3-11) might also result in no action, but can resulted in a personal adaptive action (the user performs an adaptive action that provides a personal temporal remedy such as adjusting clothing level or consuming a hot/cold drink) or environmental adaptive action (the user performs an adaptive action that changes environmental conditions such as opening/closing a window or manipulating window shading devices). Mismatch C – Comfortable and yet failing, is expected to render an enquiry/response interaction by the user to familiarise themselves with the system's reasoning. This may be followed by alteration of heating settings to manipulate the environment, or reassess the system expectations, thus returning to mismatch A. Lastly, mismatch D – Everything is wrong is deemed likely to result in an action that manipulates heating settings, possibly preceded by an initial enquiry/response interaction, however, it is speculated that most users are more outcome-orientated in this scenario and less interested in the system's reasoning.

3.5.2 Study methodology limitations

The main limitation of the housing typology infographic, combining data, was also its biggest strength. By that it is meant that the value of the infographic was presenting multiple facets of information in relation to one another, however, in certain cases, this meant that there were mismatches. For example the dwelling-focused data in the first circle differentiated between bungalows and detached houses, while the household-focused data in circle 4 did not. This could have led to misinterpretation of data.

While the data visualisations provided a direct proportional comparison, they offered little in terms of conclusive statistical results. Even though it has been noted on several occasions above that this was not the aim of the exercise, it is worth keeping this in mind for when these activities are later referred to in this research. Furthermore, any results drawn from the infographics are highly subjective, meaning that strict design guidelines could not be drawn directly from them. However, any conclusions can be used as probes or tools for directing focus in other activities, the results of which can lead to guidelines. Therefore, there were issues regarding this methodology that any reader needs to be aware of when reflecting on these activities.

Secondly, it is worth drawing attention to the application of what was learnt from these exploratory activities. Firstly, the design requirements drawn from the energy interventions infographic served as ideal tools for defining design boundaries for later activities involving a creative process. Notably, these provided a way to guide potential user design activities in the participatory design sessions that follow. Likewise, an understanding of the users and households can guide the researcher in design activities when designing interfaces for the prototype analysis or field study experiments. Lastly, since humans are extremely visual in their communication, providing these infographics establishes a memorable representation of the context throughout the activities. For example, when discussing any interface, the mere image of the housing infographic introduces key talking points such as user experience in dwellings with different layouts.

3.6 Conclusions

Several conclusions were drawn from the results and discussion:

1) It was noted that the largest proportion of dwellings in the UK are relatively "small" – i.e. large buildings with large number of flats were outnumbered by detached, semi-detached and terraced houses.

2) In addition, those houses were mostly inefficient in their energy usage.

3) These inefficiencies could have been due to one or more of several issues including age of the building, issues regarding the building's envelope, or inefficiencies observed in the heating system.

4) A large proportion of the people inhabiting those buildings included 1-2 people of 59+ years of age. For standalone (detached houses & bungalows) buildings this number was close to half. This meant that focus had to be placed on designing for an ageing population.

5) Majority of the population could be described through 3 stereotypes – 1-2 adults without children, families and 1-2 adults aged 59+.

6) While those stereotypes generally followed a similar life patter on the whole, it was noted that irregularities between groups occurred and those were very personal. Designs for this domain needed to consider these differences.

7) Design of interfaces for the field also needed to consider several qualities of communication in order to facilitate successful energy saving such as fit to the aforementioned differences in lifestyles, element of fun, different ways to convey information, and avoidance of usage stress among others.

Interpretations of these data visualisations have been combined with key findings from relevant literature fields in order to propose a model explaining the factors at play in this context and some potential interactions with the heating system that might take place as a result of mismatches within the system. The activity presented here served as the initial exploratory step and subsequent activities will focus on user-inclusion in the design process through participatory design and prototype analysis activities.

4 PROTOTYPING

4.1 Chapter overview

This chapter focuses on the early stages of the practical design process and is broadly divided into the participatory design and prototype analysis activities. The aim of the participatory design activity is to understand user values, motivations, and preferences, and include these in the design process; and create interface prototypes that will subsequently be tested in the prototype analysis activity, which aims to explore the role of different interface qualities and how these qualities affect the user experience of controlling the heating system via mock interfaces used as probes.

4.2 Participatory design sessions

4.2.1 Introduction

In tackling the task of designing for the complex environment explored and conceptualised above in Chapter 3 this research adopts a design practice methodology, for two reasons. Firstly, because the disciplines of design and design thinking (Brown and Wyatt, 2010) provide useful tools for solving complex real world problems. Secondly, because the design activity was naturally undergoing in developing the interface and system later deployed and discussed in Chapter 5. However, it was recognised that this naturally occurring activity required structure, thus prompting adoption of a design practice method. Participatory design was seen as a suitable mechanism within this method to diversify, control, and validate the researcher's efforts in creating an interface to control the proposed heating system.

4.2.2 Methodology

Both design practice and participatory design (PD) can be qualified as 'practice research', where focus is on the practice and parallel theoretical reflection. Design practice as a scientific method could therefore be criticised for its lack of focus on knowledge acquisition, in favour of application of scientific knowledge in practical tasks. In fact, some argue that "'design science' refers

to an explicitly organised, rational and wholly systematic approach to design" (Cross, 1993), indicating no intention to further knowledge through it. However, as highlighted above, this research was applicatory in its nature and at this stage of the research, creating an interface was paramount. Therefore, there was no alternative to design practice and participatory design was utilised to add structure to the practice and validate its output.

The design process that relies heavily on prototyping tends to be iterative in nature, which has been argued to cause device-dependency and hinder creativity through self-reference (Vicente, 1999). Involvement of other stakeholders, a primary strength of the PD method, was seen as advantageous over only the researcher acting as the designer. While the researcher's output as the designer could have been enhanced by creativity-enhancing methods such as function analysis (summarising and structuring information to decide where more information is needed and expressing *what* the future product should do, but not how, expressed in two words each: a verb and a noun), why-why-why (asking why questions to build a chain of connections backwards from the initial formulation), or boundary shifting (moving the exploration outside the problem boundaries that are implicitly taken for granted) as described by (Löwgren and Stolterman, 1999). This was because PD entails the values of other people and by giving a new designer the same problem space, reduced self-reference more than previously mentioned methods. Participatory design became popular in early 90s due to its user involvement in design practice, but more recently has been criticised and argued that it needs to engage with values that users bring with them (Iversen et al., 2010). Furthermore, the method does encompass a possible pitfall for the design process as ad-hoc user wishes and inputs may dictate progression, creating a need for focused analysis of the data obtained from participatory design (Bødker and Iversen, 2002). Other limitations of the method include 1) doubts whether researchers really understand their informants' world view or have simply projected their own assumptions as results; 2) participatory designers often thinking of their work as revolution, not evolution, which in turn can lead to 3) tunnel vision, in which particular stakeholders are served while others are ignored; 4) focus too narrowly on artefacts rather than overall workflow; and 5) giving up traditional research rigor in order to gain reflexivity and agreement – ethical concerns in giving workers the tools needed to do their jobs, as discussed by Spinuzzi (2005). However, in this case, the majority of these weaknesses were not seen as detrimental to the desired outcome – interface design artefacts. Furthermore, as the artefacts were not used at face value later in the research, but developed further before, the researcher was mindful of the issues affecting designs, but allowed these prevail when they did.

Therefore, it is concluded that an appropriate conduction of a participatory design session would allow extraction of values from users as manifested in their design; and - through a structured and focused analysis – creative informing of design. However, in order for that to happen, the activity requires structure and focus.

4.2.2.1 Structure

It is important to include stakeholders of various backgrounds and expertise in the design process in a familiar and relaxed setting to develop new solutions to each other’s needs (Muller et al., 1994). Techniques to achieve this goal are diverse and in abundance, but it has been suggested that selecting optimal tools is dependent on design stage, direction of participation (user participating in designer’s world or vice a versa), as well as the participant group size (Muller et al., 1993) (see Figure 4-1). This research activity locates in the top-left quadrant of the chart and focuses on small to medium size groups, which suggests Co-Development, Mock-ups, Low-tech Prototyping, Storyboard Prototyping, Theatre for Work Impact, and Card Games as appropriate techniques.

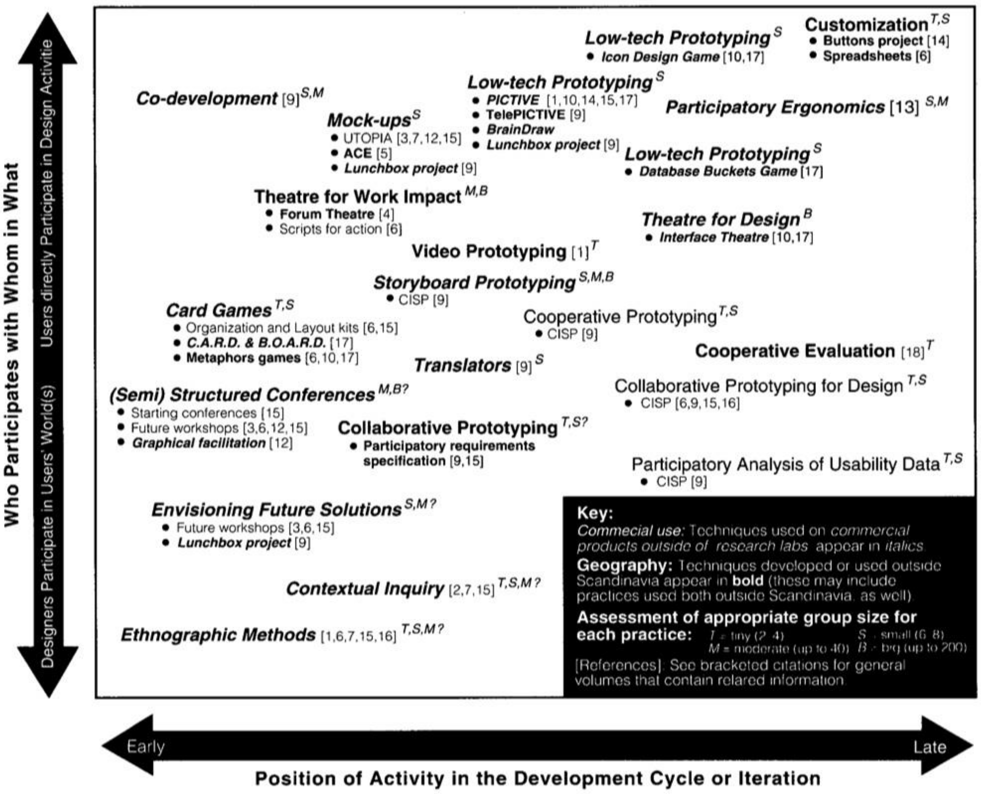


Figure 4-1 Taxonomy of Participatory Design practices (as seen in Muller et al., 1993)

The adopted methodology drew largely from the PICTIVE approach introduced by Muller (1991), for a number of reasons. Firstly, the technique focuses on design creation rather than analysis, use of design aids gives the users sense of how the system would look and behave, people less experienced in design practice are not disempowered, and the technique allows combining different backgrounds and expertise to solve a common problem.

4.2.2.2 Focus

Focus in the design exercise was achieved through 3 elements. Firstly, the users were presented with a specific system that was described using examples of mini-scenarios, to convey how the system would act in their homes. This description was displayed in condense form throughout the session. Secondly, views on such systems were extracted from users via a short brainstorming session. These thoughts were made coherent and displayed alongside the system description to define a problem-space for the session. Thirdly, for the last design exercise, Ideation Decks were used to create very specific, but random design briefs, utilising the methodology described in (Golembewski and Selby, 2010). The methodology features a deck of cards of 3 or more subcategories within the overall design brief. The sub-categories keep the outcomes within the overall design scope, but by randomisation, allow innovative and non-mainstream design solutions to be created. Mainstream, in this case, denoting people's tendency to jump to the first design that seems to solve a problem for them and subsequent inability to deviate from that design.

4.2.2.3 Participants

Participants were recruited based on a self-selection method using the academic participant recruitment service callforparticpants.com, as well as by distributing the study page from the site on University of Nottingham email mailing lists and on social media network Facebook. No barriers to entry were established and anybody interested was allowed to take part. However, at times, specific limits were created to keep the number of participants per session around 5-8 maximum in order for the researcher to be able to manage the group efficiently.

Table 4-1 displays the participant characteristics and the designs they were involved in creating as a reference-point. The created designs are discussed in the Results section below.

Participant	Age	Gender	Rating 1-7 of how comfortable they felt they were with technology	Designs
P1	29	M	6	1,4,5

Participant	Age	Gender	Rating 1-7 of how comfortable they felt they were with technology	Designs
P2	25	M	6	2,4,5
P3	26	M	7	3,4,5
P4	27	F	7	9,11,12
P5	34	M	7	10,11,12
P6	22	F	7	6,13,14
P7	23	M	7	7,13,14
P8	24	F	5	8,13,14
P9	31	F	4	17,18,19
P10	33	M	5	16,18,19
P11	53	M	6	15,18,19

Table 4-1 displaying the participating self-selected sample and its characteristics

Initially it was intended to run the session with 3 groups of people – a representative sample of targeted archetypes from the Ideation chapter, representatives of academic domains relevant to this research, and professional designers. The last segment was included for two reasons: 1) as a control group, and 2) as a catalyst for design creativity. The 'designers' group acted as a control group to highlight any differences between the preferable features or values of designers and non-designers. In reality, there difficulty in obtaining the designers group and the first two identified target groups merged together to form the participating segment.

4.2.2.4 Apparatus

Apparatus for the experiment consisted of design aids, a flip-chart for presenting information to participants, and recording equipment.

Office consumables were used as design aids including sheets of a4 paper, flipcharts, post-it notes of different sizes, highlighters, markers, pyros, blu-tack and scissors. The tools were selected to ensure all participants experienced a level playing field – expert knowledge in interface development, design or programming was directly inapplicable and participants with no such knowledge were equally proficient in the use of such aids.

Ideation decks (example cards of the 4 decks can be seen in Appendix 4 - Ideation decks presented to participatory design participants) were custom created for the exercise and had the following categories derived from previous work in the exploration of issues in the target use context (mainly through the carried out in literature review and ideation activities):

- Target audience
- Type of communication
- Design Themes
- Enhancement of mental models

Target audience deck referenced potential users to get users to think of potential users different from themselves, but later omitted as participants were selected from the target audience and thus already represented the subcategories. Type of communication included two categories of explicit or ambient and was intended to make users veer away from traditional interfaces. Design themes were derived from the research carried out into existing energy-saving devices in the Ideation activity (for more detail see 3.4.3 Energy interventions). And enhancement of mental models was included to make participants focus on design solutions that communicate themselves well to the user.

4.2.2.5 Data collection

Three types of qualitative data were collected from this session: Designs, Values/important features, and process. Designs were collected in the form of physical objects and/or sketches created by participants during the session. Values/important features were collected as spoken word by participants via two cameras that recorded the whole session including audio and a Dictaphone for audio in case cameras failed to capture talking from a distance. Process was captured using two cameras and was used to verify that the final designs did not omit any design decisions that were deemed relevant to the problem.

4.2.2.6 Procedure

The participants were seated around a circular table to encourage collaboration. They were provided with the design aids (office supplies) described above. The aims of the exercise were explained and opportunities to ask questions provided. The participants were explained the functioning of an ambient intelligence home heating system that used presence detection and temperature preference to automate home heating control and was completely invisible to them apart from the interface they were about to design. The participants were told that the system had limitations regarding accommodation of short presences in a room and accuracy in predicting preferred temperature. The explanation was provided in bullet-point form for participants to see throughout the session (see Table 4-2).

System description
Knows when you are in the room
Knows what temperature you usually like
Predicts when you are going to be in the room
Occasionally you feel it is a bit too cold or warm
Occasionally you walk into a room and it is completely cold
You can’t see the system

Table 4-2 system explanations provided to study participants

The participants were invited to tell how they would feel if they lived in a house with this system. The question served to extract people’s values about their home controls and perceptions towards such automated systems as well as set an agenda or a problem-space for the design session. Answers were recorded and displayed to participants on a flipchart for the entirety of the session. The participants were given 10 minutes to design a form of interaction with the system that they desired, while keeping the problem-space in mind. The design exercise was followed by a ‘report back’ session of 5-10 minutes where participants were invited to explain features of their design. This was used to extract and record features that users felt were important to achieve an understanding of the system.

The second design exercise included the use of Ideation Decks. Participants were introduced to how the decks work and given 15-20 minutes to answer 2-3 design briefs from the decks in pairs or groups of three. This was again followed by a report back session. Afterwards, the participants were debriefed and allowed a chance to ask any questions.

4.2.3 Results

The results of the participatory design sessions are described in three sections – first the results of initial brainstorming session, highlighting participants' values and concerns, secondly the coded design features and comparison of the designs based on the codes is presented, and lastly, focus is placed on the description of selected designs based on their performance on heuristics assessment as well as perceived design value by the researcher.

4.2.3.1 Brainstorming

During the brainstorming sessions, user-highlighted factors of importance or concern were summarised or re-worded during the session by the researcher and collected. Table 4-3 lists these factors, which can broadly be described as "important factors to consider" for these kind of interfaces or systems, alongside with the reported "feelings" or 'emotions' that users reported they felt regarding the system.

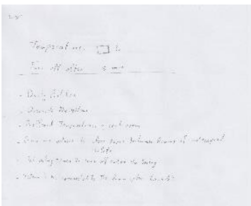
Factors to consider	**Emotions**
Overriding power (including remotely)	Sceptical towards the system
Routine / no-routine behaviours	Unpredictability of humans
Leakage between rooms	People who tend to move a lot in the house
Info about doors closed / opened	Heat inertia
Different levels of control	User location even outside the house
Errors & managing them	Switching between automatic & manual

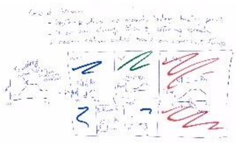
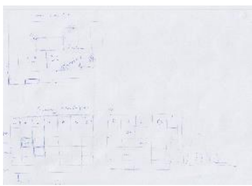
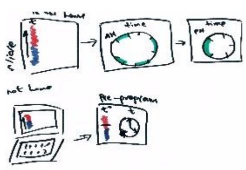
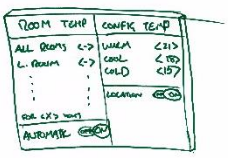
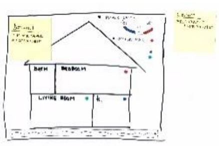
Pets	Energy consumption
Seasonal changes and heating for non-human reasons such as pipes freezing	

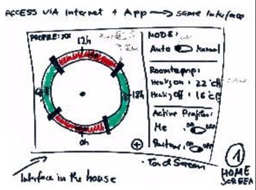
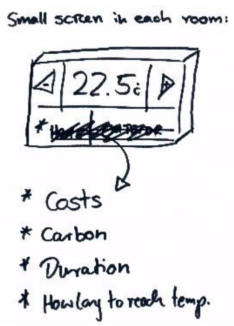
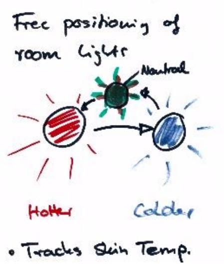
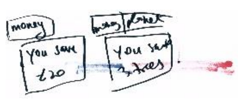
Table 4-3 highlighting the emerging factors of importance collected during brainstorming sessions

4.2.3.2 Design coding

The results of the participatory design sessions were analysed using system interface heuristics (Nielsen and Molich, 1990). Each design was given an assessment value on a scale from 1-10 with 10 being the best to reflect the design's score in that category. The designs and their associated heuristics values alongside ideation decks themes are presented in Table 4-4.

Design	Image of design outcome	Ideation decks conditions	Visibility of system status	Match between system and the real world	Consistency and standards	Error prevention	Recognition rather than recall	Flexibility and efficiency of use	Aesthetic and minimalist design	Average score
1										0.0

2			5	8	4			2	6	5.0
3			10	9	7	4	8	9	9	8.0
4		mapping ,	10	9	7	4	8	9	9	8.0
5		Educate, feedback, explicit	1		8					4.5
6			4		0				5	3.0
7			6	7	0	4		7	6	5.0
8			7	7	3			2	6	5.0

9			4	8			5		7	6.0
10			6	5				9	10	7.5
11		Feedback, Empowering, Explicit communication	9	8		8				8.3
12		Feedback, Fit, Ambient communication	7	6			5		9	6.0
13		Visibility, Stress,								0.0

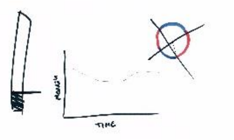
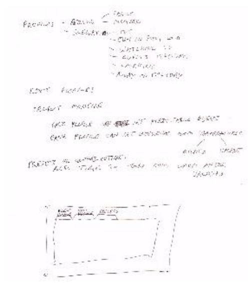
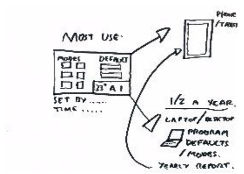
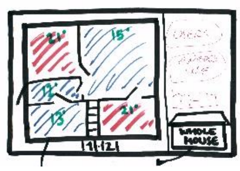
14		Mappings, Stress, Ambient								0.0
15			8	9	8		7	9	8	8.2
16			5			4	2			3.7
17			1							1.0
18										0.0
19										0.0

Table 4-4 heuristics scoring of all generated designs accompanied by images of designs

When the design or user explanations were not sufficient to deduce a feature of the interface, the value was not entered. Designs were judged only on the merits of their prevailing features, not on features assumed by the researcher.

Subsequently, an emergent themes analysis was performed on the designs and explanations of the design provided by the participant. The codes were naturally derived through an open coding approach which was thereafter combined with an axial coding technique (Robson, 2002, p. 490) where theme grouping was appropriate. The prevailed codes are detailed and described in Table 4-5 and give an insight to features or elements of this type of an interface that users perceived as important.

Feature	**Description**
Map all house	The interface gave an overview of the environmental conditions or other data for all the rooms in the house at a glance and in a spatial way
Colour-coded temperature	The interface used colours to transfer information about the environmental conditions in a space
Day Temperature profile overview	The interface gave an overview of the recorded temperature to provide the user with an overview of what the temperature had been in that space across the day up to the point of interaction
Day predicted temperature overview	The interface gave an overview of the predicted future temperature in a space to provide the user with an overview of what the system was planning to do in the future
Presenting predictions	The interface displayed its predictions about the presence of users in a room to the user.
Review & Edit predictions	The interface gave the user an opportunity to manipulate its predictions of presence and temperature

Different modes	The interface/system allowed the user to select different pre-defined operation modes (such as users are in, out, or a manual operation mode)
Suggestions	The interface gave suggestions to the user regarding environmental conditions or operation strategies
Monetary cost	The interface presented the energy consumption associated with heating usage in monetary terms for the user
Predefine starting data	The interface allowed the user to define parameters on launch to influence it's logic prior to operation
Scenarios / system activity linked to user activities	The interface/system used strings of if-this-then-that type scenarios to determine behaviour of the system. The interface allowed the users to trigger these strings.
Manual over-ride	The interface provided users with a method to correct the system's behaviour to enforce user-preferred values.
Family dynamics	The interface/system accounted for multi-occupancy and differentiated between users and different presence conditions.
Notifications about environment	The interface notified the user about other environmental conditions such as opened doors or windows in the room to try to enforce control over the wider thermal environment and maximise the efficiency of the system.
Relative temperature	The interface provided the users with an arbitrary, rather than an absolute input method for temperature selection.

selection, not specific degrees	This was aimed to make the conditions more personal and context-specific for the user, reflecting their usual habits.
Clock representatio n	The interface borrowed from time design language in the form of an analogue clock to provide users with an overview of changes over time
Different data levels	The interface allowed users to define the level of data and involvement they took in the operation. This was aimed to give users enhanced control when they requested it and streamlined communications for everyday use.
Set priorities for rooms	The interface allowed the user to define priorities and guiding roles for instances of conflict and general operation.
Customisation of data	The interface allowed the user to define the data they were presented and design the interactions they wished to have.

Table 4-5 highlighting descriptions of coded features

The designs were not compared against one another on the basis of emerged themes. Instead, the data was used to extract features that potential users deemed important. Figure 4-2 presents the total number of times a feature from Table 4-5 appeared in the participant-created designs.

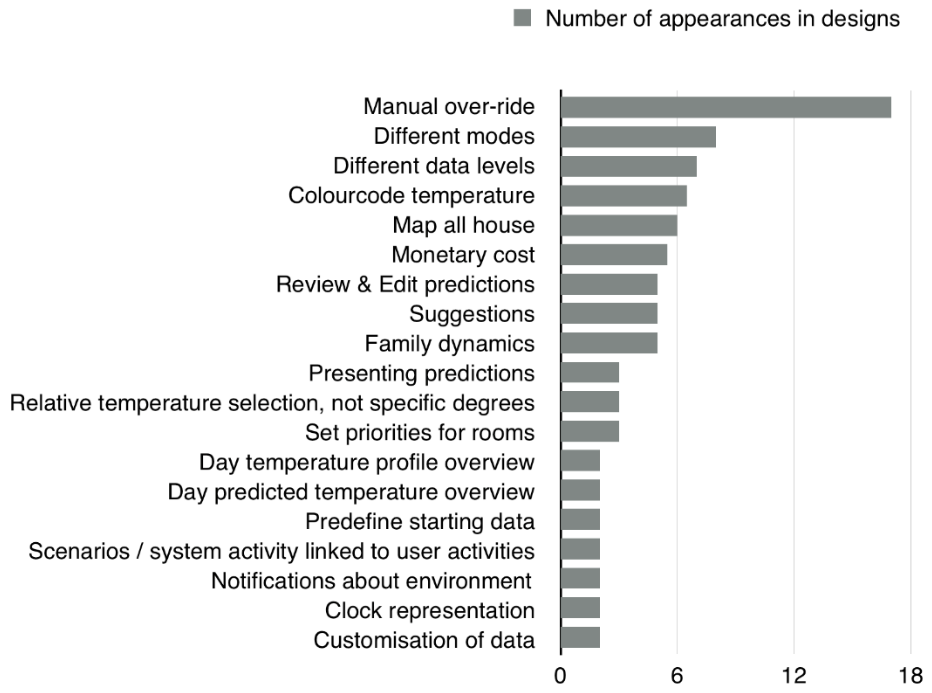


Figure 4-2 highlighting the number of times coded features appeared in designs, ordered by frequency

Somewhat unsurprisingly, the most common feature that users craved was manual over-ride. Every participant included the feature at least once and this could be interpreted as being a sign of distrust towards the system. Regardless of the interaction or information exchange that the system offers, these findings suggested that the role of an ambient intelligent home control was two-fold. Firstly, the interface needed to make it quick and easy to gain information about the system state. Secondly, it the interface had to make it extremely easy for the user to over-ride the system when the perceived state was not to the user's satisfaction.

Other features that prevailed often were "different modes", "different data levels", "colour-code temperature" and "mapping of all house". Apart from "different modes", which will be discussed below with regards to the study methodology, the other more popular features were seen as appropriate responses by users and key elements in interfaces in this domain. Different data levels, henceforth renamed to data layers referred to the user's ability to alter the granularity of data presented to them about the environment or system state and functionality. The feature was seen crucial in this types of applications as users need top-layer information, which was easily recognisable and undemanding to access, to monitor the state of system on a day-to-day basis. I.e. the user was not required to browse through a plethora of menus or views to gain an overarching understanding of what the system was doing. At this stage, the interface design ought to focus on the fit into everyday life, lightweight interaction, and could make use ambient communication. Minor adjustments to the system such as alteration of temperature set-point ought to be facilitated without a need for heavy interaction. However, when users wished to make more fundamental changes such as alter comfort temperature selection strategy for seasonal changes, or wished to enquire the system regarding its actions, the interface ought to facilitate a switch to a finer granularity of data with more detail. This researcher speculated that increasingly prevalent technology and the variety of it, could facilitate this variance in data. For example, an ambient display for current system state and temperature adjustment could be coupled with a smartphone application or computer- or online application where such finer detail could be handled. Furthermore, opting for a single interface could be cumbersome for the user as top-level information should be consumed effortlessly in passing, but when the user chooses to alter the system, the interaction becomes explicit and having to open a computer or smartphone application was not seen as excessively costly considering the purpose and intention of the user. Conversely, it would seem absurd to have to do this when the user wanted to quickly know the temperature or what the system was doing with it.

The same argument was enhanced by the remaining features of “colour-code temperature” and “mapping of all house”. Humans are innately visual in their information acquiring and use of colour can, if colour deficiency was taken into account, enhance these transactions. In most societies colours are commonly associated with certain concepts and qualities. This can vary between cultures (McCandless, 2010) but if this variation was taken into account, using colour could limit the amount of effort required by the user to acquire the aforementioned top-layer information. Similarly, mapping the whole house could provide users with a quick top-level understanding of their environment. This element was particularly important in spatiotemporal heating solutions as different parts of the house would have different temperature levels and heating patterns. However, it was important to note that while displaying all the rooms in the house or flat could be a good solution for delivering top-level knowledge about the system, it would increase the granularity of data and made the communication less light-weight. It could also be speculated that when the user required information about the whole house, they were likely to be explicitly looking into the system, rather than consuming that information in an ad-hoc manner. Therefore decisions would have to be made whether the most top-layer form of information delivered to the user was context-specific to the user's location in the household, for the whole house, or if the user could define that themselves.

All users, whether prompted or not, classified their interfaces into forms of interfaces. The provided forms included a mobile or tablet application, stationary in-house display, and a website. Similarly, many participants either disclosed or the researcher inferred from their designs the mode of interaction, this either being a touch-screen or use of physical buttons. Figure 4-3 displays breakdown of the interface form (left) and mode of interaction (right) of the created designs.

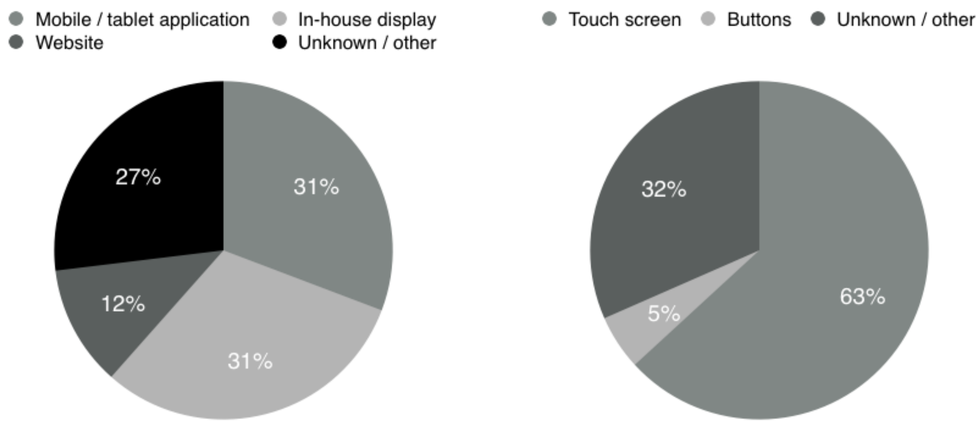


Figure 4-3 breakdown of interface form and mode of interaction

4.2.3.3 Selected designs

Three designs were selected by the researcher as output from the exercise. Selection was based on the designs' performance on the assessment heuristics. Designs 3 (and 4 since they were the same concept), design 11 and design 15 would have been selected as highest ranked on the heuristics, however, since design 15 was in its essence an interface for a manual heating system with extended capabilities and failed to cater for the autonomous nature of the described system, design 12 was used instead. While design 12 was not one of the highest scoring designs, the researchers chose this one as it was very different in its approach and would prove good starting point for later research activities. Table 4-6 compares the selected designs and further descriptions of the designs are provided.

	Design 3	Design 11	Design 12
Mode of communication	Explicit communication	Explicit communication	Ambient communication
Location in the house	Single interface per house on a smart device	Individual interface in every room	Individual interface in every room

Input method	Touch-screen	Buttons	Tactile actions
Data presented	Temperature, historic data, differences between rooms	Temperature, cost, environmental friendliness, results of alterations	Changes in temperature, impending future deviations from current thermal characteristics

Table 4-6 comparison of the three selected designs

4.2.3.3.1 Design 3

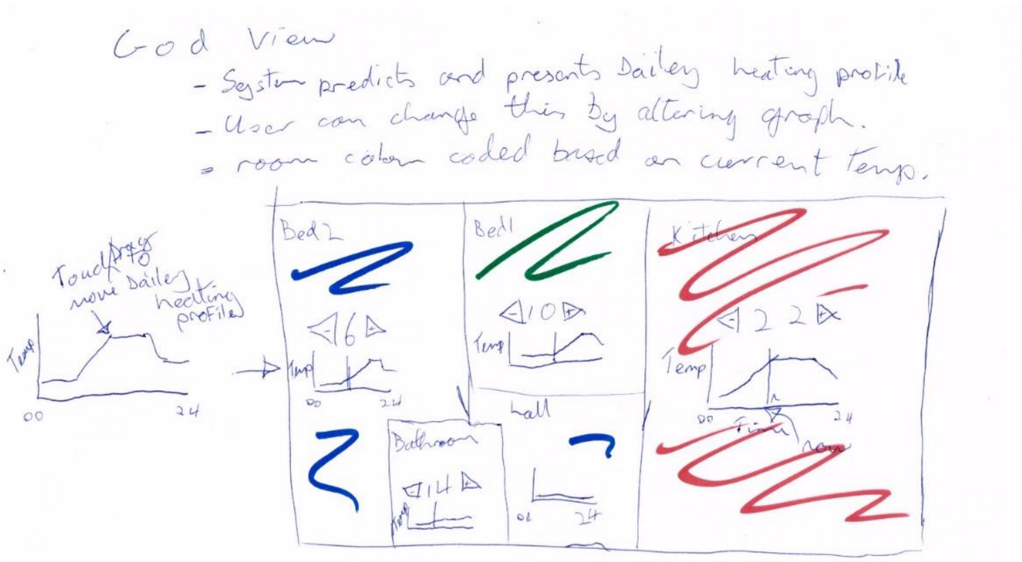


Figure 4-4 illustrating the selected Design 3

Design 3 (Figure 4-4) main functionality was a bird's-eye view of the house using the floor plan. Each room used a colour-coded feedback mechanism to convey the current temperature in the room at the time. Additionally, the numeric value for the specific temperature was also presented with adjustment buttons. Furthermore, each room area displayed a temperature profile across the day the represented the temperature in that room in the past up until midnight and into the future up to midnight. The graph also worked as an input device - users could touch the graph to alter it and make changes to temperature at specific times during the day. Meaning, that the design combined prediction, presenting the predictions and allowing adjustments to the predictions. Neither the design not the participant offered any indication as to other settings that were applicable.

4.2.3.3.2 Design 11

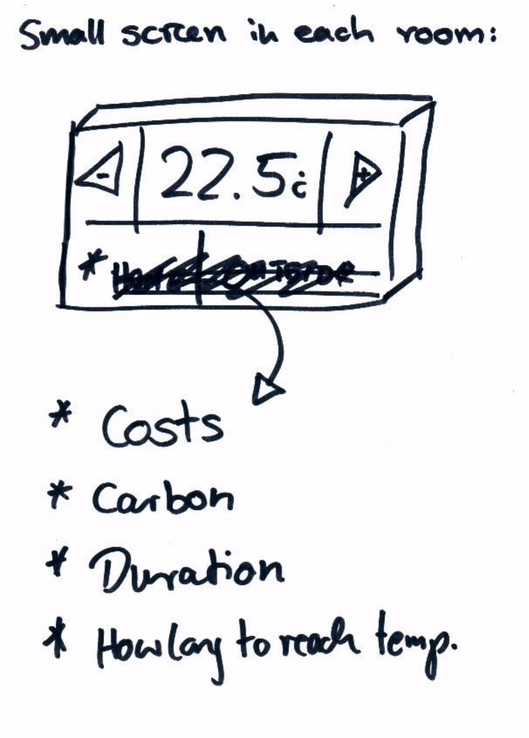


Figure 4-5 illustrating the selected Design 11

Design 11 (Figure 4-5) was a minimal display in each room with the room's temperature on it. Users could adjust the current room temperature to increase or decrease it according to their needs. Users could also select different data output. This meaning that whenever the user altered the system's proposed heating strategy, the system alerted them of the implications. Users could select from temperature, monetary cost for heating, or environmental considerations. Users could also assume higher levels of manual control, stating whether they would the heating to be on for certain durations. With temperature alterations the interface also notified the user a predicted time in which that temperature would be achieved.

4.2.3.3.3 Design 12

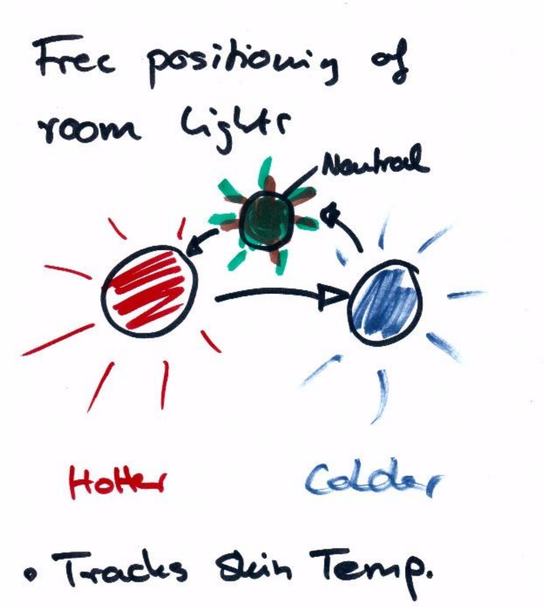


Figure 4-6 illustrating the selected Design 12

Design 12 (Figure 4-6) was an ambient interface in the shape of a small orb in each room of the house. The orbs emitted coloured light depending on the system's functionality - when the heating system was increasing the temperature in the room the orb glowed red; when temperature was being decreased, the orb glowed blue and so forth. The orbs had no direct communication with the user. Instead, the integrated heating system monitored the user using infrared cameras, thermometers and other sensors in the environment and proposed heating strategies. When the system decided the user was too cold, it started heating, when the user was deemed too hot, it cooled etc. The only over-riding way for the user to interact with the orb was to reject its strategies. The user could squeeze or throw the orb for it to reject the strategy, proposing a new one. Participants gave no further indication as to what other information would be exchanged.

4.2.4 Discussion

The designs that emerged from the exercise that were then chosen by the researcher displayed the features discussed above, ranked high on the heuristics scale and were seen as "interesting" solutions for further studies.

Design 3 displayed all the key information that the presented system used for calculating its heating patterns. However, the design displayed this was a very visual manner, which left some elements such as system's reasoning up for interpretations. This design was deemed interesting in that the intelligibility of its visual communication should be assessed and explored further. Design 11 was selected because it was seen as quite a good solution for location-specific feedback to the user with a more traditional interface, which at first impression did not support an elaborate interaction into the finer detail of functioning. The researcher though it worth developing and comparing to a different form of interaction such as a smartphone application to see if the ability to facilitate interaction on multiple levels of info granularity contributed to intelligibility of an interface. Design 12 was selected as it was the most promising ambient communication designs that emerged from the study. It was perceived that inclusion of this design gave an opportunity to develop an intriguing concept that allowed the researcher to test the value of lightweight interaction to intelligibility and experience of the user and if users were receptive to an information exchange in passing.

Although the study methodology was generally fit-for-purpose and was acknowledged as a useful tool for including users in the design process, there were a few issues that future experiments in the field can improve upon. Most importantly, while it was evident from Table 4-1 that generally the participants viewed themselves rather comfortable with technology, many of them failed to grasp key components of the system they were designing an interface for. Most importantly, a number of presented interface concepts treated the system as programmable thermostat. Meaning, the participants ignored the system's ability to learn and sense the environment. E.g. design 15 where Participant 9 described the user's ability to notify the system that they are leaving the house. Same feature was present in a number of designs e.g. most designs displaying the "different modes" feature. The system's ability to learn meant there was no need for modes and all operation was a single mode. This shortcoming in understanding for the system could have been due to various reasons. Primarily, if the methodology was to be replicated for ambient intelligent systems, it would be important that emphasis was placed by the researcher in explicitly explaining and highlighting such key elements of the system. It was speculated that the descriptions provided during these participatory design sessions were not sufficient for users to understand the concept. Secondly, it could also be possible that this shortcoming was due to the differences between designers and users - to paraphrase Henry Ford, if he had asked his friends what would make transport better, they would have said a faster horse. By that it is meant that users often fail to imagine things that have not yet been created and rely heavily on analogies of pre-existing objects. Designers, on the other hand, are known to use such analogies in looser associations to the original items, relying more on creativity and problem-solving, thus being able to create designs that are more innovative. In this sense, participants may have failed to grasp the concepts of the system they were designing for because they were not familiar with such a system first-hand.

Due to the problem of misunderstanding the system, it was not fully possible to suggest specific features that may be important to certain users. Older participants created designs with similar features to younger participants and no major differences could be observed between designs created by males and females. It is, however worth noting that the designs that scored highest on the heuristics assessment and were selected for further development, were created by users who reported to be extremely comfortable with technology in general. However, it could be that this was not because these users were better at creating design with conventionally accepted features that increase the usefulness of the design, but rather that users comfortable with technology were simply better at grasping the concept of the proposed system, meaning they addressed the design issue better.

The chosen designs were subsequently developed by the designer and taken forward to the prototype analysis activity.

4.3 Prototype analysis

Following the participatory design sessions, the design activities took a more structured approach and focused on developing several interface prototype probes with the aim of exploring the role of different interface qualities and how these qualities affect the user experience of controlling the heating system.

4.3.1 Introduction

This study explored the user experience through the conceptual model presented above (3.5.1 Conceptual model). Several technology probes were designed, motivated by key characteristics highlighted in the ideation activity and by the participatory design work described above in this chapter. The participants' responses to these probes gave an insight into how design qualities shaped the user experience and how they could be leveraged to enhance the design of control interfaces. Context to the study was created through scenarios tailored to the mismatches appearing in Figure 3-11 actions caused by mismatches in Table 3-3 and their expected outcomes (Table 4-7).

Mismatch name	Mismatch description	Expected outcome
A – All OK	The surrounding conditions are comfortable to the user and the system is maintaining those conditions	Enquiry-response

Mismatch name	Mismatch description	Expected outcome
B – Uncomfortable but succeeding	The user does not feel comfortable but the system is doing what is necessary for these conditions to be achieved	Enquiry-response OR Personal / Environmental action
C – Comfortable and yet failing	The user feels comfortable, but the system is not doing what it should be doing either in their immediate surroundings or elsewhere in the house	Enquiry-response OR System inclusive change
D – Everything is wrong	The user experiences thermal discomfort and the system is not doing what is perceived necessary by the user to restore comfort	System inclusive change – alteration to system state

Table 4-7 explanations of mismatches causing action in Figure 3-10

The study utilised Wizard-of-Oz method in which a user assumed to be interacting with a fully-functional interface, but in reality the interface was controlled by a human researcher. Imagine a voice-control computer program where building the voice recognition software would command a considerable amount of time and resource. Building a simple interface where a researcher, unseen to the participant, listened to the participant's voice commands and triggered the relevant function in the program would be far less resource-intensive.

The use of these probes was chosen for a number of reasons. Firstly, without the use of a design artefact, any knowledge gained would be hypothetical and tied to the user's idea of a design, which can almost be guaranteed to prevail in their mind. Secondly, in the participatory design activities above it was noted that users were not great at abstracting facets such as qualities and tend to manifest these into a design, thereafter being unable to deviate from that design. Lastly, in order to make results of the prototype analysis activity useful for designers developing a variety of control interfaces for the domestic setting, it was necessary for the activity not to be an analysis of a particular interface or a study into the effects of a specific interface on certain aspects of user experience. For this reason, the different technological probes were used as a collective to explore interface qualities without establishing a strong dependence on any particular design, allowing key themes to be constructed and important qualities to be evaluated.

4.3.2 Methodology

Exploring the user experiences of interacting with an autonomous home heating system control interface could have utilised any of a number of HCI research methods. Since the focus at this stage of the research is on exploring the role of specific interface qualities on UX, methods focused on evaluation, such as participatory evaluation, assisted evaluation, heuristic or expert evaluation, controlled user testing, satisfaction questionnaires, assessing cognitive workload, critical incidents, post-experience interviews, (as discussed in Maguire, 2001) would be applicable.

Since focus was on exploring user experience, rather than measuring an interface against specifications or known usability issues, it as seen crucial that potential users performed the interactions, eliminating any heuristic or expert assessment.

Controlled user testing was selected as the primary approach as it allowed a high degree of control, but the specifics of the actions performed were combined from different methods as each added specific benefits to exploring the users' experiences. Post-experience interviews, while a resource inexpensive method was substituted for verbal protocol, as this provided more timely feedback and allowed emotions to be instantly tied to actions with the interface. Furthermore, the verbal protocol method allowed critical incidents to be recorded, as well as allowed users to provide a walkthrough of their emotions. Critical incidents were seen as a useful method in highlighting system features that may cause errors and problems. Participatory evaluation was employed to allow users to perform tasks or explore the interface freely, allowing to identify user problems and misunderstandings about the system. Satisfaction questionnaires and certain cognitive measures (situational awareness) were periodically involved as the methods provide a quick and inexpensive way to get a large quantity of directly comparable data.

A mixture of Wizard-of-Oz (simulatory) and functional software prototyping was utilised as these methods provide a more realistic mock-up of the interface, and thus a greater level of realism, than possible with paper or storyboard prototyping, despite the increased complexity and set-up time. Wizard-of-Oz method was used when the skillset and time required to develop more the complex prototypes was not available. Indeed, Wizard-of-Oz method has been noted to provide means of acquiring high quality data through simulating an interface where a real interface was not available (Dahlbäck et al., 1993). However, it is worth noting that the methodology also has drawbacks, namely that users are not really using the interface, but are role-playing (Dahlbäck et al., 1993). In order to eliminate these effects, a scenario-based approach (discussed below) was taken. It is worth noting that the interfaces presented to the users in this experiment were much higher in functionality than most Wizard-of-Oz interfaces – many of the presented interfaces were functional software prototypes and could have been implemented as a working interface if back-end programming would have been implemented to connect with a heating system. However, that approach was not taken as it was deemed more preferable to explore the role of intelligibility in a much more controlled environment that wasn't plagued by real-world infrastructure issues accompanying the field study. Due to the high fidelity of the mock interfaces, the experimenter took a more orchestrating role in the experiment, rather than controlling every single response in the interfaces.

4.3.2.1 Participants

The study was conducted using a self-selected sample of male (4) and female (6) participants between the ages of 18 – 34. The participants were recruited using the open academic participant recruitment site callforparticipants.com and by distributing the study page on the site via Facebook and University of Nottingham mailing lists. The self-selected participants were exclusively of academic background (students or employed at the university) but from different disciplines (law, economics, sociology, computer science) and with various levels of digital literacy.

4.3.2.2 Apparatus

The experimental set-up featured two computers with multiple screens to allow the experimenter to present participants with key information: Figure 4-7.

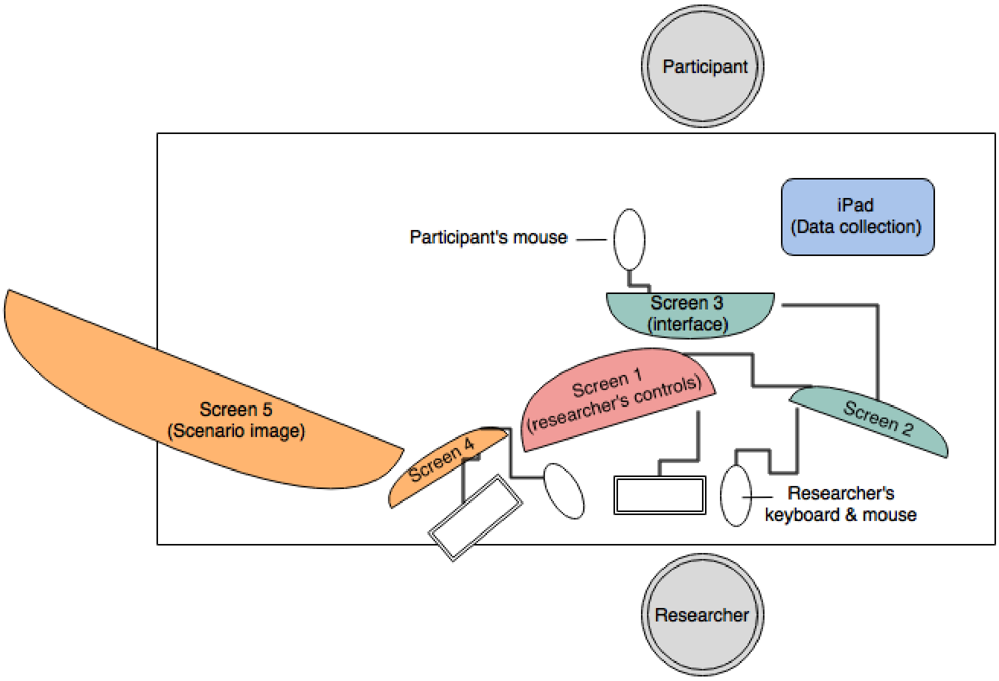


Figure 4-7 detailing the experimental set-up where mirrored screens are grouped by colour (2 and 3, as well as screens 4 and 5) are mirrored; and the participant's mouse controls the same computer as the experimenter's (screens 1, 2, 3)

The participants were presented with a screen and a computer mouse, which they used to interact with the interfaces that were used as technological probes. In total, four probes were used. These designs included two ('Graph' probe and 'Orb' probe) from the preceding participatory design study described in above, the visible version of the interface used in the field study (for more details, please see 6.3.2.1 Smartphone application) ('Study probe') and a custom interface designed for the study ('Intelligibility' probe). The Intelligibility probe was designed to match the criteria set in the definition of intelligibility by Bellotti & Edwards (2001) of "system needs to tell what it knows, how it knows it and what it is doing about it." These designs were selected as they were deemed as complimentary in their differences and implications for information communication. This is further illustrated by Figure 4-8 that compares the interfaces with regard to use of colour, intelligibility of the interface, the element of combining multiple data layers so that users can delve into system specifics when they wished to, and whether the interface was context-specific to a single room that the user was in, gave and overview of the whole house or a combination of both. The probes were assigned evaluations regarding context specificity and use of data layers by the researcher, depending on their perceived effectiveness to utilise those design qualities. The use of colour evaluation was given based on whether colour was used to indicate temperature (assigned value of 2), system functionality (assigned value of 3), or was had no specific denotation (assigned value of 1). Intelligibility evaluation was given based on how many aspects (three in total) of the intelligibility definition the probe conveyed.

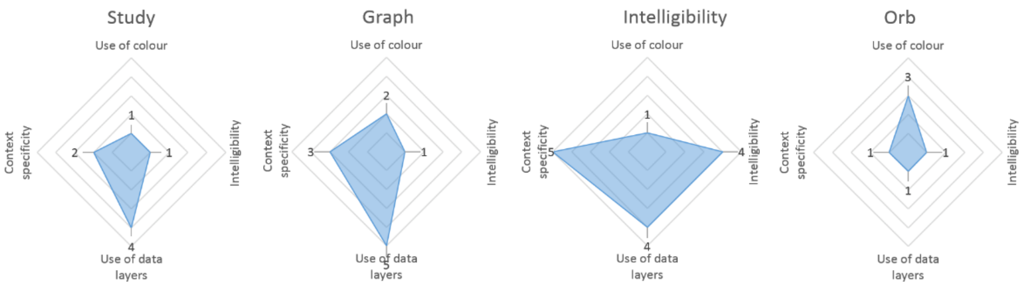


Figure 4-8 illustrating differences between interface probes based on the four design qualities - Use of colour (1- arbitrary association, 2- colour signifies temperature, 3- colour signifies functionality), Intelligibility (one point for each of three aspects of intelligibility the interface explains), Use of Data Layers (1-poor, 5-good), and Context specificity (1-very context specific to room, 5-very general to whole house)

The rest of the Apparatus section details the probes as well as the scenarios used to place user interactions in context.

4.3.2.2.1 Study probe

This probe was derived from the interface used in the field study described in Chapter 6 and featured a display of current temperature of the room alongside with ta graph. The mock interface used in the study can be seen in Figure 4-9.

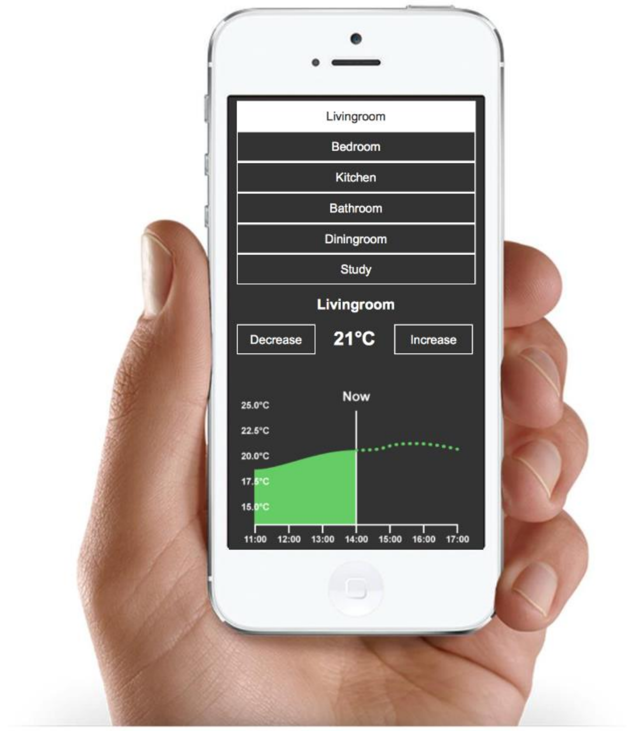


Figure 4-9 illustrating the Study probe

The interface listed all the rooms in the user's household providing him with an option to investigate the conditions in each. Upon clicking on a room the user was presented with the temperature currently prevalent in the room and a graph of the change in the temperature over the previous three hours and a prediction of the temperature in the room over the next three hours. This prediction was formed by displaying any heating activity that may have been scheduled or if none was coming up, a prediction of the temperature based on the previous 2 days' temperature in the room. If the user changed the temperature in the room up, the future graph displayed the change in temperature that would take place over the next hours in response to the user's input. Similarly, if the user decreased the temperature, the graph displayed the predicted rate of temperature decay that would occur in the room. It is important to note at this stage that only one version of this interface was used in the lab study.

4.3.2.2.2 Graph probe

This probe was developed from one of the designs emerging from the participatory design sessions. The key features of the probe were threefold: 1) an overview of the house, 2) use of colour for displaying current temperature conditions in the room, and 3) use of graphs as an input method for the user. The mock interface can be seen in Figure 4-10.

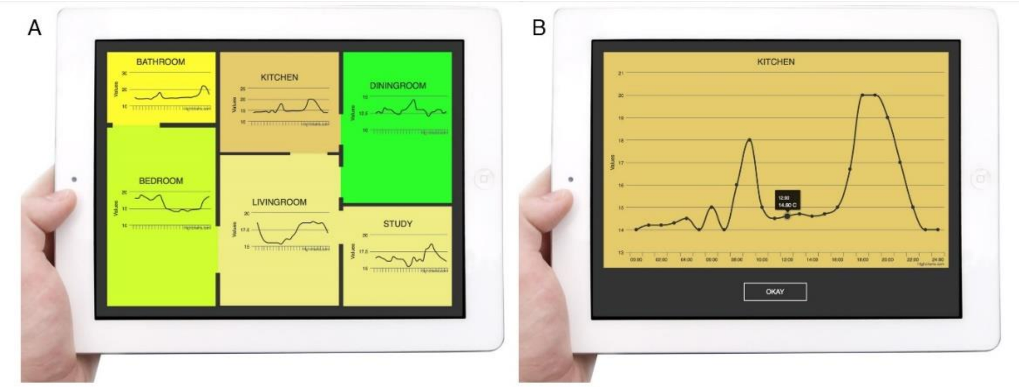


Figure 4-10 illustrating the Graph probe

The house view depicted in Figure 4-10 (A) featured a blueprint layout of the house or flat with rooms in the same arrangement as they appeared in real life. The floor or background of each room was coloured based on the prevailing temperature conditions in the room on a gradient adapted from the UK Meteorological Office guidelines on temperature prediction (Met Office, 2015). Users were able to click on each of the rooms and see an enlarged version of the graph (B) which depicted the past and future temperature in the room. The data for this graph was intended to be obtained the same way as in the study interface, as described above. On the extended view of the room, users were able to click and drag points on the graph thus altering the future or current temperature in the room. After appropriate edits were made, the user could hit “Okay” button to accept the changes and return to the house view.

4.3.2.2.3 Orb probe

This probe was designed as a semi-translucent orb, one intended to be placed in every room of the house. The orb would glow in three different colours - red, green and blue. These colours would indicate whether the heating system was currently heating the room, maintaining current temperature or letting the room cool, respectively. An illustration of the mock interface is seen in Figure 4-11.

Figure 4-11 illustrating the Orb probe

The users would be able to reject the current strategy suggested by the system by picking the orb up and squeezing it. This would make the orb cycle through the 3 options and another squeeze would select the option the orb was displaying. Selection of an action was indicated through blinking the selected colour thrice and then remaining in a solid colour. The idea behind this interface was a minimal interaction system - the system learns the user's preferences by improving towards the most suitable heating solution through a logic of elimination. I.e. if the system has proposed to maintain the temperature but the user selects the option of increasing the temperature, the system rejects the current temperature as a suitable set-point for this time and selects the next higher suitable temperature. The system behaves similarly with presence predictions - for example, if the heating system predicts the user to be present shortly and turns on the heating, but the user enters the room and turns the heating off, the system turns the heating off and uses this selection to learn that either this was not a suitable time for heating or the user prefers a lower temperature. Such arguments are being added to a pool for the system to base its suggestions on. The argument features a memory decay that keeps the system constantly adapting itself to provide the most appropriate strategies.

4.3.2.2.4 Intelligibility probe

This probe was custom designed for this experiment with the design brief of fulfilling the criteria of intelligibility definition to its best ability. For this purpose the explanations provided were presented explicitly in a written speech format. Any use of graphics of visuals was seen as a distracting factor that limited the ability to test whether users simply wanted to be told what the system was 'thinking' as if told by a human. The mock interface can be seen in Figure 4-12.

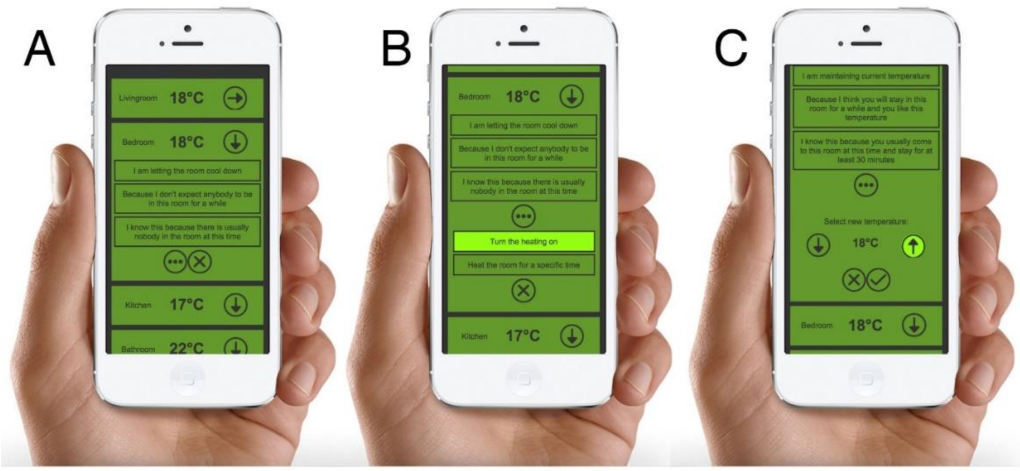


Figure 4-12 illustrating the Intelligibility probe

The users were presented with a glance overview of all the rooms as seen in the 'collapsed' view of a room in top section in part A of Figure 4-12. This glance view was made up of the room name, the current temperature in the room and an arrow icon that was used to indicate system functionality. Arrow pointing up meant that the system was increasing the temperature in the room, arrow from left to right meant current temperature was being maintained and a downward arrow indicated that the system was letting the room cool down. When the user clicked on a room button, they were presented with a more in-depth view seen in the second green box of part A of Figure 4-12 that showed what the system was doing, what it based this decision on and how it knew its information. The users could then reject the proposed strategy or alter it by clicking the three-dotted “more” button that revealed the alteration options illustrated in part B. In cases where users wanted to alter the specifics regarding times or temperatures, they were presented with additional input options displayed in part C. The decision-making of the interface is displaying in Table 4-8.

What it is doing	**Why it is doing it**	**How does it know this**	**Alternative options**	**Target**
I am heating to ##C	1.1 - Because I think you will be here soon	I think this because you usually come into this room at around ##:##	Change temperature	1.1/1.2
			I will be there at a different time	1.1/3.4
			Turn heating off	3.5
	1.2 - Because you changed the temperature	I know this because somebody from the household gave me this temperature for this room	Change temperature	1.1/1.2
			Turn heating off	3.5

What it is doing	Why it is doing it	How does it know this	Alternative options	Target
I am maintaining current temperature	2.1 - Because I think you will stay in this room for a while and you like this temperature	I know this because you usually come to this room at this time and stay for at least 30 minutes	Change temperature	1.1/1.2
			Turn heating off	3.5
		I know this because you haven't changed the temperature	Change temperature	1.1/1.2
			Turn heating off	3.5
I am letting the room cool down	3.1 - Because I don’t expect anybody to be in this room for a while	I know this because there is usually nobody in the room at this time	Turn the heating on	1.2 / 2.1
			Heat the room for a specific time	1.1
		I know this because	Turn the heating on	1.2 / 2.1

What it is doing	Why it is doing it	How does it know this	Alternative options	Target
		somebody was just in the room and now they have left	Heat the room for a specific time	1.1
	3.2 - Because I heated the room as I expected somebody there, but nobody showed up	I did this because I know usually somebody shows up at this time but I didn't see anybody for 10 minutes	Turn the heating on	1.2 / 2.1
			Heat the room for a specific time	1.1
	3.3 - You changed the temperature to ##C	I know this because somebody from the household gave me this temperature for this room	Change temperature	1.1/1.2
			Turn heating off	3.5

What it is doing	**Why it is doing it**	**How does it know this**	**Alternative options**	**Target**
	3.4 - Because I don't expect anybody until ##:##	I know this because somebody told me to heat the room for that time	I will be there at a different time	1.1/3.4
			Turn the heating on	1.2 / 2.1
	3.5 - Because you told me to keep the heating off right now	I know this because somebody told me to do so	Turn the heating on	1.2 / 2.1
			Heat the room for a specific time	1.1

Table 4-8 detailing the decision making logic implemented in the Intelligibility interface

The system thinking of this interface was very similar to the one described for the Ball interface above in that it suggested a strategy for heating the room in response to its presence and a comfortable set-point temperature predictions. This interface also featured an arbitrary colour selection – a single colour was used for the whole interface, which signified nothing regarding the environmental conditions or the system functionality.

4.3.2.2.5 Scenarios

Since the experiment took place in a lab setting, it ignored several key elements - the wider environmental context that have emerged in this research (see Chapter 3 Ideation),comfort feedback through the environment, interactions between the users, as well as the fact that successful and efficient heating controls operation are not primary activity goals in a domestic setting. In contrast, in the experimental setting, interaction with the interface was the users' primary focus, thus greatly differing from real life. In order to counter these elements or rather the lack of, the study design utilised scenarios, as the methodology has been suggested to provide an opportunity to simplify a vast quantity of data to a limited number of possible states, and tell "a story of how various elements might interact under certain conditions." (Schoemaker, 1995, p. 26) More specifically, scenarios defined scene and context of use and tried to influence the user into thinking of their own domestic practices and imagine to use the interfaces in that context. In total, four scenarios were used that can be seen in Table 4-9 and were accompanied by illustrations of the rooms in which the scenario took place, displayed on Screen 5 in Figure 4-7.

Mismatch	**Scenario as recorded for participants**	**Scenario number**	**Expected outcome**
A – All OK	"It is midday. You go to the living room to sit on the sofa and read a book. The room feels at a comfortable temperature to keep you warm as you sit in one place and read."	1	None
B – Uncomfortable but succeeding	"It is 6PM. You are finishing dinner and decide to read a book in the study for a couple of hours since you don't feel up for doing anything else. But	4	None

	before, you must wash the dishes."		
C – Comfortable and yet failing	"It is midday. You have guests coming over in a couple of hours' time and you are busy preparing the dinner party. Since there is quite a few guests coming, you decide to lay the table in the dining room even though the room is usually empty."	3	Turn heating on in dining room immediatel y or for the time guests are expected to arrive
D – Everything is wrong	"It is 6 PM. You have just finished cooking and sit down in the kitchen to have your dinner. Since you have been moving around a lot and the cooker has been on, the room feels very hot."	2	Turn temperatur e down or turn the heating off

Table 4-9 Highlighting scenarios used in the experiment including the mismatches in Table 4-7 they relate to and expected outcomes

The accompanying illustrations were created as humans are highly visual in their nature and this was taken advantage of in order to heighten the participant's sense of interacting with the interface in the home setting. The images were developed in a style that tried to imitate sketches of new architectural drawings, relying on heavy lines and light, faded colours in order to describe the scene, but not make in excessively 'real' for participants. The latter meant that the aim was not to create an environment that the participant had to imagine themselves living in, but rather to create a cue that triggers the participant's mind to think of their own home. All of the room illustrations can be seen in Figure 4-13.

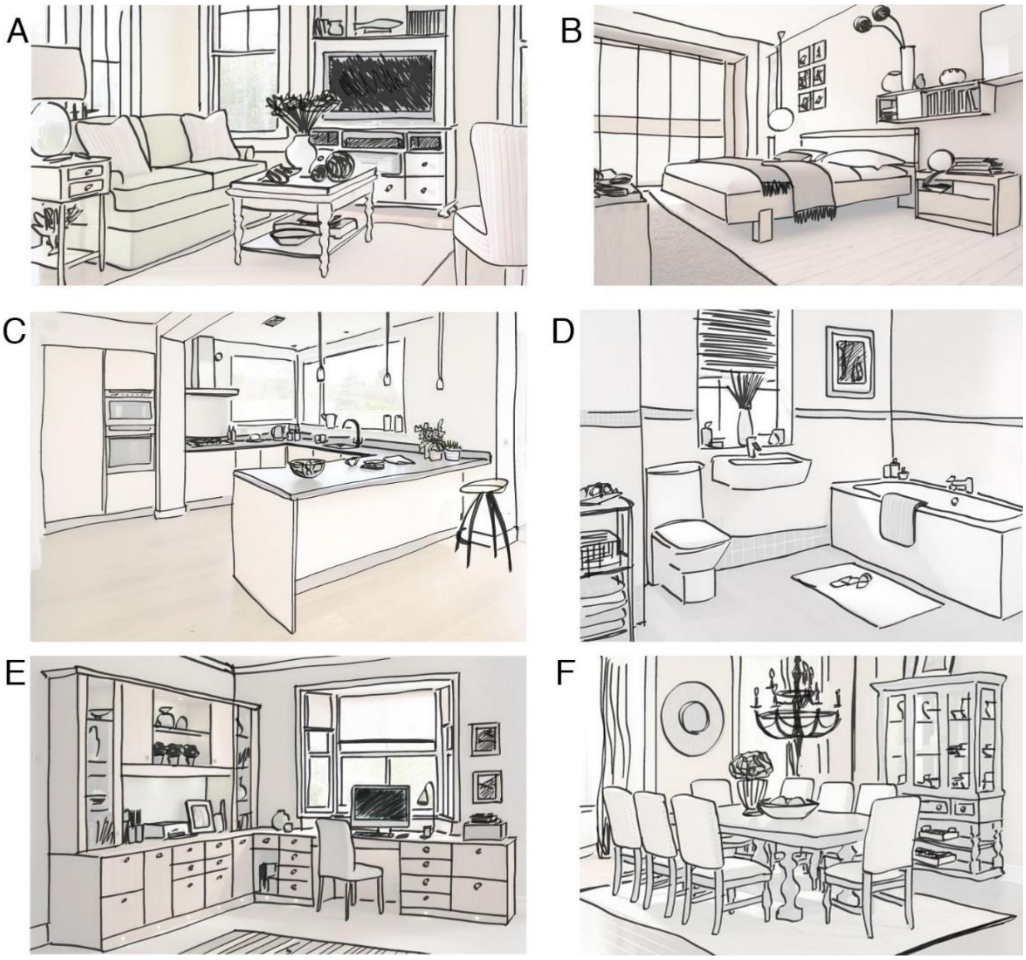


Figure 4-13 detailing the illustrations presented to participants (A – Living room, B - Bedroom, C - Kitchen, D - Bathroom, E - Study, F – Dining room)

4.3.2.3 Materials

During their interactions participants were asked to perform verbal protocol (participants verbalising, or thinking aloud their thoughts regarding what they are doing, the goals of their actions etc. (Johnson and Briggs, 1994)). Ericsson & Simon (1984, 1980) elaborated on the method and added rigour by implementing encoding to the recorded verbal reports. This approach makes the obtained data more valid and useful in understanding and analysing the tackled issue. Same approach was taken in this research where the users were instructed to verbalise their thoughts, which were later encoded and categorised to provide an overview of their experiences with the interfaces. In addition, the participants' interactions were screen-captured along with the audio of verbal protocols, and after each interaction several verbal and written questions were asked (see Table 4-10 for data collection). The latter two were elicited together as some questions were deemed easier and faster for participants to answer verbally and an interview format was introduced.

	Interactions	**Verbal protocol**	**Questionnaire**	**Interview**
Collected data	All interactions with interface as on-screen clicks & other events	Verbal utterances & users' descriptions of their thoughts	Selection of multiple-choice / Likert-scale / SAGAT-type questions (Endsley, 1988)	Multiple open-ended questions
Method of collection	Video Screen-capture	Audio recording	Online questionnaire via an iPad	Audio recording
Data processing	Coding events as "viewing events" and "altering events"	Coding data according to tags emerging from the data	N/A	N/A

Table 4-10 detailing the data collection

A situation awareness approach to some questions was adopted through SAGAT-type questions. Intelligibility shares a lot in its essence with situational awareness (SA), defined as "… the perception of the elements in the environment within a volume of time and space. The comprehension of their meaning, and the projection of their status in the near future (Endsley, 1988, p. 792)." The different levels of situation awareness can be seen in Figure 4-14 in which the relationship between SA and decision-making are highlighted.

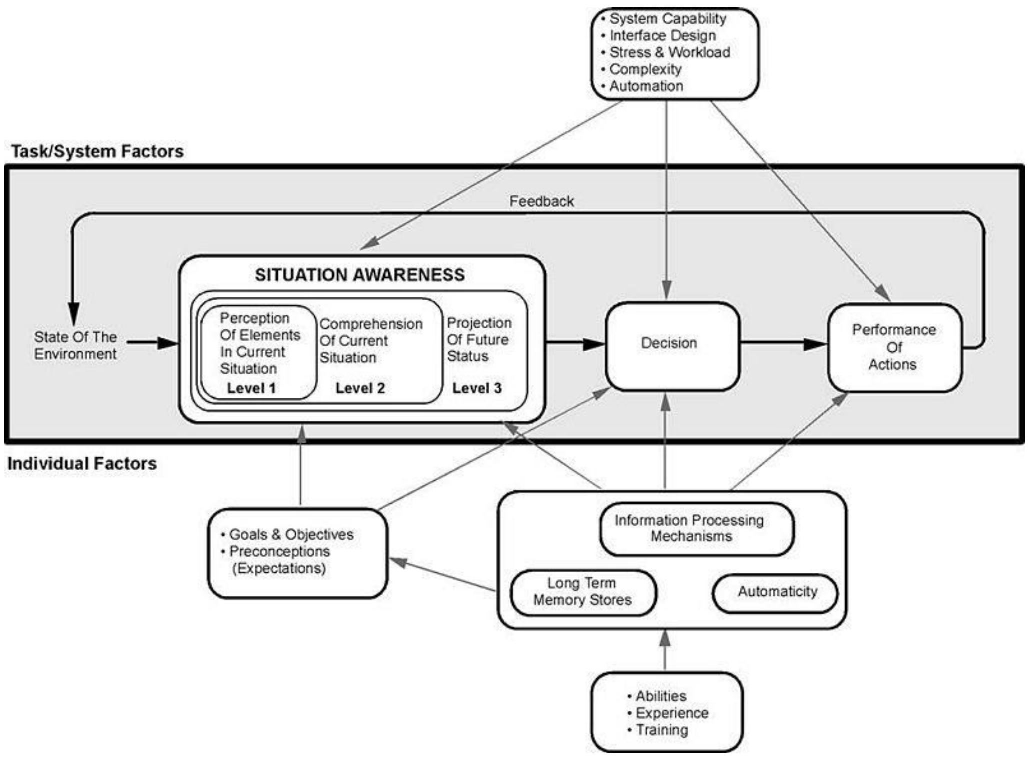


Figure 4-14 Situation awareness and decision-making model, as seen in (Endsley, 1988)

SAGAT type questions, as described by Endsley (1995a) allowed collecting detailed and specific information about user's situation awareness that could then be measured against reality. However, in contrast to the manner in which the questions were asked by Endsley (Endsley and Kiris, 1995; Endsley, 1995a, 1995b) the current experiment the questions were still administered after the conclusion of each interaction, primarily because the interactions were very short in duration.

After all interfaces were used in all conditions, the users were asked two final questions regarding the system functionality. Table 4-11 highlights the written and verbal questions.

Question number	Question	Modality	Question type	Insight gained
1	How many rooms are currently being heated?	Written	Multiple choice (options: 1,2,3,4,5,6)	Measure of intelligibility
2	Provided you carry doing the same activity for the next hour, how many rooms will have the heating on in 3 hour?	Written	Multiple choice (options: 1,2,3,4,5,6)	Measure of intelligibility
3	What was your aim in interacting with the interface?	Verbal	Open-ended interview-type question	Insight into the users' responses to situations in comparison to the proposed actions in response to mismatches
4	Do you feel you accomplished your aim?	Written	4-point Likert scale from "Failed to accomplish my aim" to "Successfully accomplished my goal"	Effectiveness of the design & ease of use
5	What did you like about this interface?	Verbal	Open-ended interview-type question	Design feedback relating to the 4 dimensions on which the interfaces were differentiated on and clues to a better interface design
6	What did you not like about this interface?	Verbal	Open-ended interview-type question	Design feedback relating to the 4 dimensions on which the interfaces were differentiated on and clues to a

				better interface design
7	If this interface controlled the heating in your home, how confident would you be that you have control over the heating?	Written	5-point Likert scale from “Not confident at all” to “Extremely confident”	Perception of control in relation to the 4 dimensions highlighted above
8	How much detail do you think interface gave you?	Written	5-point Likert scale from “Not enough detail” to “Too much detail”	Perception of info exchange. Interface’s aim is to visualise an invisible system so shortage of data renders the interface useless.
9	Why was the heating system behaving the way it was? Please select all correct answers:	Written	Multiple choice with the following options: - It knew which rooms were empty - It knew I like to read in the living room - It knew when I go to work - It knew the boiler was on - It knew my preferred temperature - It knew I would be in the room soon - It knew I had a window open - It knew what I was doing	Measure of intelligibility
10	The heating system made its decisions about when and what temperature to heat based on two factors. What	Verbal	Open-ended interview-type question	Measure of probes’ ability to transfer knowledge about the heating system functionality to the user

	were those factors?			
11	And how do you know this?	Verbal	Open-ended interview-type question	Measure of probes' ability to transfer knowledge about the heating system functionality to the user

Table 4-11 detailing the questions asked from the participants

4.3.2.4 Design

The study used a repeated measures design with every participants being exposed to all conditions. There were altogether 16 conditions with each probe interface used in combination with every scenario. The qualities of the interfaces were used as probes to explore the interactions and user experience within the suggested framework. The activity was not seen as a comparison of possible interfaces, but rather the interfaces were used as a collective set of tools to probe the user experience of (1) understanding, (2) control, and (3) quality of interaction. In addition, validation of the proposed framework was sought by using the scenarios as independent variables and the recorded actions of the participants as dependent variables.

4.3.2.5 Procedure

Participants were invited to take a seat at the apparatus as detailed in Figure 4-7. They were presented with the study information sheet, explained that there was an assistant helping with the experiment. The assistant was an image of a female presented on the screen and multiple statements read out by a computer-generated voice, henceforth called "Sound-bites". Full detail about the wording of each Sound-bite can be seen in Appendix 5 - Interface probe study soundbites. Participants were played Sound-bite 1 explaining the study. After being given an opportunity to ask any questions, the participants' consent was gained with the help of Sound-bite 2 and the study started (Sound-bite 3). Subsequently, the participants were presented the scenarios in a particular order using Sound-bites 4 - 8 that read out the scenario and the relevant room illustration was displayed. Where the required interface was the orb interface, Sound-bite 8 was played after the scenario description. Following the scenario presentation, the researcher presented the participant with the interface and asked them to interact with it and perform verbal protocol (Sound-bite 9). When the participant looked as if they were finished, the researcher played Sound-bite 11 to confirm this and if confirmed, Sound-bite 12 was played instructing the participant to answer the first set of multiple choice questions (see Appendix 6 - Probe study multiple choice questions for more detail). Subsequently, verbal questions using Sound-bites 13 - 17 and the remaining multiple choice questions were asked according to the order detailed in Appendix 6 - Probe study multiple choice questions. When the participant had finalised answering questions, the next scenario was introduced and the cycle repeated. When all interfaces had been tested with all scenarios, the participant was asked final questions regarding the heating system's decision making using Sound-bites 18 & 19. Following that Sound-bite 20 was played to debrief the participant and provide them with an opportunity to ask any questions that they may have had. Sound-bite 21 was used as and when deemed appropriate by the researcher to thank the participant for their actions.

4.3.3 Results

A lot of the data was in the form of answers to open-ended questions or verbal protocol. It was important to understand the user experiences from this data in a structured way and thus, thematic coding analysis was used. For the interpretation of verbal protocol data a selective coding approach was used to identify pre-defined instances of errors, confusion, revelations of usage or usage 'in the know', meaning participants appeared to be familiar with the functionality enough to use the interface with fluidity. However, for feedback on interface likes / dislikes, an open coding approach was combined later with an axial coding technique (Robson, 2002, p. 490) to group experiences into themes in order to tell a story of user experience. Questionnaire responses were analysed using descriptive statistics. The findings were interpreted using the proposed conceptualised model and the behaviours described therein.

4.3.3.1 Quality of interaction

The quality of interaction was assessed through verbal protocol and design feedback data. The verbal protocol results can be seen in Table 4-12, which highlights counts of each of the codes for all interfaces and a verbal protocol score that was calculated by deducting the sum of negative codes from the sum of positive codes. The 'annoyance', 'confusion' and 'error' codes were labelled negative as frustration with the interface, inability to understand the interface, or making mistakes were regarded detrimental to the user experience. In contrast, 'in the know' and 'revelations' were considered positive as they either allowed the user to use the interface with confidence, or facilitated learning for the user, respectively. Both traits were assumed to have a positive effect on the user experience.

Sentiment	**Code**	**Graph**	**Intelligibility**	**Orb**	**Study**
Negative	Annoyance	5	0	9	9
Negative	Confusion	24	20	35	28
Negative	Error	0	5	4	8
Positive	In the know	40	31	13	33
Positive	Revelations	16	35	13	18
Verbal protocol score		27	41	-22	6

Table 4-12 results of verbal protocol coding counts and score

The results show that users experienced very different experiences between different probes. The Graph probe scored higher on "in the know" code than the Intelligibility interface and noticeably lower on the "revelations" code. These results suggested that interface qualities that facilitate intuitiveness as well as discovery were required for a meaningful, pleasant interaction. In other words, interfaces should be designed to be as intuitive as possible, but failing (or in addition to) that, they should offer explanations to allow users to discover functionality. To better understand these experiences, it is worth taking a look at the qualities that users reported to like or dislike in the probe interfaces.

Figure 4-15 below highlights the codes or qualities that emerged and the total number of times the code prevailed.

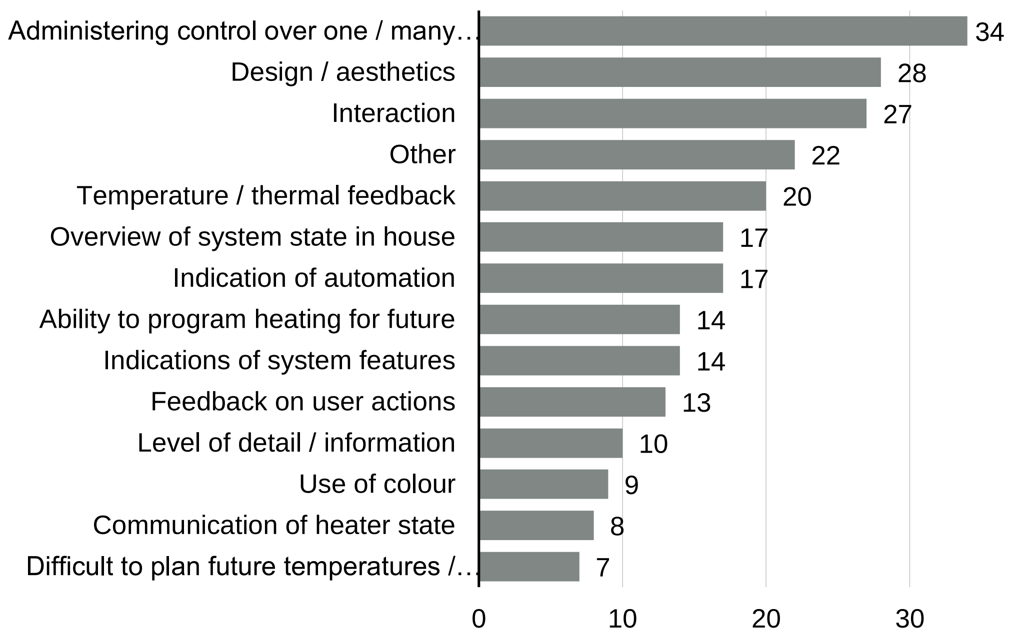


Figure 4-15 Total number of times feedback codes appeared in participant answers

Feedback on user action denoted any mention of the interface's communication in reaction to an action performed by the user e.g. *"I didn't know what it meant when I squeezed it harder or when I squeeze it less."*

Interaction referred to any feedback on the quality of giving commands to the interface such as button presses, drags, navigation through menus etc., as well as data insertion for example *“you can specify the exact temperature you want your rooms to be”*. Design / aesthetics denoted any comment about the visual qualities, interaction qualities, features of any graphs or other visual content such as *“it's very playful to use”* or *“it's awful hard to compare the curves because the scales are all different”*. Administering control over one or many rooms denoted the over-riding control element of an interface where users wished to change the heating system’s settings such as *“I had full control over which rooms have higher temperatures and which ones have lower temperatures”*. Overview of system state reflected the user’s ability to understand the status of any change occurring in the environment e.g. *“it gave me a good overview of what is happening in the different rooms”*. Temperature / thermal feedback referred to the user’s ability to obtain information regarding the thermal conditions prevailing in the room, for example *“I can't see what temperature [it] is.”* Use of colour referred to any comments that the users made regarding any colours prevalent in the interface – *“I still don't understand the colour scheme.”* Indication of automation referred to any feature that users communicated as assisting them understand the functionality or existence of the automation element of the heating system, for example *“how the rooms will be heated or cooled down over the next couple of hours or over the course of the day”*. Communication of heater state referred to any comment that addressed the element of heaters being ‘on’ or ‘off’ in the room, e.g. *“I didn't know whether 15 degrees meant that the heating was off”*. Programming heating in the future was concerned with the element of users being able to administer change in the system for a time period other than the current moment in time – *“I could set the heating for a specific time.”* Indication of system features denoted any mention of explanations the interface offered regarding its functionality – helpful hints such as *“I wasn't sure on how to do it.”* Level of detail captured any comment that users made regarding the lack or overload of information that they may have experienced – *“without giving me too much information about what is happening in the entire house”*. Other ease of use or complication denoted any other element that the users may have mentioned that did not suit the codes highlighted above e.g. *“That I couldn't really understand it.”* Difficulty to plan activities referred to the fact that participants, if using the proposed interface, would be required to think ahead to their activities during the day and plan their day to match the heating system or vice-a-versa e.g. *“I have to predict where the guests and I will be in at that time.”*

These results showed that the most important theme for users was administering control over the heating system (Figure 4-15), reflecting the user’s need to exercise their overriding power over the interface – what Baker and Standeven (1996) term their innate adaptive aptitude. The amount of feedback also related to the participants’ ability to inflict the desired change and their subsequent need to receive feedback on any success or failure in doing so. Qualities of probes that enhanced this were concerned with the visibility of the actions, the preciseness of alterations, granularity of temperature adjustment, and the effectiveness of override. Interestingly, the results highlighted another element of override for humans - participants’ frustration in their inability to establish a link between system functionality, temperature, and heater state. Several participants were searching for clues in the interfaces to find out whether heaters were “on” or “off”. This was seen as a completely separate piece of information from temperature as users were often (particularly regarding cooling down or periods of absence) not interested in the temperature but simply the knowledge that the heaters were off. This element seemed to be especially important when administering override to curtail temperature rises. These findings suggest that the availability of override and the feedback on any overriding action significantly influence the user experience and should be carefully considered when designing such interfaces.

Furthermore, each code (except for difficulty to plan activities) had a positive and negative connotation – whether the participant liked or disliked the interface quality they described. Figure 4-16 shows the sentiment breakdown for all used probes.

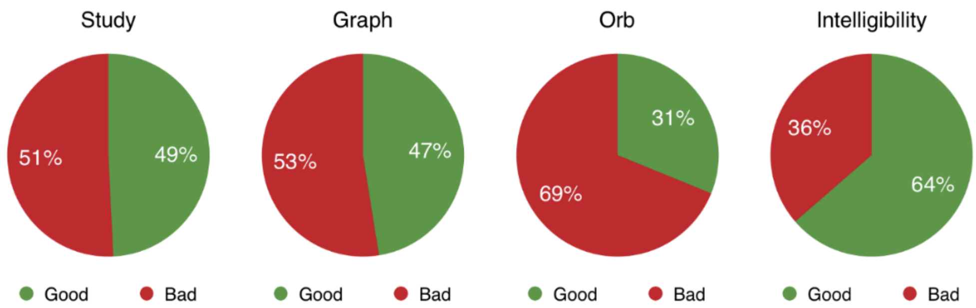


Figure 4-16 Sentiment breakdown of each tested interface

The results of the sentiment analysis coincide with the statement above that intuitiveness, discovery, and override provide a pleasant user experience. The probes that offered most explanations about themselves, allowed users to understand the interface and the consequences of their actions, had the most positive feedback. To understand the elements highlighted by users in Figure 4-15 further, *Figure* 4-17 show the sentiment of feedback for each emerged theme and probes.

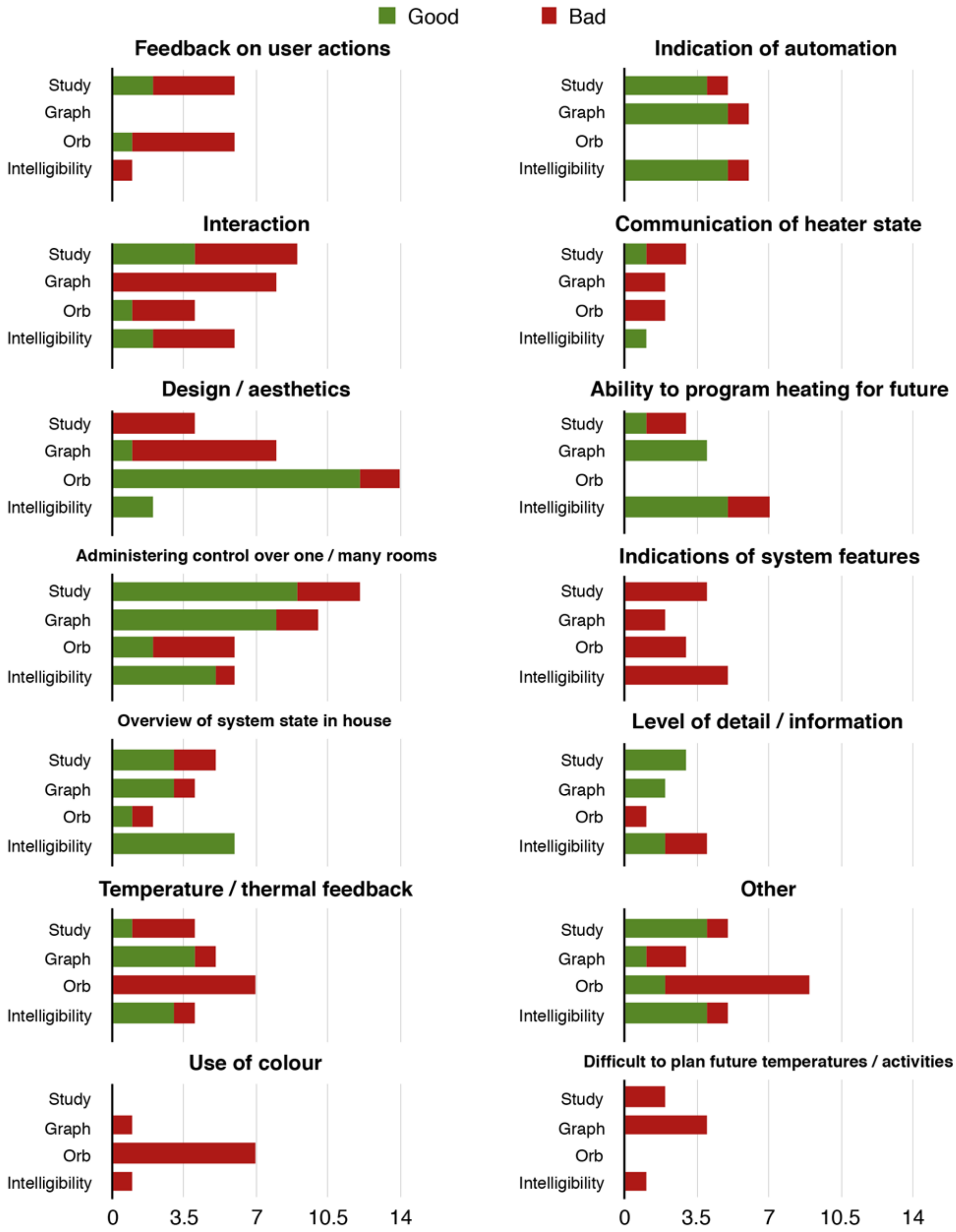


Figure 4-17 Highlighting feedback on each emerged theme for all four interface probes

Interestingly, design / aesthetics was the second-most common code (Figure 4-15) and a large amount of the feedback under that category can be attributed to the use of graphs in two of the probe interfaces, which was not necessarily the most traditional method of communicating heating system functionality, resulting in a lot of negative feedback from the participants. Aesthetics became even more interesting when observed in combination with results on the quality of thermal feedback (Figure 4-18), which revealed that users preferred an overview of temperature across a period of time as displayed by the Graph interface combined with the ability to get an exact value. On the other hand, the “Orb” interface was perceived to have the worst thermal feedback features, primarily due to a common inability to decode the meaning of the three colours in relation to prevailing temperature (it is worth noting the participants’ instincts to attempt this interpretation despite the fact that the colours represented system state). These results and the qualities of observed probes tell the story of the complexity when communicating temperature. This suggests that attention must be paid to the type of information presented (trends vs snapshot) and that aesthetics or colour can easily be misinterpreted by users due to a large number of existing conventions from water taps, weather maps, warning signs etc. requiring the use of colour to be explicitly explained.

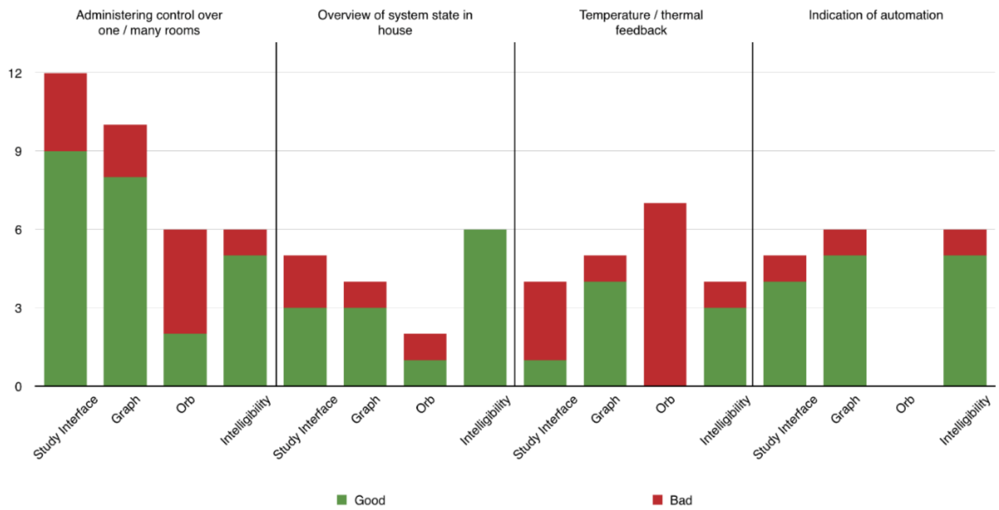


Figure 4-18 Feedback sentiment analysis of key analysis codes for all 4 interface probes

The four factors compared between probes in Figure 4-18 were important as they concern the experience of communicating and understanding an actor in the user’s environment that can change the environment. Results of the feedback on system state, highlighted in Figure 4-18, revealed that there were no negative reports from participants for the “Intelligibility” probe and it appears that the users' appreciation of it was a combination of the justification of system state and the different levels of information with which they were communicated. Several users said they enjoyed the explanations that the interface gave for its current system state. For example:

"I liked how it described the logic behind the decisions it made on whether it is heating up or cooling down a room" (Participant 5), "…and actually getting some feedback from the system as to why it is doing certain things" (Participant 4), "And it also said why all the temperatures [prevailed], like if it was something that you just turned on or if it was [automation]" (Participant 3).

These findings suggest that detailed accounts of explanations were important not only with respect to the functionality of the interface itself, but also regarding the functionality of the otherwise invisible heating system.

However, lengthy explanations also diminished the user experience, so that it is important to understand when providing extra detail was appropriate. In this study explanations were deemed more useful in more complex scenarios (Scenario 3 & Scenario 4), with participants indicating that the level of detail in the information was more appropriate (value of 3 on Figure 4-19), in contrast with simpler scenarios, when this was judged as closer to "Too much information".

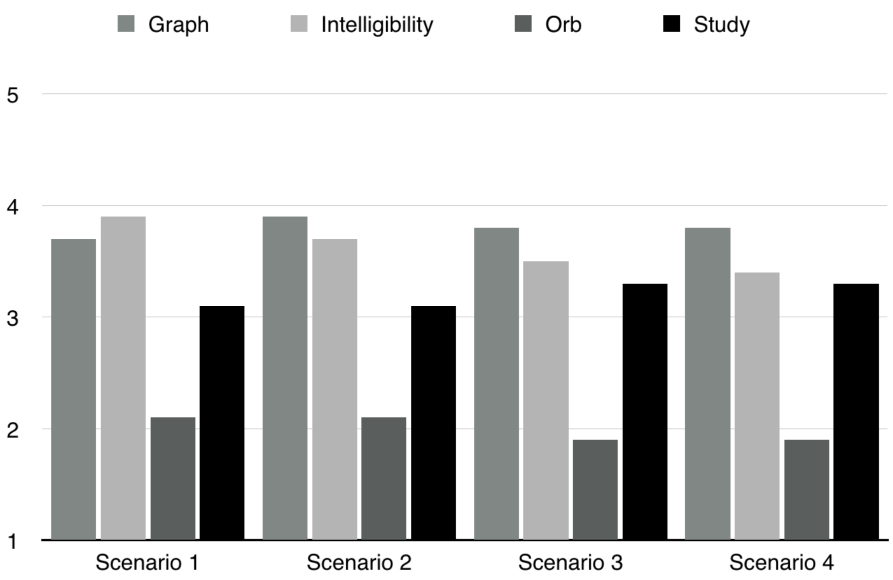


Figure 4-19 Illustrating user perceptions of information amounts of the 4 tested interfaces for each of the tested scenarios (1 – too little information, 5 – too much information)

Overall, users seemed to thoroughly enjoy the experience of their ability to delve into finer detail of information when they needed to:

"I liked that it was quite minimal to start with, and once you knew what the arrows meant, you wouldn't need to expand it and need all the extra information that is available [to] you if you need to know" (Participant 8); "…the interface gave me an indication, like a quick overview of whether the rooms were being cooled down, the temperature being maintained or heated up. And it also allowed me to get into a bit more detail and give me some idea of what's happening in that room" (Participant 4).

These results highlight the need for smart home interfaces to vary their data layers based on the type of interaction that the user seeks, and to use these opportunities to provide explicit explanations of system functionality and behaviour of automation on lower data layers.

4.3.3.2 User experience of control

The experience of control was explored through several pieces of data including answers to questionnaire questions regarding perceptions of control, users' perceptions of their ability to fulfil their goals, as well as their recorded interactions to highlight their perceptions of control in comparison to actually performed actions.

The participants were asked to rate their perceived level of confidence in their ability to maintain control of the heating system if these interfaces were in charge of controlling the heating system in their homes, on a 5-point Likert scale from "not confident at all" to "extremely confident". The results showed that users preferred the "Graph" and "Intelligibility" probe out of the four (Figure 4-20) and rated highly their ability to control their home heating systems using these probes.

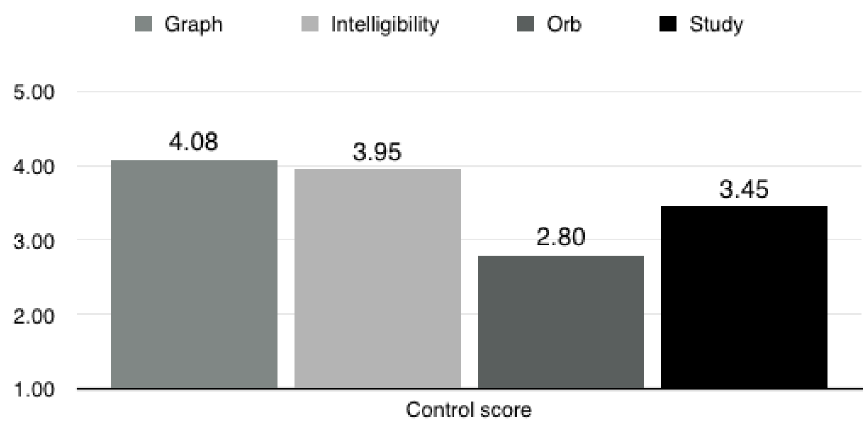


Figure 4-20 illustrating the perceived level of control if the interfaces were installed in participants' homes (1 – No control, 5 – complete control)

In addition, answers to users' perceived ability to accomplish their aims showed similar results (Table 4-13).

	Graph	Intelligibility	Orb	Study
Scenario 1	3.6	3.4	3.0	3.0
Scenario 2	3.2	3.4	2.6	2.6
Scenario 3	3.5	3.1	2.3	2.8

Scenario 4	3.6	3.3	2.8	2.8
Total	3.48	3.30	2.68	2.80

Table 4-13 Results of aim accomplishment question (1-Failed to accomplish my aim, 4-Successfully accomplished my aim)

These results suggest that large amounts of feedback on user actions and system functionality, combined with high granularity of control could be used in interfaces to enhance users' experience of control.

However, it is worth noting that when this data was cross-referenced with user-reported aims and data from the screen-captures, some interesting observations emerged. In order to analyse the participants' aims, their answers to the question "What was your aim in interacting with the interface?" were assigned a category of "change" or "monitor", both of which were "inclusive" actions, meaning that they included the heating system and interface. The other two routes of action – personal and environmental were not tested as the experimental methodology did not allow for this. The "change" category referred to Interaction Case 4 where the users highlighted a desire to alter the environment. This was deduced from participants' answers including phrases such as *"I wanted to make [the room] a little bit colder", "switch off unnecessary heating", "cool down the study"* or *"see if I could get the heating to come on"* etc. In contrast, the "Monitor" category referred to Interaction Cases 2 or 3, or additionally Interaction Case 1. In a real life setting, the enquiry-response action would not be expected to be taken in Mismatch A, but the experimental setting provoked this behaviour from the participants. The "monitor" category was used for phrases that expressed following the enquiry/response route on Figure 3-10. These 'passive' interactions had the aim of obtaining information such as *"check the temperature in the room I was", "to work out which rooms had the heating on", "wanted to see how the temperature is"* or *"make sure that I would still have some heating in the kitchen"* and so forth. In other words, focus was on obtaining knowledge rather than inflicting change. Additionally, an "Interface" label was used. This label was assigned when the aim was focused on the interaction with the interface, for example *"To work out what it did. And how it worked"* or *"trying to find out what the light means"*, but this was treated separately from the first two.

Figure 4-21 highlights the differences between reported actions and screen-captured actions. Users reported less aims in changing the system state than they actually did. In other words, they often reported their aim to be monitoring the system, but in reality they altered the system state. This could have been due to an error in coding or the fact that users' aims were tied to the room in focus, while 'peripheral' rooms i.e. rooms that the scenario did not concern, were altered to match the scenario. For example, if the scenario stated the user was in the kitchen, participants often turned down the temperature in the other rooms. Although interesting in themselves, if these facts were not true, it meant that users' perceived levels of control may have been misguided by the interface's poor feedback.

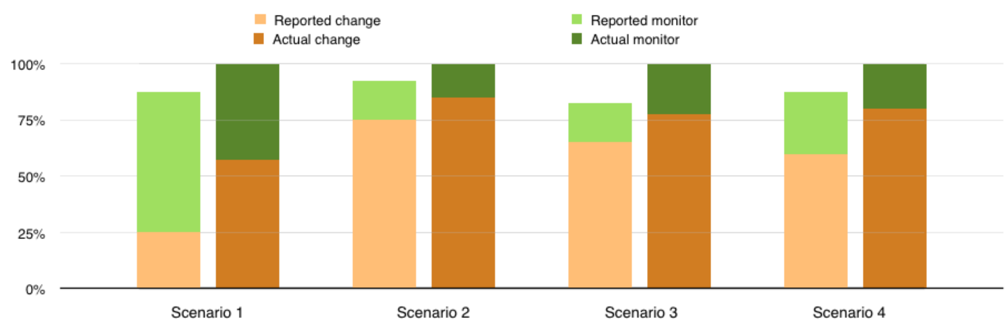


Figure 4-21 illustrating user actions from screen-capture in comparison to self-reported aims

This related to the element of feedback and system state discussed above, in that the user needed clear feedback on the overrides they applied to the automation and the consequences of their actions. A long delay in receiving feedback from the environment could mean that the users' overrides were contrary to the best operation of the system or to the users' intentions. However, the results highlighted in Figure 4-21 also showed that with the exception of Scenario 4 (Mismatch Case B - Uncomfortable but succeeding), the proposed actions in response to expectation mismatches held true. These results suggested that while interface design can enhance users' perceptions of control, it must use correct feedback on actions to prevent mismatches between actions users assumed were taken and what was taken in reality.

4.3.3.3 User experience of understanding

User's understanding of the heating system was also analysed using multiple data sources. Firstly, the users were asked SAGAT-type questions to assess current and future system state. The results showed that the qualities of detailed, granular information at the point of request as well as explanations enhanced the users' ability to correctly assess the heating system state, as seen in Figure 4-22.

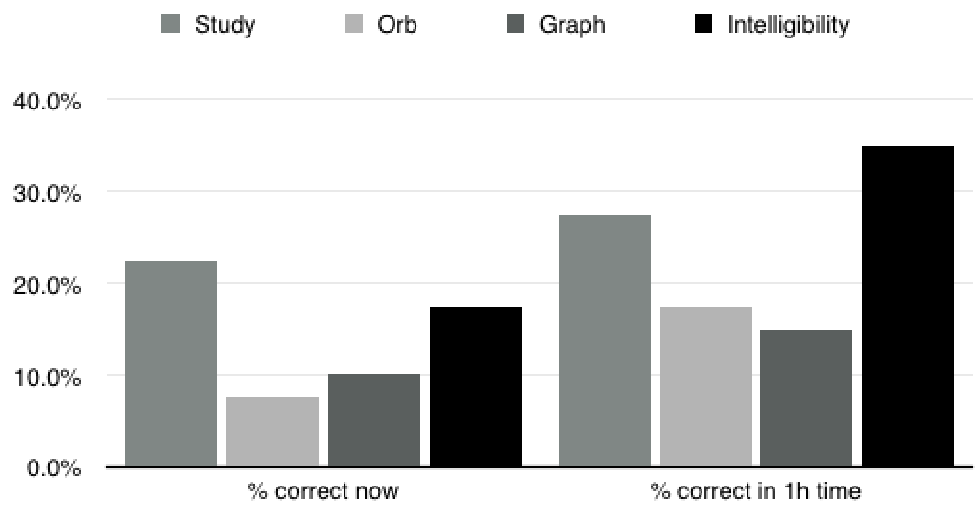


Figure 4-22 illustrating % of correct answers to system state currently and in 1 hour from now

This was also attributed to the interface's context specificity – the "Intelligibility" probe was more tailored towards showcasing conditions in a single room, but made it very easy to access all rooms. Interestingly, the results showed a trend towards interfaces with a balance in context specificity to be best at establishing context awareness. The results contradicted a common standpoint that a wider overview establishes a better awareness of system state. In comparison, the Intelligibility interface was seen as the best for inferring future system state with an accuracy measure of 35% in answers regarding future questions in the room. Meaning users were most able to correctly infer future system state and environmental conditions from this probe. This was attributed to the interfaces ability to give explanations as to what it is doing in response to its knowledge of the situation. It is worth noting that both percentages for current and future system state were relatively low, peaking at 35%. This was deemed to be due to people's misconception of whether maintaining temperature meant that heaters were on or off. It was therefore important for interfaces to communicate this measure in addition to temperature.

After each scenario users were also asked why they thought the heating system was behaving the way it was. Figure 4-23 highlights the total number of correct and incorrect reasoning responses received from a multiple-choice question by each probe interface. Users could choose as many reasons for system functionality as they wished, causing some probes to get more responses than others.

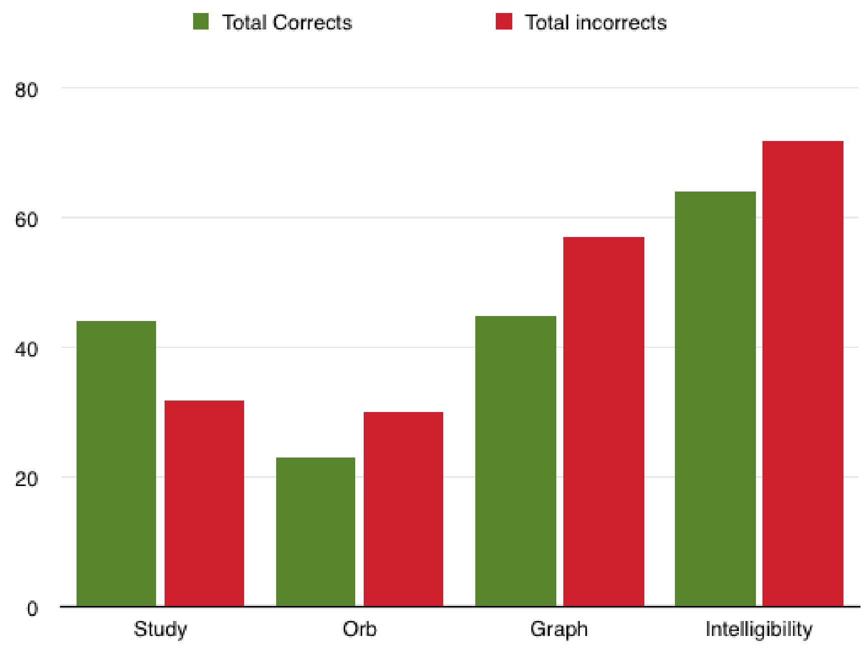


Figure 4-23 highlighting the total number of correct and incorrect reasoning responses obtained by 4 interfaces

Interestingly, the “Intelligibility” interface that received the highest number of correct answers also received the highest number of incorrect responses, which indicates that users expected the system to know more than it did from the information that it provided. This was likely to be caused by the wording of explanations in the interface. Furthermore, when asked about how the heating system made its decisions about when and what temperature to heat to, 80% of participants failed to outline both of the correct two answers – predictions of presence based on historic data and preferred temperature form previous interactions. All participants’ answers indicated some knowledge of the system adapting itself to their presence and when over the course of the day this occurred, but only two mentioned target temperature selection. Table 4-14 highlights all answers provided and also details participants’ answers to the second part of the questions – how participants knew what they outlined.

Participant	What factors the participant thought heating system based its functionality on and how they knew this
P-1	Based on location in the house because they noted an interface adjusting itself as it expected them at a later time
P-2	Historic data and presence from guessing and feedback from Intelligibility probe.
P-3	Whether somebody was in the room or not, deduced from the fact that different rooms were turned off at different times
P-4	When somebody was going to be in the room and historical data, from graphs and explicit explanations from interfaces.

P-5	The system could guess when you were in the room, and they noted not knowing, but guessing their response based on what they saw in the interfaces.
P-6	System operated based on time of day, deduced from the interfaces already adjusted to observable routines in the system.
P-7	Based on the room they were in and the time of day. The user guessed they had acquired this knowledge from the interfaces, but they were not sure
P-8	Previous preferences set in the interface and their past behaviour, which the user deduced from logical reasoning, hypothesising that the system must have logged their previous interactions with it.
P-9	Their preferred temperature and their location at the time. The participant assumed this because these would be the factors they would focus on when building such a system.
P-10	They guessed it was from motion sensors recording their location, which they deduced from the explanations the Intelligibility interface gave.

Table 4-14 showing participants' paraphrased answers to questions regarding heating system functionality

The answers to the second part of the question showed that this knowledge was built from interactions with the interfaces with several participants highlighting the Intelligibility interface in particular as it told them outright why certain things happened. Interestingly, many participants deduced the system behaviour from overall behaviour trends in the interfaces. By this it was meant that rather than getting a specific cue towards something triggering behaviour, they analysed the system's behaviour over time and deduced that it replicated their behaviour in the house. Additionally, it is worth noting the low levels of confidence in the answers given by the participants. Many used terms such as *"I guess"*, *"maybe"* and *"I don't know"*, indicating that they were not entirely sure how the heating system behaved from their interactions. These results showed that users more familiar with such systems or data representations are able to learn an automated heating system's functionality more independently, however, it would be the interface's job to explicitly teach its users to know its capabilities.

These results show that interfaces for smart home heating systems should be designed with care to unambiguously indicate the system state for both the past and present, as well as the future. In other words, the 'snapshot' way of presenting system state, conventional to existing heating systems, is not sufficient for quasi-autonomous or autonomous systems. Qualities of probes that enhanced this feedback involved explanations of activity or temperature trends. In the latter case, temperature trends should be augmented with those of heater state.

4.3.4 Discussion

The presented results provided an insight into the types of interactions that could prevail in the use of an automated home heating system, as observed through a wizard-of-Oz methodology and interpreted through the conceptual framework presented in section 3.5.1 Conceptual model. From this it was concluded that:

- User override needs to be provided in a manner that displays visibility of the actions, the precision of alterations, the granularity and specificity of temperature alterations, the effectiveness of overrides, and the implications for heater state.

- Appropriate feedback on users’ actions and overrides needs to be provided to prevent misunderstanding of the consequences of their actions and to enhance their perception of control over their own forward-planning as well as the system’s actions in the future.

- Thermal feedback has to be provided in a meaningful way that allows users to understand the current situation as well as trends where appropriate, while ensuring that colour is used unambiguously.

- Different layers of data should be used to facilitate a suitable amount of context specificity, allowing users to gain insights into automation, system state and system reasoning at key points during interaction.

- At lower data layers, the system needs to make its capabilities and reasoning clear to the user.

It is worthwhile discussing the implications of each design dimension individually and how these can combine to provide a user experience rich in intelligibility at different times during the user’s interactions.

Figure 4-24 identifies where the mismatches discussed in Table 4-7 are positioned in the conceptual model and which action routes the user might take based on these mismatches. From users’ interactions, it emerged that people observe, at different times, their home as either a single unit, or as collection of individual rooms. In the “All OK” and “Uncomfortable but succeeding” mismatch (A & B on Figure 4-24, respectively) the interface needs to display “overview” qualities. This means that it must display information about all the rooms in a top-layer manner – users require information about the environmental and system state in each room, which would allow them to establish an a-priori understanding of what is happening in the house as a whole. System state should include temperature, any automated temperature adjustments, and heater state. In the overview layer, it was not necessary to present users with information about reasoning or how the system knew anything. At this stage, the heating system could be interpreted as a black box. The focus should be on providing users with a view on “what is going on in the house”, with the use of colour being utilised to enhance this communication. However, it is paramount that the cognitive associations in the user’s mind are considered. For example, if the colour red is used, it needs to be understood that for users it can mean either hot / warm or off. The respective opposites of the colours would be blue and green. Colour should thus be used with caution and augmented or explained with icons or other identifiable elements.

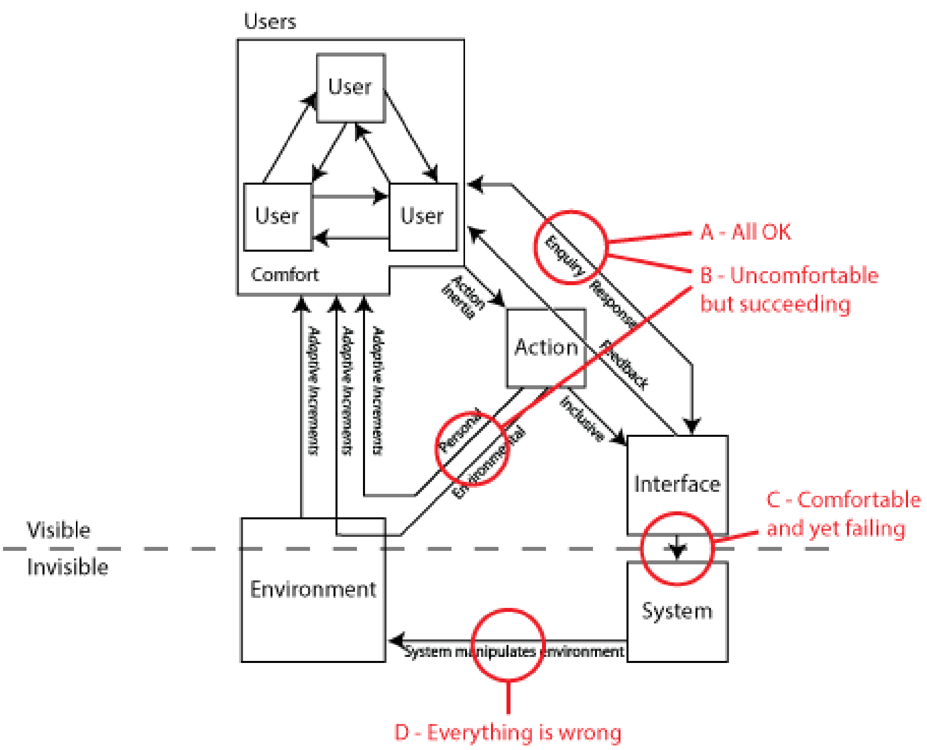


Figure 4-24 Proposed model with mismatch routes

If, on the other hand, users are experiencing mismatches whereby the system is deviating from established comfort (“comfortable and yet failing” in Figure 4-24) or failing to provide comfortable conditions (“Everything’s wrong” in Figure 4-24), a more in-depth interaction will be required. In those cases, users are likely to make alterations to the current or future system state. For them to be able to do so, they require more detail, lower-layer information context-specific to that room. At this layer the interface should communicate all three elements of intelligibility (what it knows, how it knows it and what it is doing about it) explicitly, as well as why it has chosen to behave the way it has. System state should provide feedback regarding temperature and heater state into the past and future. This communication should reveal the system's logic to the user in a meaningful, human-understandable language. Any graphs or other visual aids should be well explained so that the user can impose informed change on the system. Explicit feedback that users' changes have been implemented should be given, as thermal feedback will be slow over time.

4.4 Conclusions

The work presented in this chapter has provided an interesting insight into the user experiences of an automated home heating system control interface at a conceptual level. However, as highlighted in Chapter 0, in order for a truly meaningful insight to be gained, research must be conducted in the wild – in real homes. The subsequent chapters focus on the design and implementation of such a heating system in situ.

5 PROPOSING A NEW CONTROL ALGORITHM

This chapter combines knowledge from the previous chapters and focuses on the logic behind the provision of spatiotemporal automated heating control. A novel control algorithm is presented, discussed and assessed in an emulated environment regarding its fitness for purpose in providing a spatiotemporal heating solution that reduces energy use without compromising on user thermal comfort.

5.1 Introduction

In the literature chapter above the need for a control system that could ensure users' thermal comfort expectations are satisfied while maximising energy efficiency was demonstrated. Thermal comfort in this case meaning that the occupant experiences a sensation of (close to) thermal equilibrium with the prevailing conditions in the space they occupy in accordance with their thermal preference and energy efficiency referring to the delivery of these conditions at minimal energy usage. For a heating system to achieve such goals it needs (i) to account for individual differences in occupants' thermal preference, (ii) to demonstrate an ability to adjust itself to its context, (iii) to operate at relative autonomy to limit energy use in heating unoccupied spaces, and (iv) to facilitate an appropriate degree of manual over-ride for occupants. The control algorithm of such a system would therefore need to include components aimed at: (**a**) capturing and predicting occupant presence in the space, (**b**) including occupants' thermal feedback and adaptation in thermal set-point calculation, and (**c**) adjusting heating operation through optimum start, to reflect the thermodynamic characteristics of the space within which it operates. In addition, such an algorithm could be enhanced by a nudging mechanism that utilised the occupants' thermal feedback to develop an understanding of the range of temperatures at which the occupant feels comfortable and subsequently to adjust the heating set-point temperature to the lower boundary of that range, thus limiting the amount of energy required without compromising on comfort. This researcher's interpretation of an algorithm with these qualities is presented below.

5.2 Algorithm

This research proposes a spatiotemporal heating control algorithm, meaning that it aims to deliver energy saving by matching heating periods with occupants' presence in both space and time, and according to their spatiotemporal thermal preferences. The algorithm operates by predicting future presence probabilities (steps 1-3 in

Figure 5-1) based on past presences for that weekday (addressing item (**a**) above). Predicted presences would thereafter be provided a temperature set-point (step 4 in

Figure 5-1) based on occupants' thermal sensation feedback relating to previous set-points (addressing item (**b**) above). Two variations of the algorithm are presented, differing in the manner in which the set-point calculation performed. A 'maximise comfort' strategy calculates a temperature at which the occupant is predicted to experience thermal neutrality on the ASHRAE 7-point scale (ASHRAE, 1966), while the 'minimise discomfort' strategy opts for the 'slightly cool' sensation. The latter is considered the lower boundary of the occupant's thermal comfort range that would not cause discomfort. Presence prediction and temperature set-points for those presences then allow the algorithm to pre-heat the room (steps 5 & 6 in

Figure 5-1) for impending presence (addressing item (**c**) above). The preheating activity utilises an optimum start algorithm that initiates activation of the heaters so that the target set-point temperature can be reached by the time presence is predicted to start. The optimum start algorithm continually updates itself to reflect the physical characteristics of the space it occupies as well as other factors such as seasonality. In addition, the algorithm accounts for occupant-dependant departure schedules, referring to extended, abnormal periods away from home such as holidays or other absences (establishing quality (**d**) in algorithm operation). This ensures the algorithm resumes normal operation following this planned interruption.

This functionality of the algorithm is summarised in

Figure 5-1 followed by a more detailed explanation of each key feature.

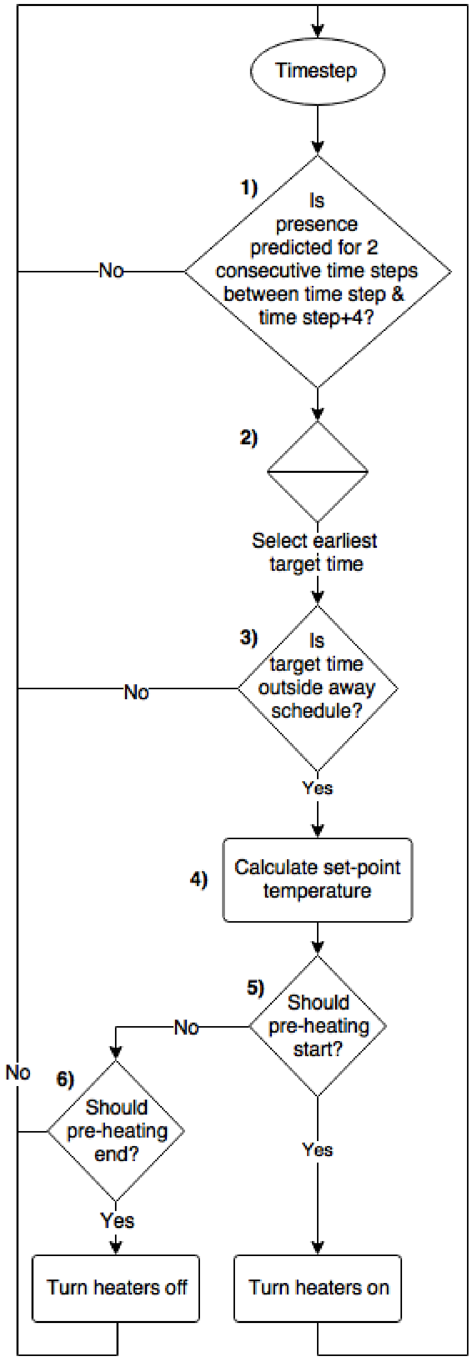


Figure 5-1 depicting the functional flow of the proposed control algorithm

At step 1) in

Figure 5-1 the algorithm calculates presence probabilities for the current and four subsequent 10 minute time-steps. This calculation is performed using an exponentially weighted running mean (1) (Spider financial, 2015), which uses inputs from previous calculations for that weekday and the measured presence from the last occurrence of that weekday. Weekday differentiation is utilised to accommodate common changes in people's activities between weekdays and weekends, as well as between individual days within these work pattern-orientated categorisations.

$$P_i = (WP_{i-1}^2 + (1-W)PM_{i-1}^2)^{1/2} \tag{1}$$

The presence probability *P* for current day *i* is calculated using previous predictions, measured presence *PM*, and a weight *W* of 0.8. By using previous calculated predictions in this way, the need to store the entire series (or some subset thereof) is avoided, therefore limiting the number of data lookups and calculations that the algorithm has to perform in comparison with other exponentially weighted running mean expressions. The algorithm performs this calculation for current time step as well as four time steps into the future, aiming to identify 'meaningful presences'. These 'meaningful presences' are defined as two consecutive time steps where $P \geq 0.4$, which represents a threshold between predicted presence and absence, with predicted presence probabilities below this value being treated as predicted absence. The value of 0.4 was established during a calibration exercise. In addition, four consecutive time steps was chosen as this equates to 40 minutes. This process allows the algorithm to predict far enough into the future to have sufficient time for preheating. Weighting the use of previous predictions and measured presence allows the algorithm to stay up to date with the latest changes in behaviour, without being overly influenced by erratic and non-repeating behaviour, or indeed by outdated historic data. Consider two cases – firstly, an occupant of the household started working from home half the days of the working week. The algorithm needs to learn this new behaviour, but, must be robust enough not to be too influenced by an occupant that stayed home sick for a few days. Secondly, let us consider a case where occupants of the household moved out and new occupants moved in. In this scenario, the algorithm must progressively learn the presence and temperature preferences of the new occupants. The memory decay introduced with an exponentially weighted running mean ensures that such nuances are accounted for, as the algorithm learns new and reduces the importance of old behaviours.

When such instances are identified, the algorithm (step 2 in

Figure 5-1) sorts them and selects the earliest occurring meaningful presence, utilising this as the target time for which to achieve the desired conditions. It performs checks (step 3 in

Figure 5-1) to ensure this does not fall within any away schedule that the occupants may have listed to notify the system of their absence from the dwelling. If the target time is unaffected by away schedules, the algorithm proceeds to calculate a preferred set-point temperature for that room in step 4 in

Figure 5-1. Set-point calculation utilises occupant thermal sensation feedback votes on the ASHRAE 7-point scale (ASHRAE, 1966), in conjunction with coincident measured temperature data. All provided thermal comfort votes are retrieved and the average of these temperatures calculated based on the Griffiths (1990) method, which states that for every 0.5 point change in thermal sensation on the ASHRAE scale, there corresponds a 1°C change in temperature, meaning, the sensation votes and temperatures for which the vote was given are adjusted to achieve the preferred sensation and the average temperature at which this sensation would be felt. At this step the algorithm could utilise either the maximise comfort or minimise discomfort heating strategy. The former would cause the algorithm to adjust votes to a thermally neutral sensation and the latter to a ‘slightly cool’ sensation, requiring less heating.

Subsequently, (step 5 in

Figure 5-1) the algorithm determines whether pre-heating should commence, switching heaters on if the current time exceeds or equals the optimum heating start time t_{start}, thereafter re-starting the whole process.

(2)

$$t_{start} = t_{end} - \frac{T - T_{now}}{S}$$

Here t_{end} corresponds to the predicted end of the preheating, which also coincides with the start of the forecasted period of presence, while T_{now} is the current temperature, T is the set-point temperature and S is the slope. Slope captures the rate at which the heating system in any room could increase the temperature in that room, and is (re-)calculated (step 6 in

Figure 5-1) following the pre-heating period as follows:

(3)

$$S_i = W * S_{i-1} + (1 - W) * \frac{\Delta_T}{\Delta_t}$$

The new slope S_i is calculated using a weighted W (0.8) value for the previous slope S_{i-1} and the changes in time Δ_t and temperature Δ_T that occurred during the pre-heating period. This is a linear simplification (Levermore, 2000) of more complex optimum start algorithms, such as the one proposed by Birtles & John (Birtles and John, 1985). This re-calculation of slopes enables the algorithm to adapt to changes (influencing heat storage and time-taking heat gains and losses) that might impact future optimal start times.

Following pre-heating, the algorithm enters a state of monitoring, which causes the heating to maintain the set-point temperature as long as occupant presence is detected. The set-point temperature is also maintained for one time step following the end of preheating but without occupant presence to account for minor variance in occupant presence behaviour. This state was seen as a post-process for the algorithm that maintained its outcomes during occupant presence and prevented further pre-heating activities from occurring while the set-point temperature was being maintained in order to prevent the slope calculations from being skewed due to pre-existing elevated temperatures.

The rest of the chapter presents the testing of this algorithm's control logic in an emulated environment with regard to its four distinct qualities: a) occupant presence prediction, b) temperature set-point calculation from thermal sensation votes, c) utilisation of an optimum start algorithm to pre-heat rooms in response to these, and d) handling occupant-created away schedules and their effect on limiting energy use. In addition, its energy saving potential is assessed through comparison with a pre-determined schedule common for a programmable thermostat.

5.3 Methodology

A large variety of methods exist for testing or assessing an algorithm, or in its broader form – software (see Myers et al., 2004 for an example review) and indeed, many techniques such as code review and function testing the written software were implicitly performed while writing the code, this chapter is concerned with the broader functionality of the proposed algorithm. In order to assess that, it was necessary to allow it to convert a set of inputs to outputs and assess these. This could have been done in two ways – pilot deployment in situ or by emulation. The former would provide extremely useful data regarding both the algorithm as well as its technological manifestation, but would require a lot of resource for a small amount of test data and be affected by a multitude of extraneous variables affecting the output. The latter, emulation, would lack the ecological validity, but would provide means of simulating the algorithms operation for long periods of time. This was determined to be paramount at this stage and preferential, provided that input data representative of the real world was applied.

The fitness-for-purpose of the proposed algorithm was tested by. Prior to simulating the algorithm's control logic in an emulated environment, its code was calibrated for appropriate use of motion sensor data (intended technology in the deployment that followed these tests).

5.3.1 Code calibration

It was recognised that sensing motion was not an entirely accurate measure for inferring person's presence because people may be present but undertaking a relatively sedentary activity so that the sensor is unable to detect motion (there is none to detect) and infer correctly that the user is present. For this reason, a calibration exercise was undertaken to ensure the algorithm's configuration best reflected people's observed presence. The results of this exercise provided the meaningful presence value of 0.4 discussed above through reviewing the amount of observed presence that was detected by the sensors.

The calibration was conducted in two stages. Initially, a "presence check window" was introduced into the algorithm code. This window referred to a duration of time during which, if motion was detected again, two instances of motion were treated as a continuous presence. Six different check window sizes were tested ranging from 30 seconds to 180 seconds, increasing in 30-second increments. If motion was not detected again during the check window, it was assumed that presence ended after motion was last detected. To obtain test data, sensing equipment comprised of a Raspberry Pi computer combined with a PIR motion sensor was set up in an office with 3 individuals working on computers and seated at desks. While people moved in and out of the office on a regular basis, it was unusual for the office to be empty except during a lunch break. Based on this, the assumption was made that presence from first to last detection was constant.

The recorded office presence data spanned from 8:39 in the morning until 19:11 in the evening with a gap from 14:01 to 15:10 when nobody was present.

Figure 5-2 illustrates this time period in comparison to presence captured by selected check windows.

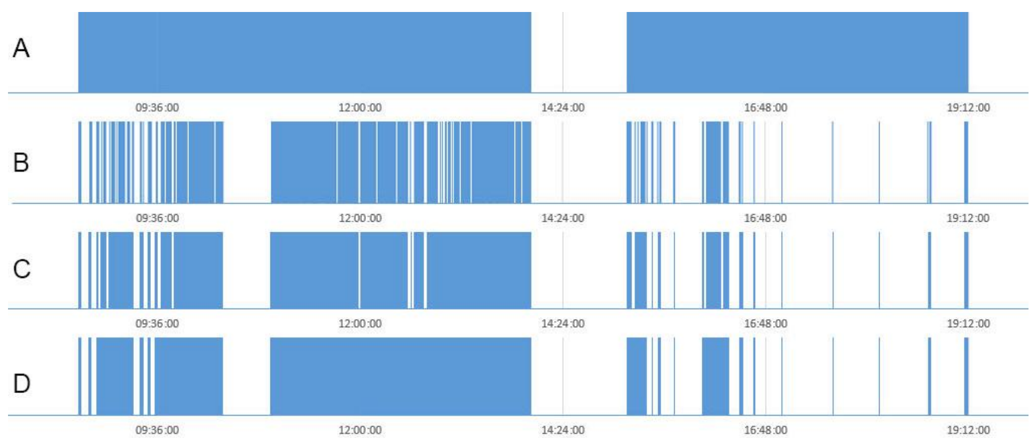


Figure 5-2 comparison of (A) actual presence, (B) no check window, (C) 120 second window, and (D) 180 second window recorded presence durations

It is worth noting that the motion sensor positioning was not ideal. The sensor was located in the corner of the office, where two rows of desks were positioned facing each other in the middle of the room. This meant that the sensor was behind two of the occupants and its vision obscured by computer screens for the remaining two occupants. This explained the lack of data in parts of the morning and in the second half of the day - relatively subtle motions of hands and upper body associated with working at a computer were out of sight for the sensor. This resulted in extremely low recorded presence in comparison to actual presence (15-55%). Despite this, the effectiveness of different check windows could be assessed from the recorded data.

The general trend was that the increase in window duration corresponded to an increase in the percentage of actual presence time covered by the sensor data. However, it was important to find a window size that captured a significant enough amount of presence while still accounting for occupants' dynamic mobility patterns. This meant that too long a window would 'join' too many instances of motion detection and not reflect real life presence correctly. It was important for the algorithm to be responsive enough to record absence accurately as well to maximise heating efficiency. Figure 5-3 plots the check window percentage against actual presence and the required queries and illustrates the appropriate window size selection process, based on the dual objectives of accurately capturing presence whilst avoiding unnecessary connections (queries) between sensing equipment and data repository in a remote database.

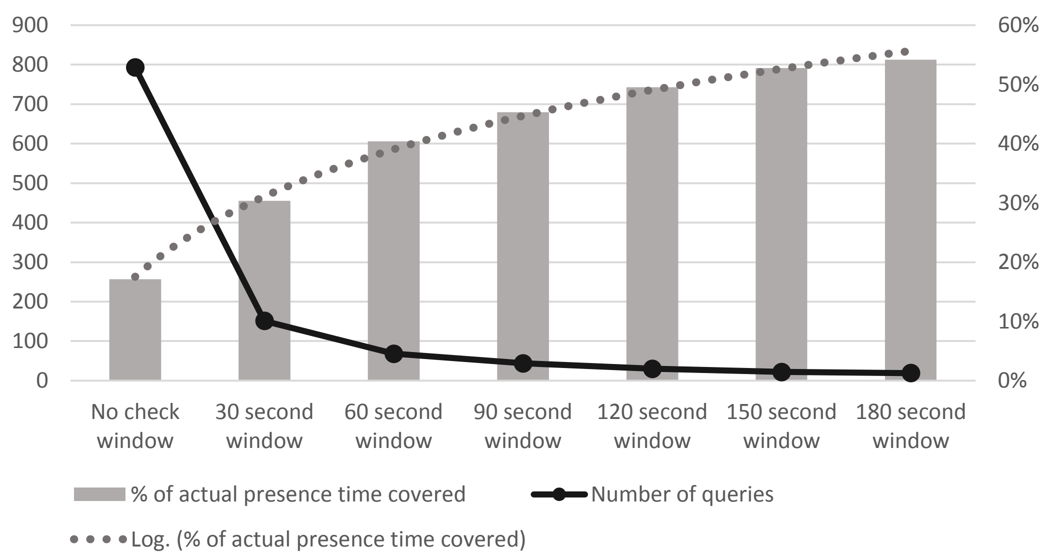


Figure 5-3 illustrating the % of actual presence covered by different check window sizes and the number of queries required for logging that data.

The percentage of correctly recorded presence time is asymptotic, with little improvement beyond 120 seconds, beyond which there would be an increased risk of failure to adequately detect presence dynamics (arrival/departure times).

Consequently, 120 second window was deemed most fit-for-purpose and selected for testing in a real setting.

To increase the ecological validity[1] of calibration, the equipment was also installed in an open-plan kitchen/lounge of a 2-person household. The occupants of the house were asked to manually record the times they entered and exited the room, just as the sensor should over the course of a day. Supported by literature (Page et al., 2008) and the first calibration activity, a 2-minute check window was deployed in this test.

Figure 5-4 plots the differences in manually recorded presences in a room and those recorded by sensors using a 120 second check window from the calibration exercise conducted in a 2-person lounge. Similarly, there were periods in the late afternoon where occupants were present but the sensor did not record them. This was again due to the placement of the sensor – it can be speculated that occupants were watching TV or performing sedentary activities on sofas that were the furthest location from the sensor, causing slight posture changes to be missed.

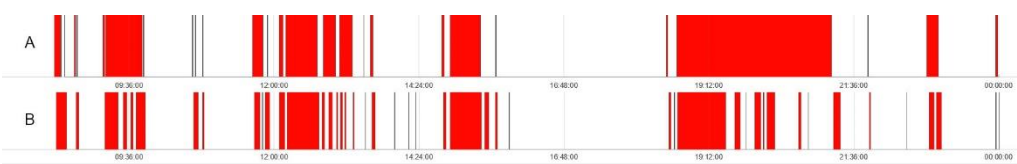


Figure 5-4 displaying the user-recorded (A) and sensor recorded (B) presence data across a sample day

The initial activity showed that with a 120s window, the sensing equipment was only capable of recording 49.5% of total presence. Deployment of the equipment in an ecologically valid setting showed that this number would be lower still. Based on this data, it would be unrealistic to assume that he algorithm would

[1] By ecological validity it is meant that a phenomena observed in a hypothetical situation also proved true when applied in the real world setting.

achieve around 80% probability of presence. Therefore, it was assumed that around 50% of presence would be captured and subsequently, a 40% probability of presence was sufficient to merit heating, causing the 0.4 target in combination with the 120s window to be chosen for the algorithm. If different presence capture technology was intended to be used, these values should also be revisited.

5.3.2 Simulation

The algorithm's functionality was thereafter assessed by simulating its output in an emulated environment. The industry standard EnergyPlus (Energyplus, 2016) software was utilised for simulations and coupled with the Building Control Virtual Test Bed (BCVTB) software (Simulationresearch, 2016), which was used as a graphic interface to implement the algorithm's functionality. This setup allowed for different house models and algorithm configurations to be tested with ease.

Since the focus of this exercise was merely to validate the algorithm's logic (its fitness for purpose) prior to a real-life deployment only a single room was simulated rather than a whole building. A living room was chosen for this exercise as it was considered to offer a variable presence profile due to the different activities performed in that space. Four room configurations in total were used, representing two different house types (a purpose-built flat, and a Victorian house) and two different heating system types (electric heating & central heating). Table 5-1 below summarises the differences in the modelled rooms between the two house types and Figure 5-5 details their geometry and outer wall cross sections.

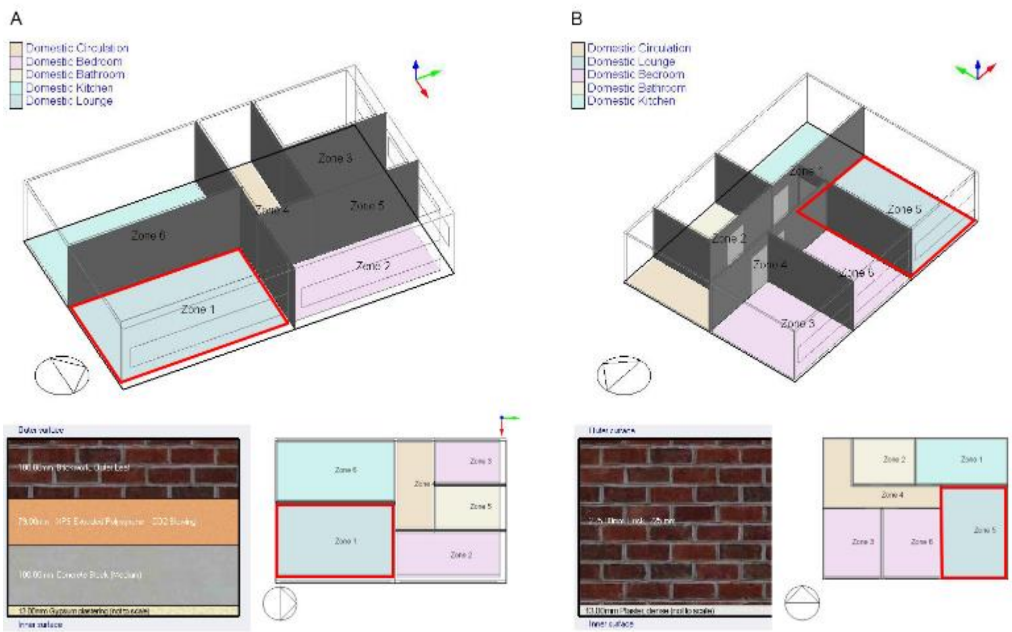


Figure 5-5 Layout of modelled houses (A – Modern flat, B – Victorian house), simulated rooms highlighted with marker (diagrams are not to scale in comparison to each other)

Characteristic	Modern Flat	Victorian house
Volume	43.17 m^3	44.86 m^3
Floor area	17.27 m^2	17.95 m^2
Window area (Cardinal direction)	3.53 m^2 (E)	2.34 m^2 (S)
Glass U-value	3.004 W/m^2-K	5.827 W/m^2-K
Exterior wall area (Cardinal direction)	13.65 m^2 (E)	9.25 m^2 (S)

Exterior wall U-value (with film)	0.355 W/m^2-K	2.152 W/m^2-K
Annual Infiltration heat removal	3.633 GJ	4.320 GJ

Table 5-1 Comparison of modelled rooms

These models are of two houses in Nottingham, UK with one occupant simulated for each. In order to provide a representative depiction of the occupant's presence in the room, United Kingdom 2000 time use survey (TUS) data (Gershuny et al., 2011) was integrated, which describes 20,981 people's activities in diary format across the day in 10-minute time steps, was cleaned to eliminate individuals younger than 18 years, wrapped to match simulation start time of midnight (TUS diaries started at 4am), and grouped by weekday. The data was thereafter filtered to have activities that the user reported to take place at home, and were likely to take place in the lounge. These included all reading-related activities, TV and video, radio & music, hobbies (including IT, arts etc.), socialising with household members, and household management using the internet. For each 10-minute time step of every weekday, the Bernoulli process was utilised to assign an occupant as present or absent.

The simulation models used an ideal loads HVAC system, which allowed for the performance of the algorithm to be tested without the need to model a full HVAC system and specify all air loops, water loops, etc. The component only required zone controls and zone equipment configurations. The ideal loads system was modelled in two configurations to reflect heating systems of differing capacities – one to simulate an electric convector heater (limited at a capacity of 1kW zone sensible heating power) and another to represent a central heating system three times as powerful (3kW capacity). Without these limits, the ideal loads system would provide heating of infinite capacity, making it impossible to realistically assess the algorithm's heating control output. The simulation used Nottingham, UK weather data and was run from first of January for 180 days (matching the estimated deployment time for the succeeding field trial) in order to test the algorithm's fitness for purpose.

	Process referred to	**Input data and simulation process**
Presence	Algorithm calculating the probability that a user is in the room, based on previous predictions and recorded presence.	An initial value of 0 for presence probability and recorded presence
Slope	Calculation of a slope value that is used in the optimum start algorithm to predict when heaters needed to be turned on in order to reach a desired temperature by a desired time.	An initial value of 1 was used for subsequent adjustment by the algorithm.
Temperature set-point	Effects of user-provided feedback on thermal sensation votes for set-point temperature	An initial value of 10°C was used. This was below anticipated values but not extremely so as to influence the calculations in a significant way. Vote casting was simulated using the SCATS data

	Process referred to	Input data and simulation process
		of thermal sensation votes provided in (Nicol and McCartney, 2001). Vote simulation was performed by probability sampling based on the vote probability distribution that corresponded to the current observed temperature in the SCATS dataset.
Away schedules	Users detailing periods for the system when they are away from the building to have heating turned off.	Two away schedules were built on days 19-21 and 113-119 to simulate the occurrence of a weekend and a week away from home.

Table 5-2 describing the, input assumptions for the four tested aspects of the control algorithm

A control configuration was also included that utilised Energy Star recommended thermostat settings for a programmable thermostat (Energy Star, n.d.). The implemented settings utilised an occupant presence schedule between 6am-8am and 6pm-10pm with a 21°C set-point temperature and 16°C setback temperature at other times.

A total of twelve configurations were simulated, as illustrated in Table 5-3.

Configuration number	House	Heating system	Algorithm setting
1	Modern	Electric	Maximise comfort
2	Modern	Electric	Minimise discomfort
3	Modern	Central heating	Maximise comfort
4	Modern	Central heating	Minimise discomfort
5	Victorian	Electric	Maximise comfort
6	Victorian	Electric	Minimise discomfort
7	Victorian	Central heating	Maximise comfort
8	Victorian	Central heating	Minimise discomfort
9	Modern	Electric	Control configuration
10	Modern	Central heating	Control configuration

Configuration number	House	Heating system	Algorithm setting
11	Victorian	Electric	Control configuration
12	Victorian	Central heating	Control configuration

Table 5-3 illustrating all eight simulated configurations

5.4 Results

This section discusses the results from the evaluation of our four key algorithm features, regarding presence prediction, slope prediction, temperature set-point calculation, and incorporation of away schedules, and the final section covers energy saving potential of the proposed algorithm in comparison to standard programmable thermostat controller.

5.4.1 Presence prediction

Figure 5-6 depicts the algorithm predicted and observed TUS data presence profiles for all days for the Modern-Electric-Minimise discomfort condition and Figure 5-7 compares Wednesday profiles between all simulated conditions.

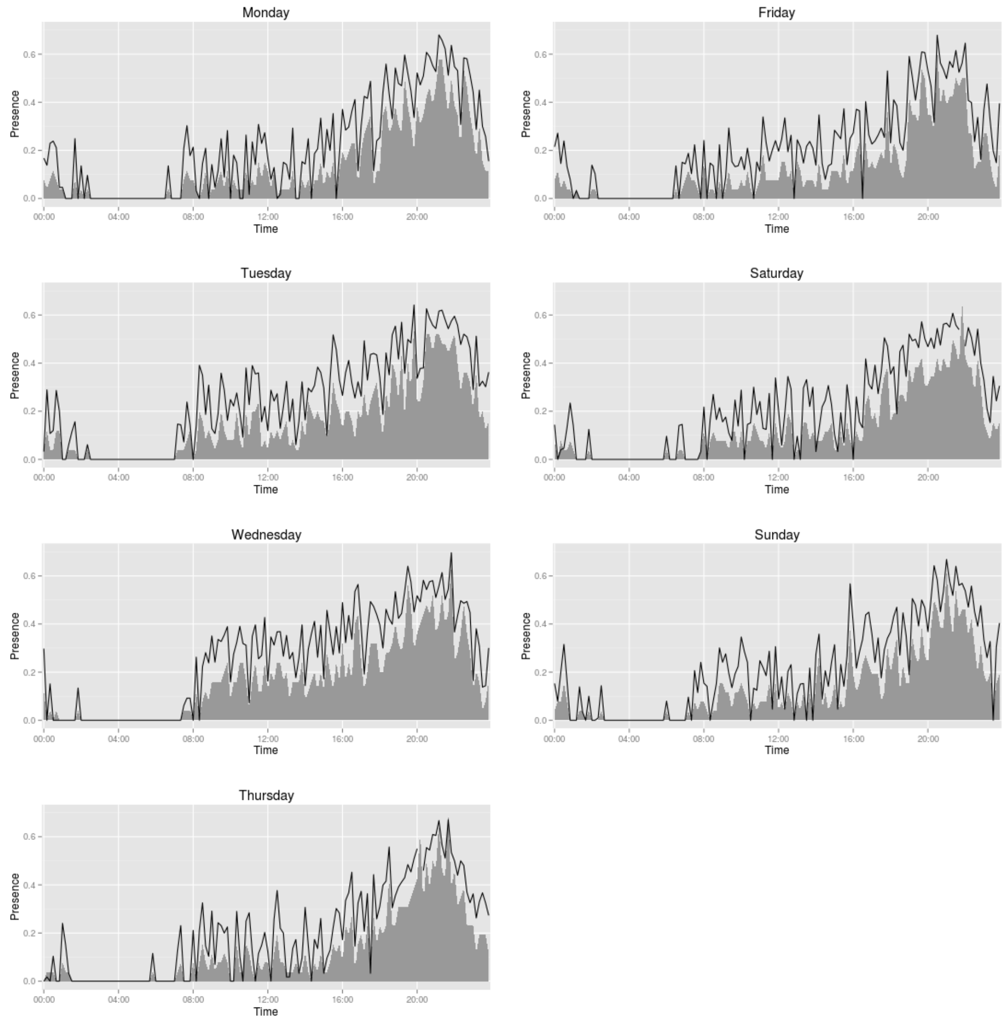


Figure 5-6 depicting average simulated (grey) and algorithm predicted (line) presence probabilities for all days in Modern – Electric – Minimise discomfort condition

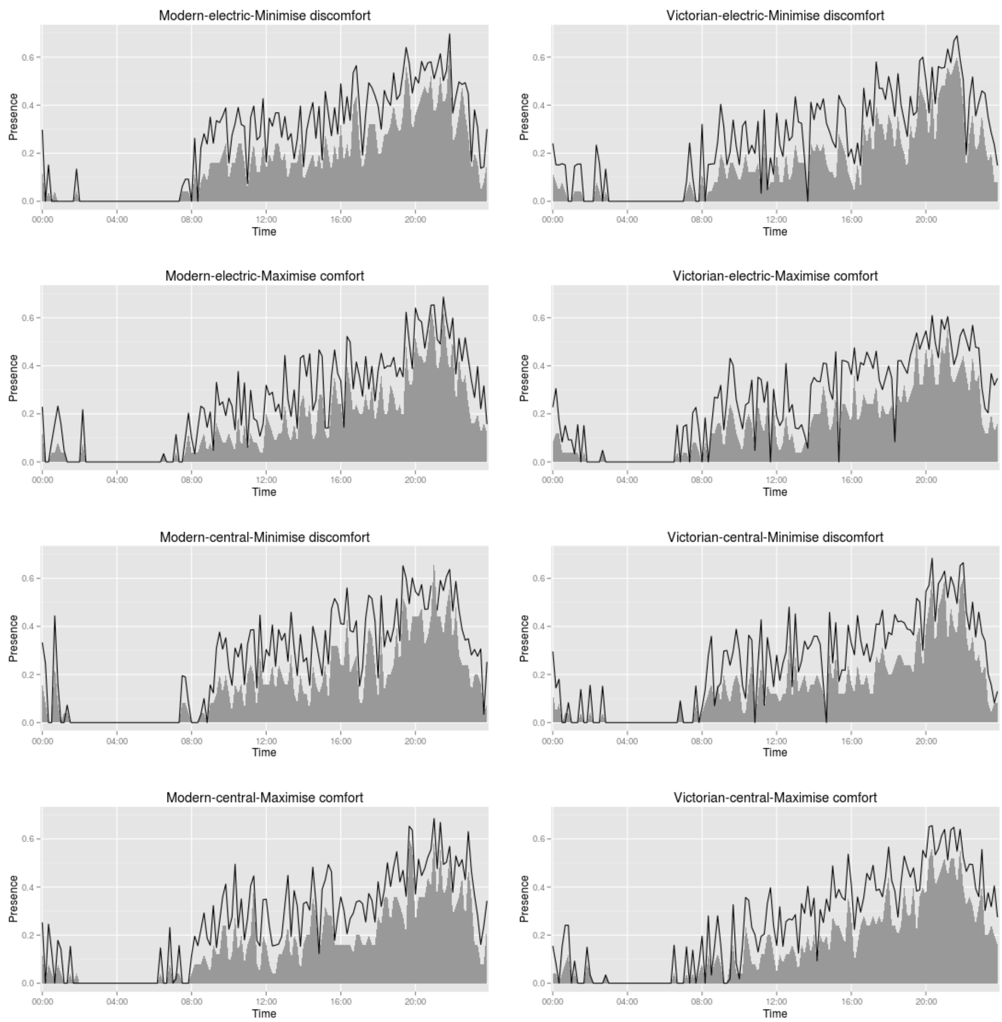


Figure 5-7 depicting average simulated (grey) and algorithm predicted (line) presence probabilities for all Wednesdays in all simulated conditions.

The algorithm was able to develop these profiles without it having been provided with any initial training data. First algorithm-scheduled heating periods occurred in the second simulated week, indicating that the algorithm was relatively quick to learn new behaviours. However, it is worth noting that this element was significantly influenced by the simulated presence value. Within the simulation software, when a person was present in the room, the observed presence value for that time step would be 1. It is speculated that real-life presence sensing apparatus would produce a decimal and thus elongate the training period to 1-3 weeks depending on the activity levels of users during presences and capabilities of any such equipment.

These results display a relatively good match between the shapes of observed and predicted presence profiles. From Table 5-4 it can be observed that he algorithm performed consistently between all conditions. However, evolvement of root mean square error for the Modern-Electric-Minimise discomfort condition through the simulated days (Figure 5-8) shows that no convergence occurred, meaning the algorithm did not re-train itself.

Simulation condition	**RMSE**
Modern - electric - Maximise comfort	0.3630
Modern - electric - Minimise discomfort	0.3716
Modern - central - Maximise comfort	0.3667
Modern - central - Minimise discomfort	0.3670
Victorian - electric - Maximise comfort	0.3686
Victorian - electric - Minimise discomfort	0.3701
Victorian - central - Maximise comfort	0.3672
Victorian - central - Minimise discomfort	0.3647

Table 5-4 root square mean error of presence prediction for all simulated conditions

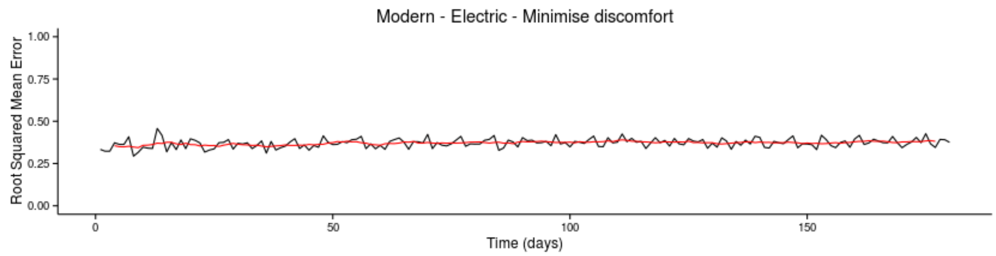


Figure 5-8 RSME (black) of predicted presence in comparison to observed for all days in Modern – Electric – Minimise discomfort condition, fitted with a 7-day running mean (red)

Furthermore, there appeared to be a consistent calculation error in the probability magnitude. This was assumed to have originated from the presence probability calculation's weighting towards previous predicted presences over previous observed presence (W in (1)) despite the fact that the algorithm adapts to observed data. The algorithm could thus be modified to use the weighting to compensate for any potential shortcomings in the measuring equipment and re-train itself adjusting the W value. For this to be effective, further hardware-specific calibration (of W and P-meaningful presence) may in addition be required.

The above results also suggest that the weighting introduced a reasonable memory decay. By that we mean that the algorithm gradually adjusted itself to the latest behaviour trends and presence predictions.

Furthermore, Figure 5-6 indicates that the algorithm successfully displayed an ability to formulate a distinct presence profile for each day of the week. While it is accepted that an individual weekday configuration would make the algorithm slower to adapt to abrupt behaviour changes (due to a relative lack of training data for this weekday as opposed to using more abundant data for all weekdays), it would also allow it to account for differences between weekdays and weekend presences.

From these results this researcher concludes that the proposed algorithm performs adequately in predicting users’ presence at home.

5.4.2 Slope

The slope refers to a variable that describes the rate of increase of the temperature in the room following activation of a heater. The variable was utilised and recalculated at every pre-heating instance. Figure 5-9 depicts a distribution of all calculated slopes for all simulated conditions evolving from an initial value of 1; the results indicating that the algorithm quickly (within 2-3 instances) adjusted the initial value to reflect the building's characteristics (position on the x axis).

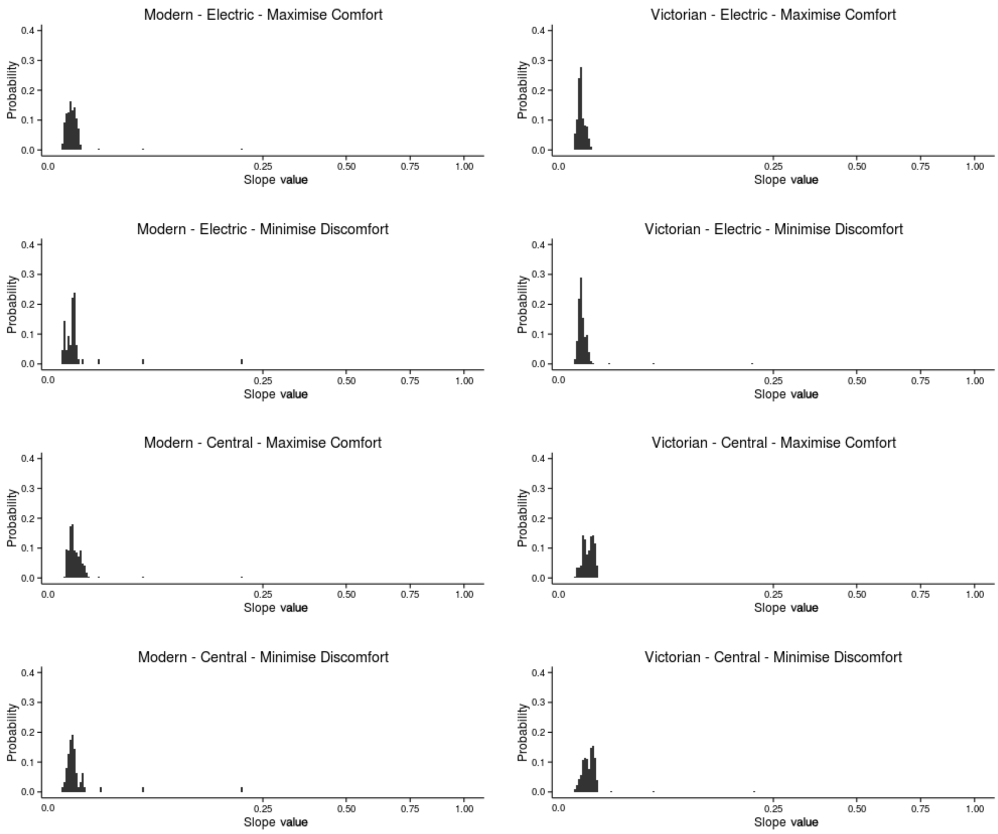


Figure 5-9 slope distribution for all simulated conditions

It is also clear from Figure 5-9 that slope values were rather stabile but not constant, meaning that the optimum start algorithm (3) not only adapts itself to the fixed characteristics of the building (its envelope and construction materials), but also to the day-to-day variation in heat flows within the room, affected by thermal gains from occupants, outdoor weather conditions, solar gains, leakage from adjacent rooms, etc.

These results show that the slope calculation and preheating functionality in the algorithm were functioning as expected.

5.4.3 Temperature set-point

Prior to any exploration of the results, it is important to note that the thermal sensation data used to simulate user voting was from an experiment assessing occupants' thermal comfort in the summer. This was likely to cause a lower preferred set-point than usually expected for winter months so that users may report to be comfortable at temperatures that would otherwise seem unlikely or difficult to obtain via heating during winter months.

Figure 5-10 highlights the thermal sensation distribution from simulated votes, as well as the cumulative distribution function of prevailing temperatures in the simulated environment throughout the duration of the simulation. Variations between conditions suggest that the simulation introduced an element of diversity in thermal preference, as different votes were submitted at similar temperatures. Furthermore, the algorithm succeeded in building a custom thermal preference profile for every occupant without any training data. A single value of 10°C was inserted at the start of the simulation to prevent calculations from failing.

As expected, temperature data (cumulative distribution function lines on Figure 5-10) suggests that prevailing temperatures throughout the simulation were around 1°C lower for maximise comfort (average 18.1°C) and 2°C lower for minimise discomfort (average 17.2°C) strategy than the control condition (19.8°C). The average votes given suggested that simulated occupants experienced similar levels of comfort with average votes of -1.1 for minimise discomfort, -1.0 for maximise discomfort, and -1.0 for control EnergyStar condition. The author attributes consistent average votes below 0 across all conditions to be the result of using a summer thermal sensation vote dataset.

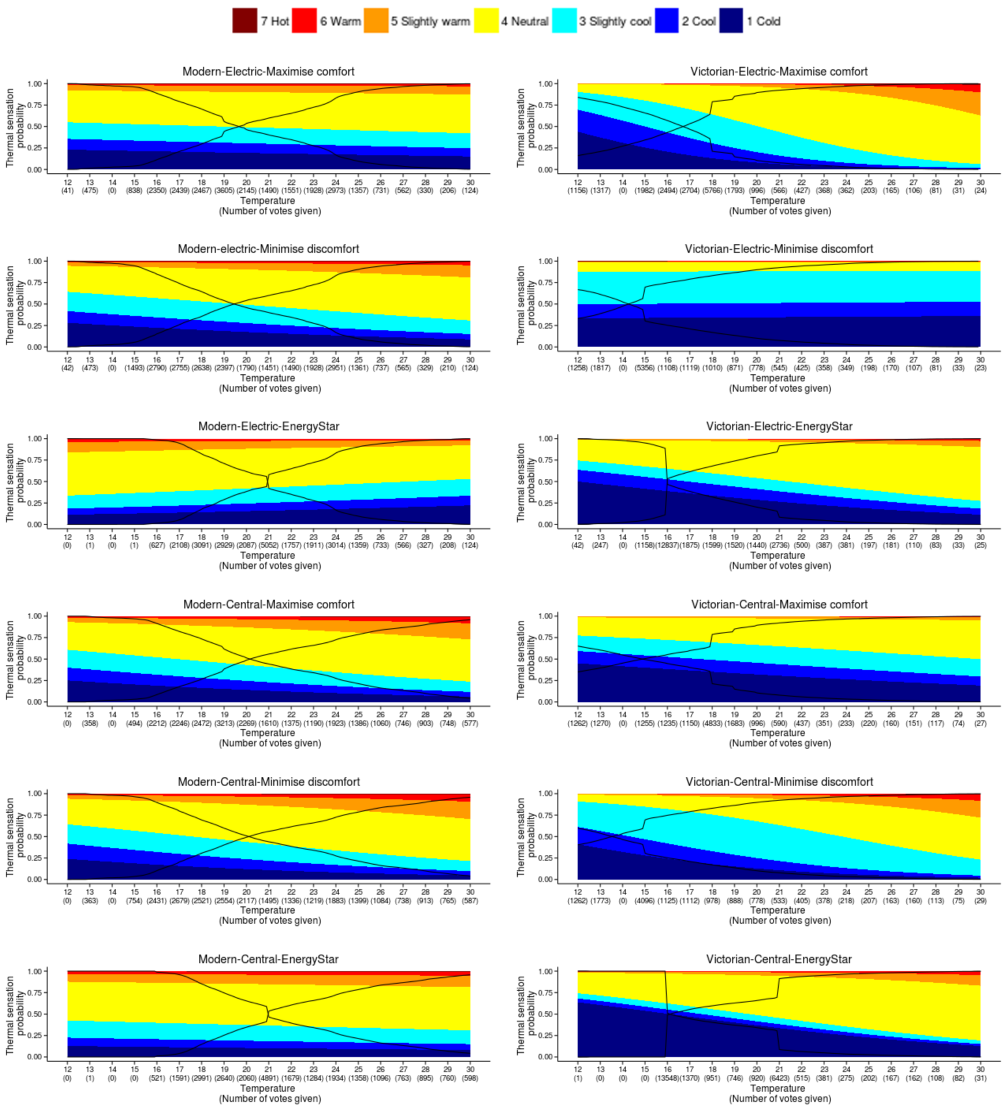


Figure 5-10 thermal sensation distribution fitted with an ordinal logistic regression model (stacked area chart) with positive and negative temperature cumulative distribution functions (black lines) for all simulated conditions

On this basis it was concluded that, the algorithm succeeded in adapting itself to users' thermal preferences and accommodated diversity on these preferences between households.

5.4.4 Away schedules

Two away schedules were incorporated in the simulation and the effect of these can be seen in Figure 5-11. As explained in

Figure 5-1, the algorithm calculated a presence probability regardless of the away schedule. However, if the calculated time step fell within an away schedule, the calculation result was not output for the set-point calculation, therefore preventing any heating activity from taking place.

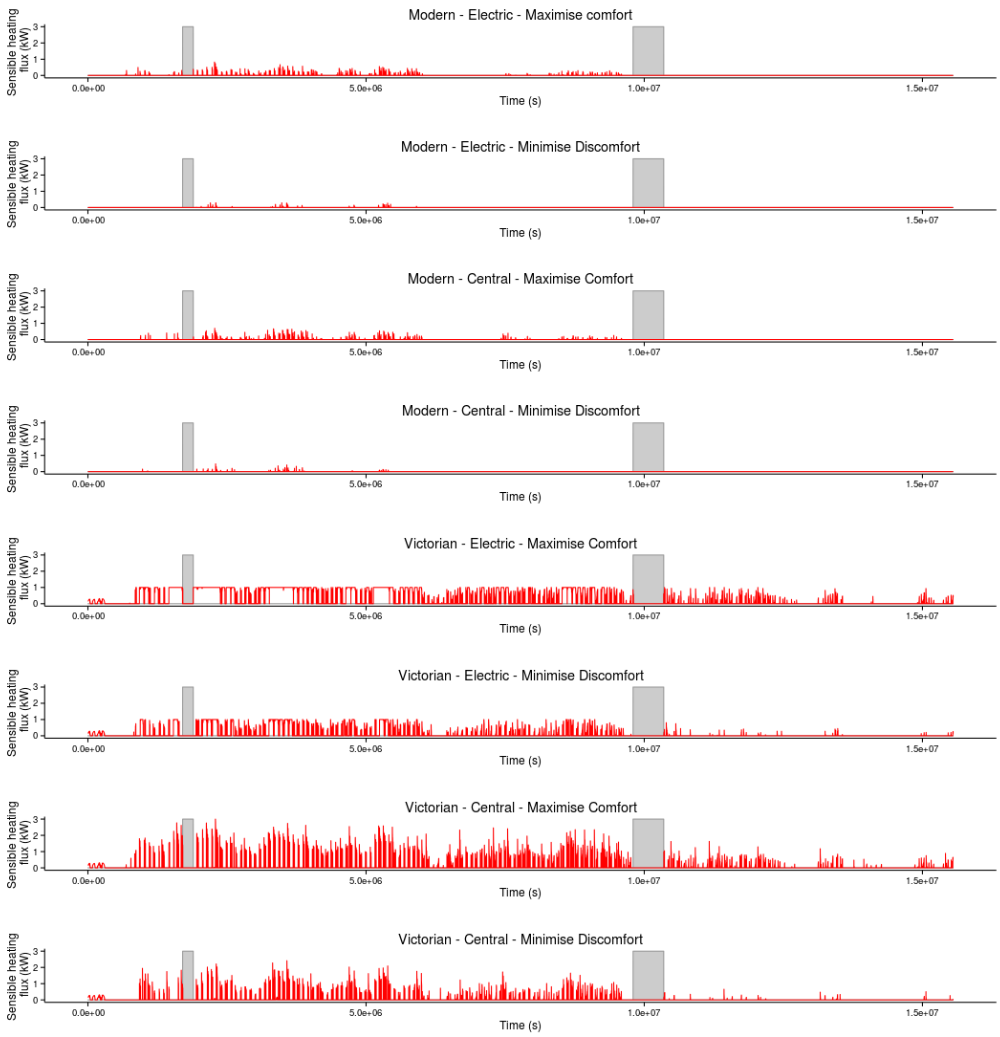


Figure 5-11 effect of away schedules (grey) on heating system sensible heating flux (red)

Figure 5-11 highlights that during both away schedules, heating schedules were suspended and thus no energy was used. In addition, long periods toward the end of the simulation can be observed in Figure 5-11, where there was no heating output. This was due to the relatively warm summer weather during which no additional heating was required to achieve comfortable conditions.

Thus it is concluded that the algorithm acted as expected for the straightforward case of handling away schedules.

5.4.5 Energy implications

As the simulation was configured to model both the electric and water-based central heating systems as an ideal loads HVAC system, it was possible to draw direct comparisons between the predicted energy demand. Figure 5-12 compares performance criteria (energy demand, mean indoor temperature, and mean sensation) between all simulation conditions utilising the proposed algorithm as well as the control condition set to use Energystar recommended programmable thermostat settings.

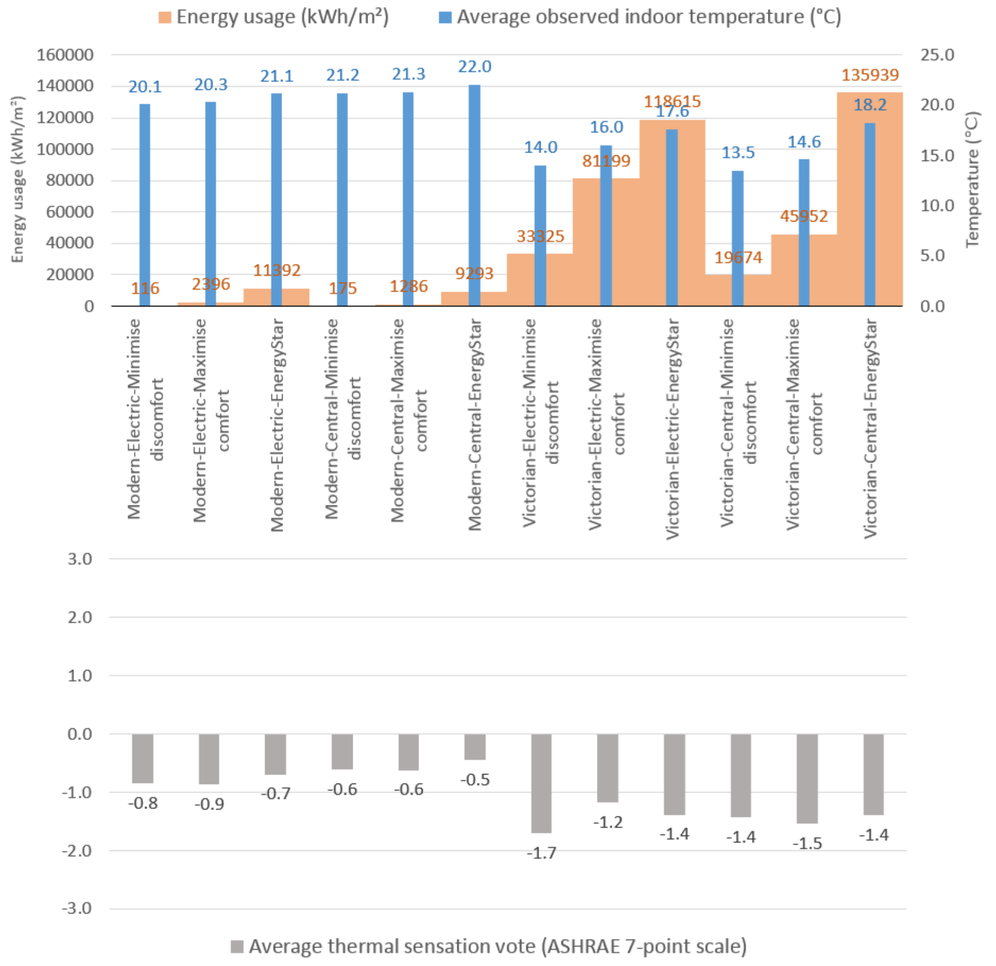


Figure 5-12 Energy and comfort implications comparison between all simulated conditions

These results show that the proposed algorithm significantly outperforms the recommended (EnergyStar) programmable thermostat settings, reducing energy demand without compromising on comfort. Across all maximise comfort and minimise discomfort conditions, the proposed algorithm delivered an average 46 kWhm^{-2} saving in comparison to a programmed schedule. Furthermore, the minimise discomfort algorithm configuration used on average 78 kWhm^{-2} less energy than the maximise comfort condition, with simulated average thermal sensation votes only 0.1 lower on the ASHRAE 7-point scale. These results suggest that the energy use reduction occurred without an additional cost in user comfort.

5.5 Discussion

As noted earlier, the aim of this exercise was to validate the suitability of the proposed algorithm in order to proceed with confidence in implementing it in field trials and assess its energy saving potential.

Results suggest that the proposed algorithm was able to develop a presence profile for a single room for every day of the week. In this the research viewed a room in isolation and simply observed or predicted whether somebody was present in that space. This is appropriate for this researcher's purpose (as compared say to explicitly considering which occupants are where and when) since the objective is simply to activate heating to satisfy the mean comfort preferences of each room independently whilst occupied by one or more people; through this simplicity to provide for adaptive spatiotemporal heating control. While the proposed algorithm is relatively simple in its logic, for example always selecting previous weeks recorded presence data to predict future presence, rather than compare multiple datasets to find the most suitable match, as was the case (Scott et al., 2011) or (Mozer et al., 1997), it does account for real life complications.

Firstly, the algorithm's memory decay allows it to perform well in changing conditions – the impacts on occupancy of changes in ownership or tenancy, work patterns, or major life events like having children. Secondly, the algorithm is able to adapt itself to interpersonal differences in thermal preference and a reasonable degree of resilience to seasonal changes has been demonstrated. In the version presented here, memory decay was not applied to thermal preference or set-point calculation, but this could be accommodated. Thirdly, the results have shown that the algorithm was able to adapt itself to its environment; to the building envelope, heating system specifications, daily changes in climate conditions. Lastly, the algorithm is able to achieve this level of operation and performance with virtually no training data. This is believed to be paramount for systems designed for the home setting.

So far, users have dictated the conditions within the domestic environment, spurred by their thermal preference and knowledge they have of the dwelling's thermal performance and practice. However, in contrast to other algorithms identified in the literature, this proposal includes an element of the algorithm learning the user's preferences and the building's capabilities. By combining these elements, this work paves the way for future algorithms to better balance thermal preference and energy use by becoming active in nudging the thermal practice within the space towards more efficient behaviour that utilises a more accurate understanding of the building, while remaining within the boundaries of the users' thermal preferences. Such an implementation would be a significant step towards an autonomous home system that delivers a meaningful and useful experience.

The chosen control algorithm emulation and evaluation methodology is built on industry-standard Energy+ software, and this performed well. However, since the algorithm was re-created in Building Control Virtual Test Bed rather than utilising a direct implementation of it written in a compatible programming language, it is possible that small discrepancies occurred. Other potential weaknesses of the methodology relate to the fact that the dwellings were modelled using an ideal loads HVAC system. Modelling a full HVAC system with all heating elements, coils, and other components would have made the simulation more accurate; particularly in respect of the slope calculation. Nevertheless, the simplified approach has enabled testing and evaluation of the core component parts of the algorithm.

5.6 Conclusions

This chapter evaluates the fitness for purpose of a simple spatiotemporal home heating control algorithm, using Energy+ (building simulation) and the Building Controls Virtual Test Bed (algorithm emulation). From this it has been demonstrated that the algorithm can reduce the amount of energy required to provide adequate levels of thermal comfort, and that these savings can be increased by including occupants' thermal preference as a variable in the control algorithm. The work demonstrates that appropriately formulated automated heating can straightforwardly accommodate users' thermal preferences in a more meaningful way than a snapshot set-point temperature provided by the user. This understanding may allow for future homes to push the boundaries of energy saving without compromising the comfort of their occupants.

The proposed algorithm was next deployed in a field-study spanning 6 months to test its usefulness in creating a quasi-autonomous, spatiotemporal heating system and assessing its impact on the user experience of living with such a system explored in the next chapter.

6 ENTERING THE REAL WORLD

6.1 Chapter overview

The aims of this chapter are to explore the thermal, social, and technical user experiences of the proposed algorithm implemented through an automated heating system in a highly ecologically valid setting over an elongated period of time to allow for concepts and behaviours to emerge.

6.2 Introduction

The study described in this chapter utilised a technology intervention method that deployed a quasi-autonomous spatiotemporal heating system in people's homes for six months. The heating system used sensor kits to detect occupants' presence using motion sensors and recorded ambient air temperature in each room of the participants' homes. This data was stored and used on a central university server as input to the control algorithm that calculated a heating schedule for each room. The sensor kits implemented the schedules through controlling standalone electric heaters. Occupants were given input capabilities through a smartphone control application. Details of the implementation of this method including apparatus, data capture, and procedure follow below.

The literature review and ideation sections described the complexity of the observed domestic environment (highlighted in Figure 6-1) and the importance of exploring user experiences of such systems in the wild has been made evident.

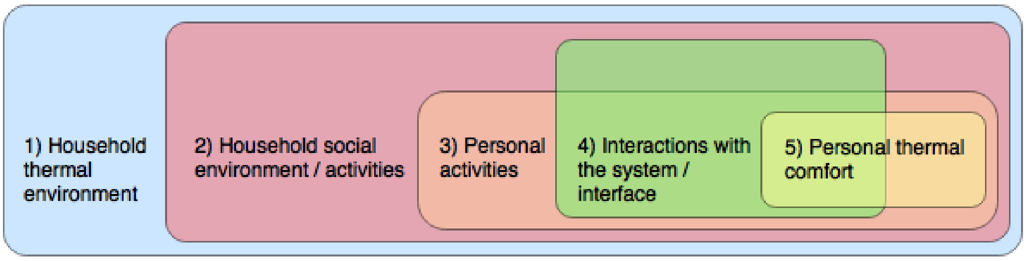


Figure 6-1 illustrating the complexity of the observed environment, the factors influencing personal thermal comfort, and their relations

Furthermore, as it has been suggested above that the likelihood of performing any thermal comfort or heating energy-related action is a result of matches or mismatches between user expectations and prevailing conditions (Figure 6-2), it is necessary to understand the interactions users have with the heating system in a real-life setting and what factors influence these interactions.

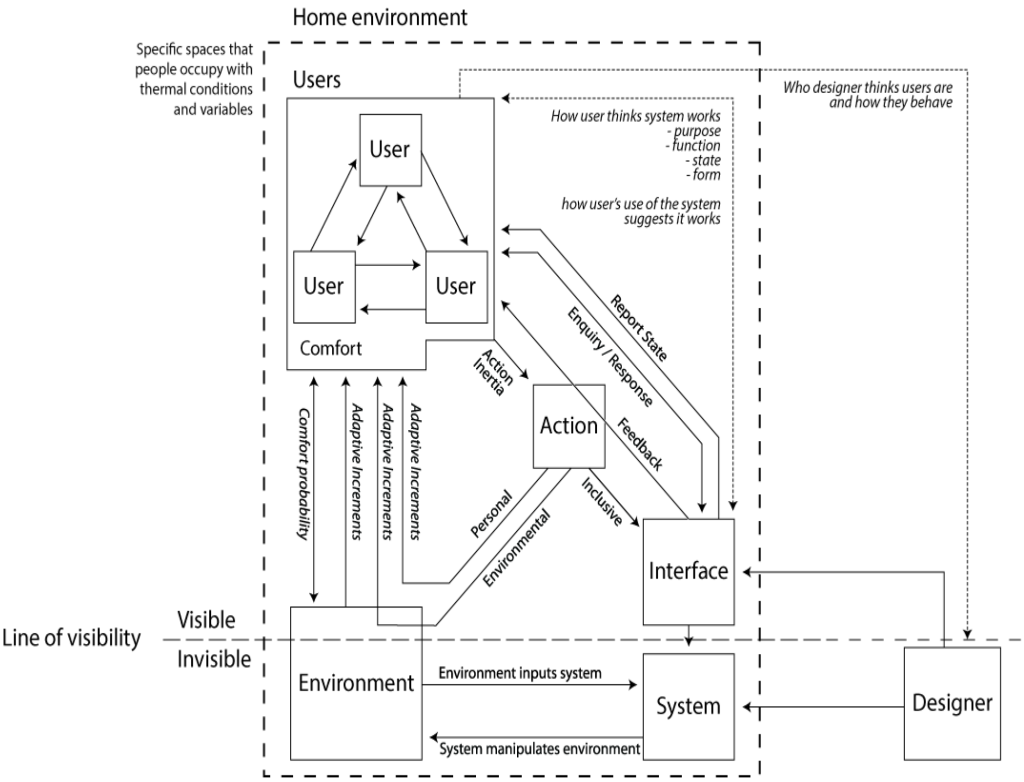


Figure 6-2 illustrating the conceptual model that explains the context of use for home heating controls, types of interactions taken by users, and the role of the designer

Similarly, it is important to understand the nature of the interactions, as well as the social context of them. This meaning, that the wider environment primarily include the 1) social environment of a multi-occupant household and 2) the context of all activities and 'living' in general (Figure 6-1), of which, while biologically vital, thermal comfort forms a relatively small amount. As a result, assessing one's thermal comfort and subsequently interacting with the heating system is not something most people wish to spend much time doing over the course of a day. Therefore, exploring the relationships between appropriate dialogues, performed interactions, as well as the user's thermal preference in a real world context, becomes vital.

In order to make sense of all these elements, a mixed methods approach using data triangulation was used. This methodology limited to study's ability to provide statistically conclusive results regarding any of the observed factors, however, it is important to note that this was not the goal. The aim of this study was to explore the heating system and user experiences in a highly ecologically valid setting, which would allow for factors to emerge, that might otherwise be overlooked in a different study method or design. Through this, the study aimed to answer research question Q3 - How are different heating strategies experienced by users, and in combination with results from the simulation activity, answer question Q2 - To what extent can spatiotemporal automated heating minimise energy use while providing thermal comfort? By answering these questions, the study would give an insight to the users' behavioural adaptation to an automated heating solution and their experiences of collaborating with it to provide thermal comfort in their home.

6.3 Methodology

This study centred around a technological intervention approach situated in individuals' homes. The field study method, albeit without its flaws, notably sample biases and difficulty in obtaining data, was chosen over alternatives (see Table 6-1 for comparison) as it is extremely high in ecological validity and allows for phenomenon to be observed in their natural setting, a key factor in this research.

	Method	Strengths	Weaknesses	Use
Natural setting	Case studies	Natural settings Rich data	Time demanding Limited generalizability	Descriptions, explanations, developing hypothesis
	Field studies	Natural Settings Replicable	Difficult data collection Unknown sample bias	Studying current practice Evaluating new practices
	Action research	First hand experience Applying theory to practice	Ethics, bias, time Unknown generalizability	Generate hypothesis/theory Testing theories/hypothesis
Artificial setting	Laboratory experiments	Control of variables Replicable	Limited realism Unknown generalizability	Controlled experiments Theory/product testing
Environ-ment independ-ent setting	Survey research	Easy, low cost Can reduce sample bias	Context insensitive No variable manipulation	Collecting descriptive data from large samples
	Applied research	The goal is a product which may be evaluated	May need further design to make product general	Product development, testing hypothesis/concepts
	Basic research	No restrictions on solutions Solve new problems	Costly, time demanding May produce no solution	Theory building
	Normative writings	Insight into firsthand experience	Opinions may influence outcome	Descriptions of practice, building frameworks

Table 6-1 comparison of research methods (as seen in Wynekoop and Conger, 1990)

In the context of HCI research, field studies have been used with the goals of understanding, engineering, and evaluating technology (see Figure 6-3). The field study method can take a number of different approaches ranging from ethnographic studies where phenomena is observed to complex field experiments manipulating a number of variables in situ.

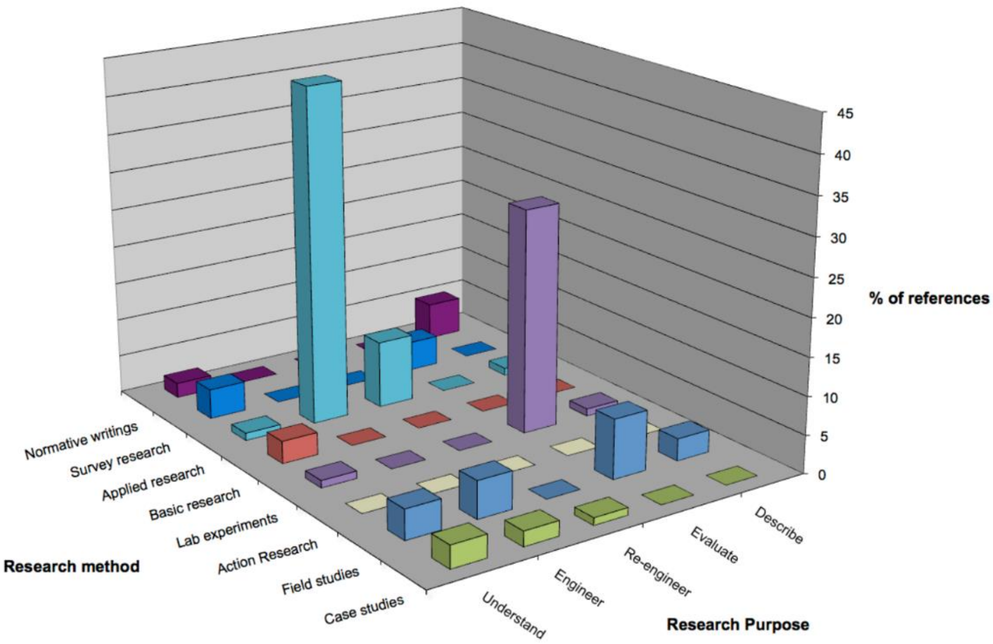


Figure 6-3 comparison of reported research methods from a longitudinal review of literature (as seen in Kjeldskov and Paay, 2012)

The key benefits of field experiments are “increased realism and increased control in comparison to ethnographic field studies and support for studying complex situated interactions and processes. Disadvantages include limited control of experiments and complicated data collection compared to, for example, experiments in laboratory settings." (Kjeldskov and Graham, 2003)

This approach of using a technology intervention in the field experiments 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, to elicit patterns of behaviour that may emerge in a larger scale deployment. In order to comprehensively capture the effects of the deployed intervention, a combination of quantitative and qualitative measures was used, which aimed to capture much of the system actions and user interactions with it, as well as elements of the wider context such as the social context and activities surrounding the interactions.

6.3.1 Participants

The sampling for this experiment was done largely on availability and self-selection basis. However, several requirements were posed for 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, (3) they lived in a house/flat no bigger than 5-6 rooms, (4) apartments had to have a minimum of 2 rooms, and lastly, (5) to be eligible, the participants were required to own and use a smartphone running either an iOS or Android operating system.

Participant selection aimed to reflect the UK housing stock breakdown provided in Chapter 3, however, this was seen as preferential as the researcher acknowledged the aforementioned biases in the sampling process and self-selection could provide a different sample. Participant recruitment was done using the academic participant recruitment service callforparticpants.com, as well as 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 were recruited and several others showed interest, but despite qualifying to take part, chose not to. The characteristics of the prevailed sample can be seen in Table 6-2.

Characteristics	**House 1**	**House 2**	**House 3**
House exterior			
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	Minimise discomfort	Minimise discomfort
App visibility	Visible	Blind	Visible
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

Characteristics	House 1	House 2	House 3
Existing heating system	Gas central heating	Electric convector heaters	Electric convector heaters

Table 6-2 displaying the characteristics of the participating households (all names are pseudonyms)

6.3.2 Apparatus

The 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, placement of sensors and heaters can be seen in Figure 6-4.

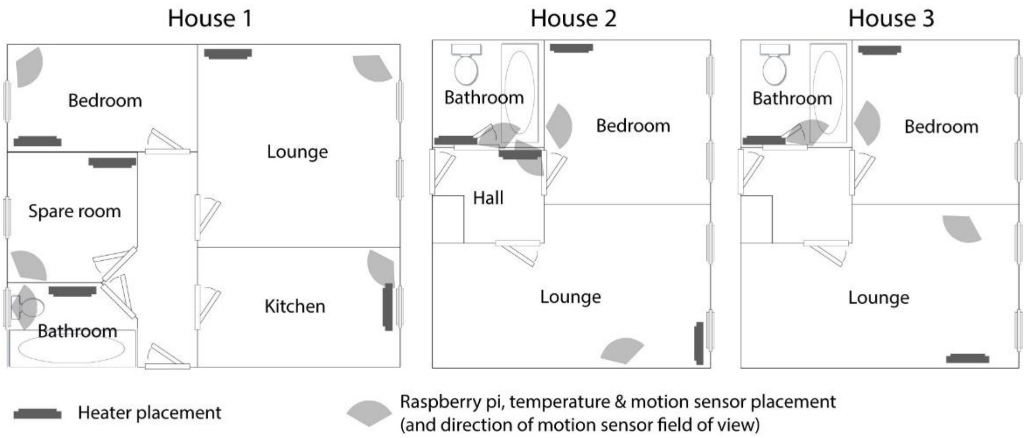


Figure 6-4 floor plans highlighting the placement of sensor kits and heaters in the participating households (diagrams are not o scale)

Each room was fitted with a kit of these components that all communicated to a central database on a University of Nottingham server that also hosted the control algorithm (system architecture is highlighted in Figure 6-5). Users were presented with a smartphone or tablet application that acted as their interface for communicating with the heating system and displayed data about the internal environment of every room in the participants' houses.

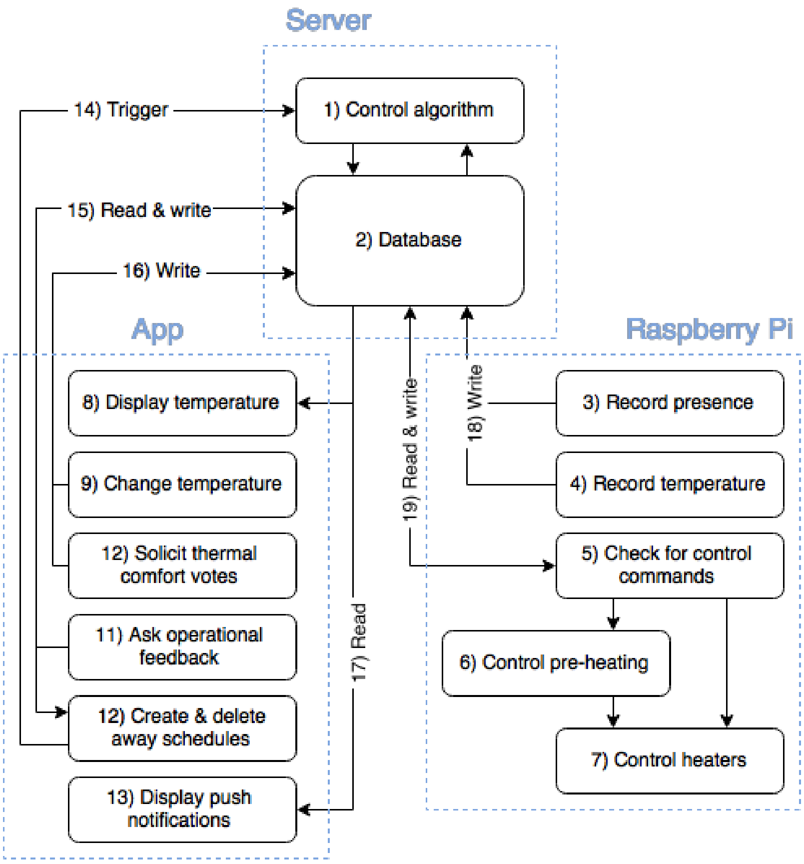


Figure 6-5 illustrating the system architecture of field study technology and the operational interactions between the server, raspberry pi and phone app components

Item 2 in Figure 6-5 depicts a database, from which the Raspberry Pis smartphone apps read data and wrote data to. These interactions were completed using several server-side scripts, the nature of which can be seen highlighted in items 14, 15, 16, 17, 18 and 19 in Figure 6-5. Further to that, Figure 6-6 illustrates the structure and contents of tables within the database. The database design was approached from both the functionality (simplicity of queries for system components to make while maintaining data integrity between households) and research data collection (easily sortable and retrievable data) points of view.

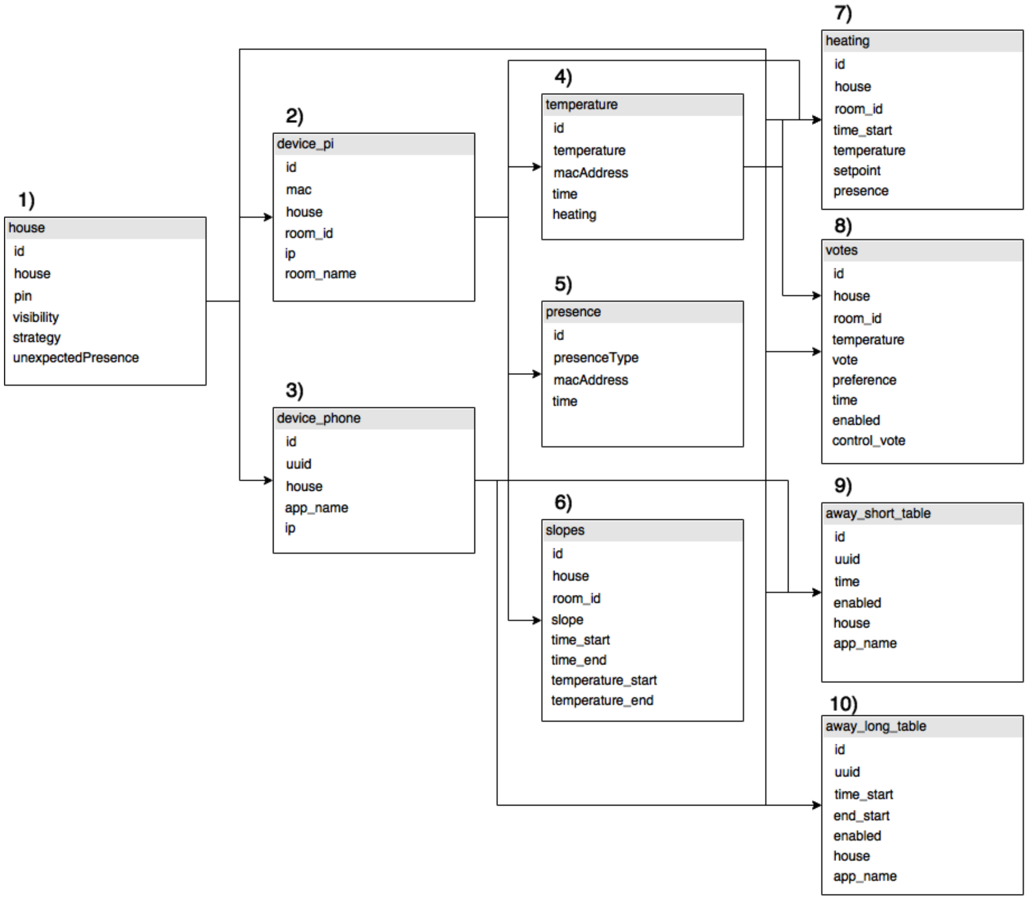


Figure 6-6 illustrating database design and showing tables present in the database

6.3.2.1 Smartphone application

The application design was driven by the system's functionality and design considerations deriving from the ideation activity described in Chapter 3 as well as potential users' input obtained in participatory design sessions described in Chapter 4. Initial sketches for the application's graphical user interface can be seen in Figure 6-7.

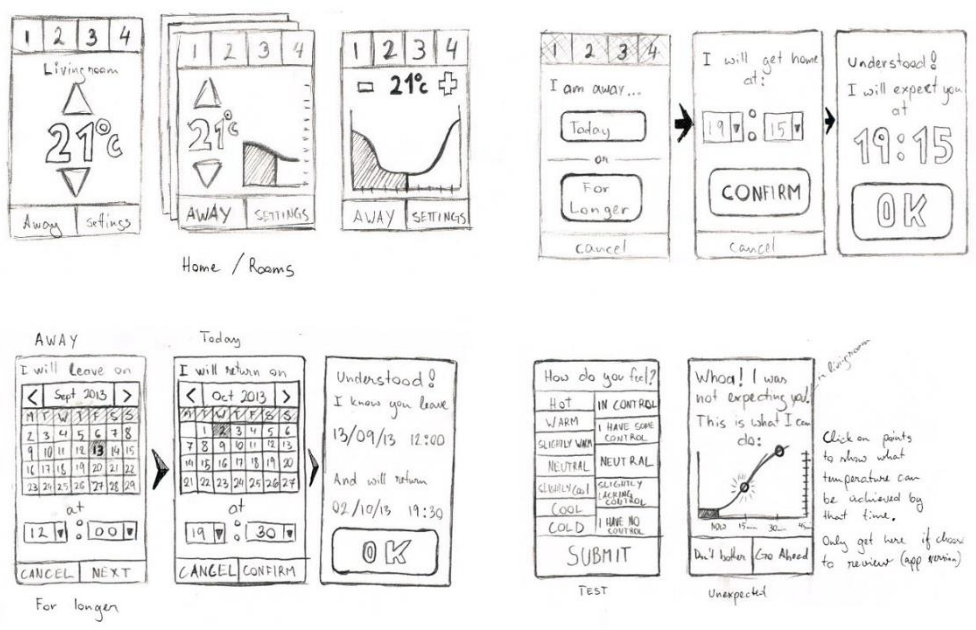


Figure 6-7 illustrating initial sketches of the system interface

The interface, seen in Figure 6-8, had three primary functions – it provided users with thermal information about their house and allowed them to administer manual over-rides if requested (a on Figure 6-8), provide feedback regarding thermal sensation & preference as well as perceived control votes (b on Figure 6-8). It allowed users to create and manage "away" schedules that denoted periods when the user was uncharacteristically away from home (c on Figure 6-8).

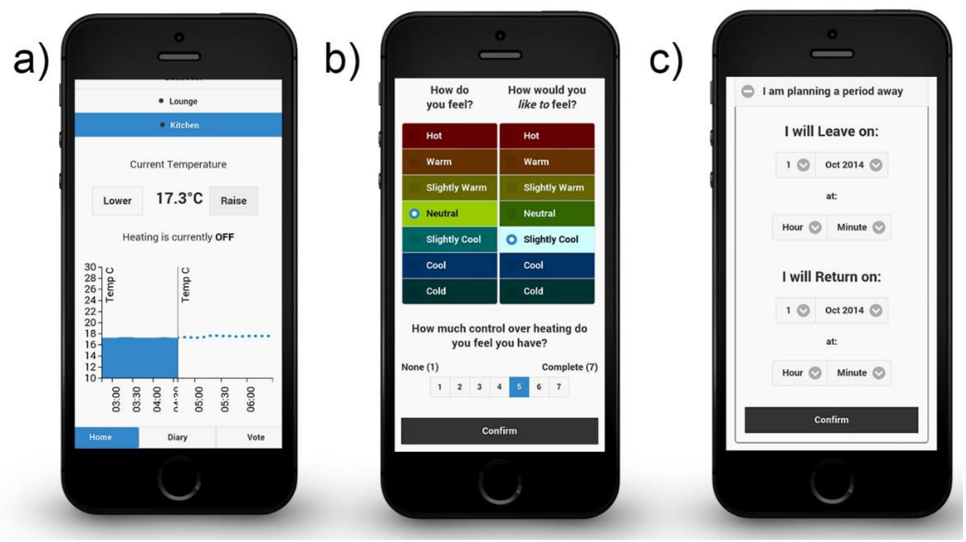


Figure 6-8 illustrating the smartphone application given to study participants

The users were free to utilise the smartphone application as they wished and Figure 6-9 highlights all interactions possible with the application and possible use cases.

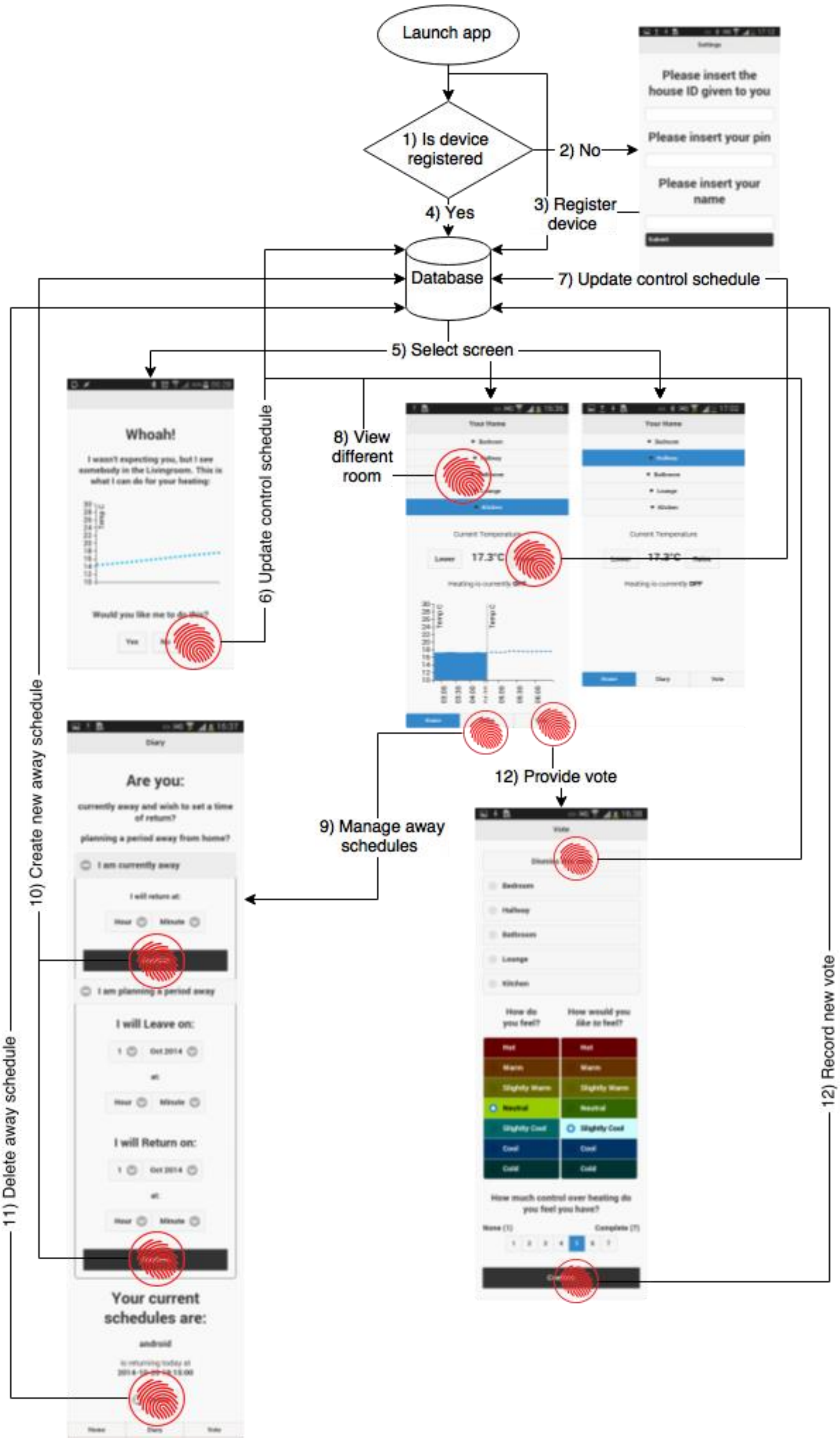


Figure 6-9 illustrating the user interaction flow and functional logic of the smartphone application

Upon opening the app, it checked if the user was registered (1 on Figure 6-9) to keep user data private and differentiate between users. If the application was not registered, the user was shown a registration screen, where participants needed info from the experimenter to register their app (2 & 3 on Figure 6-9, screenshot seen in Figure 6-10).

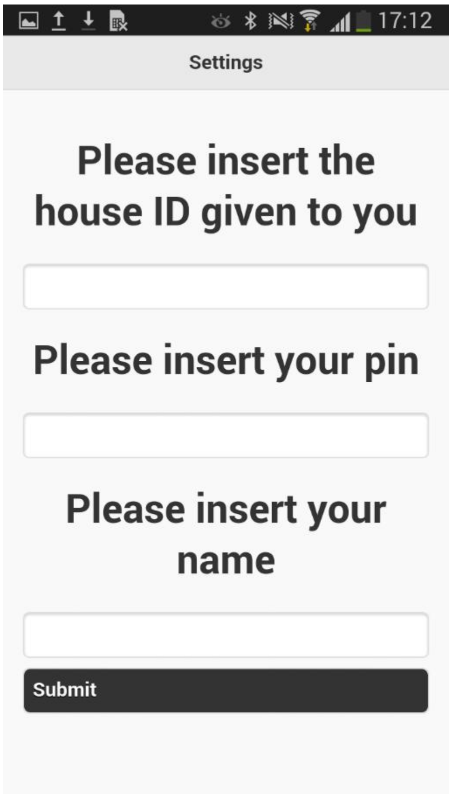


Figure 6-10 illustrating the Register screen of the smartphone app

App registration utilised the device's UUID - a unique identifier that was used throughout the application to identify the device's identity for data posting and requesting. Apple iOS devices experienced a certain quirk with regard to this feature as the UUID was not a constant unchanging value for security reasons imposed by the hardware manufacturer. This meant that on iOS the UUID was an arbitrary code that could change when the application was re-installed or the device operating system updated. Regardless, during the application's testing phase the UUID seemed to be stable enough to be used as a key for user and device identification. To complete registration, the user was prompted for their permission to log usage data via Google Analytics and after permission was granted, the application was internally restarted (no application close and re-launch by user was required) and the launch process repeated.

For registered users, the application selected which screen to show the user out of six possibilities (seen in Table 6-3) based on a number of condition.

Condition	**Screen pointed to**
Device is not registered on the database	Registration (Figure 6-10)
Device is registered on database, application is up to date, app version is visible and household doesn’t have a pending unexpected presence notification	Home visible (Figure 6-11 left)
Device is registered on database, application is up to date, app version is visible and household has have a pending unexpected presence notification	Unexpected presence screen with graph (Figure 6-14)
Device is registered on database but is not up to date	Error screen telling user to update the app
Device is registered on database, application is up to date, app version is blind and household doesn’t have a pending unexpected presence notification	Home visible (Figure 6-11 right)

Condition	Screen pointed to
Device is registered on database, application is up to date, app version is blind and household has a pending unexpected presence notification	Unexpected presence screen without graph (same data as Figure 6-14 expressed in text)

Table 6-3 application-shown screens based on server-returned conditions

Most commonly, the application directed them to the home screen (5 on Figure 6-9) where the app obtained and displayed the names of rooms (supplied by participants prior to deployment), the latest temperature reading and current heater state for all rooms in their house (item 4 in Figure 6-9). Two configurations of the application were deployed – the 'visible' app configuration users saw a feedback graph of temperature for the last two hours in the viewed room and also the temperature that the system algorithm predicted to be observed in that room two hours into the future. Participants in the 'blind' app condition only had a numeric display of the indoor ambient air temperature (Right on Figure 6-11). The comparison between these two versions of the home screen can be seen in Figure 6-11. This variation in the interface was used to see whether there were differences in the user's understanding of the heating system functionality, resulting from feedback or feed-forward data provided by the interface.

Figure 6-11 comparing the 'visible' (left) and 'blind' (right) versions of the home screen

Users could view (8 on Figure 6-9), or alter the temperature for any room in their house (7 on Figure 6-9), which sent the new temperature set-point to the server to be recorded and picked up by Raspberry Pis (see section 6.3.2.2 Raspberry Pi Computers and sensors). After a temperature alteration, the users were automatically redirected to the vote screen (Figure 6-12) to provide thermal sensation feedback on why they altered the temperature,

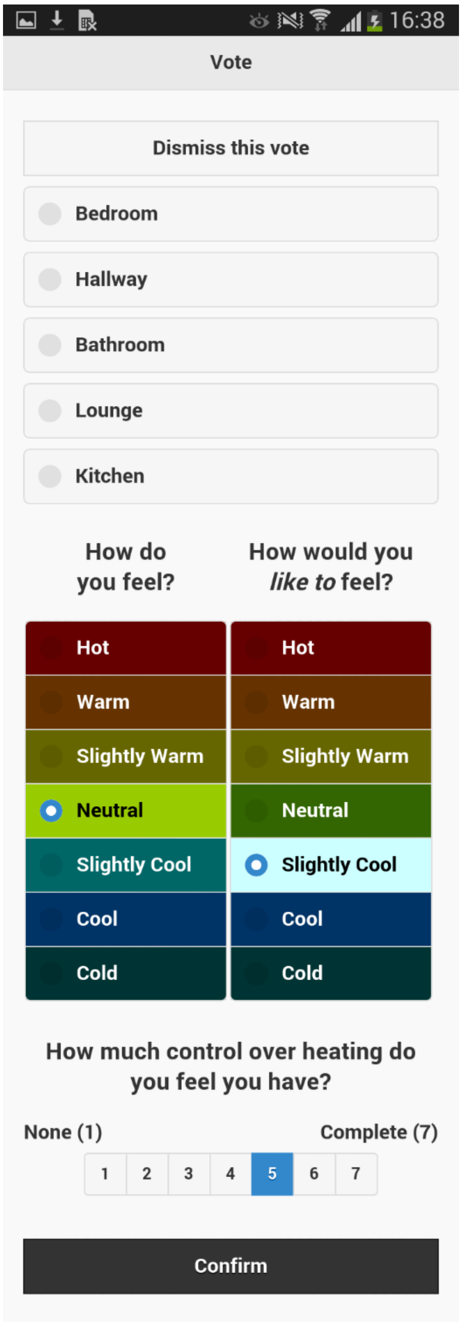


Figure 6-12 illustrating the Vote screen of the smartphone application

submit a vote (12 on Figure 6-9), which consisted of selecting the room they were providing feedback for, indicating what thermal sensation they felt on the ASHRAE 7-point scale, and which they would prefer to feel, as well as a perceived control over the heating system vote from 1 to 7 (no control at all to absolute control respectively). On the server, the most recent temperature reading for that room was added to the vote data. Users were provided with the option to dismiss the vote (this redirected them back to the home screen), but were also allowed to submit a vote whenever they wished by accessing the page from the home screen menu (item 12 in Figure 6-9). Periodically, users were also notified via push notification to provide a thermal feedback vote (see more on the frequency of this in the Procedure section below).

Users could also access a Diary screen (Figure 6-13) where they could create 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 Figure 6-9). 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. Abilities to view and delete created schedules were provided (11 on Figure 6-9), however, schedules were not fully deleted but kept disabled as data for the researcher.

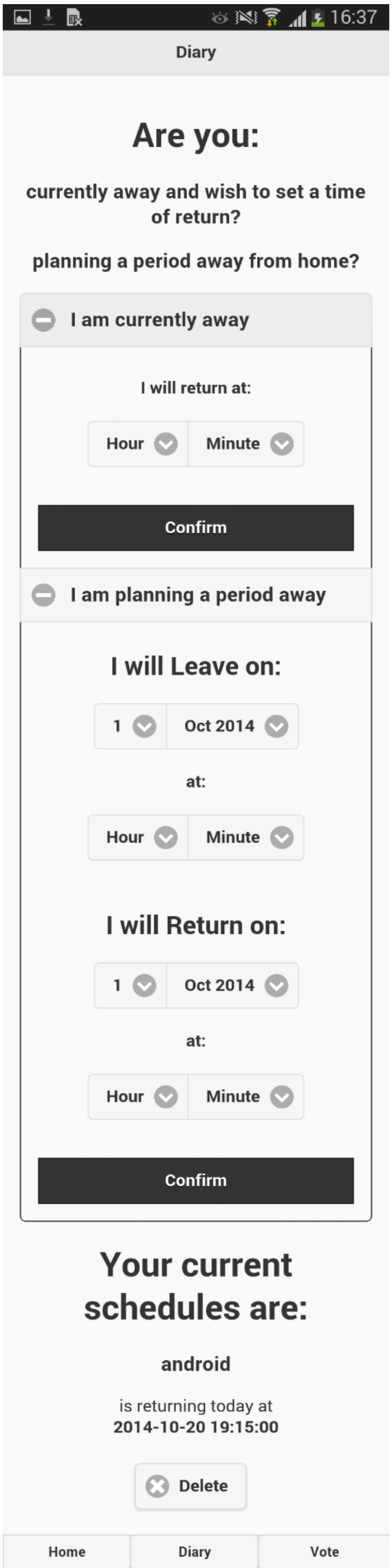


Figure 6-13 illustrating the Diary screen of the smartphone application

Lastly, if the sensors in the participant's home had detected activity that the algorithm was not expecting, the users were prompted with a push notification and directed to an "unexpected presence" screen (Figure 6-14), where the user was informed about what the heating system suggested to do and given the opportunity to provide feedback on whether to proceed or not.

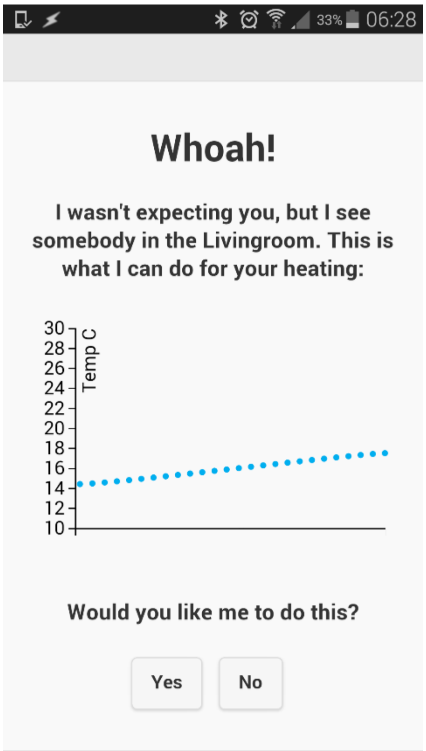


Figure 6-14 illustrating the application's unexpected presence screen

'Visible' app users also saw a graph of the proposed adjustments while 'blind' application users did not. On any response (item 6 in Figure 6-9), the database flag causing users to see this screen was lowered, and if no user responded to it, it was also lowered 5 minutes after triggering.

The PushWoosh service was used for triggering all push notifications, as it 1) allowed integration into the PhoneGap Build framework and 2) it allowed push-notifications to be triggered by an API. The latter was important to allow Raspberry Pis to automatically trigger communications to the user's smartphones.

Usage tracking

Usage tracking was one of the key elements that was necessary to be incorporated into the application. For this purpose, the Google Analytics third party plugin was used, which allowed key actions such as temperature changes, viewing various rooms in the house or viewing different pages within the app to be logged. This plugin was chosen over a conventional method of sending values to a server on button clicks as it automatically logged additional information regarding the usage of the application such as usage times, device statistics, events and geographical information. It was possible to raise some concerns regarding the safety of logging personal information such as periods when users are away from home and geographical positioning of users when they interacted with the application, notably since the Google servers are located in the United States, where data protection laws are not as stringent as in Europe. However, it is important to note that the away periods from homes were not stored in the same location as the Google Analytics data - away schedules were stored on a University of Nottingham server in the UK. This separation of data compensated for the vulnerability of the application tracking data.

Error handling

The application functionality was heavily dependent on queries being sent over Wi-Fi or mobile internet. This could be seen as a weakness in the system, however, all necessary steps were taken to ensure the applications functionality to the maximum. All functions that featured an Ajax query sent to the experiment server included device's connections checks and prevented advancement unless there was a connection. In cases where users were not in Wi-Fi range or did not have 3G, 4G or LTE capabilities, users were alerted and the functionality of the app suspended. Under these circumstances, the users were notified with a pop-up message and directed to a blank "Refresh" screen (Figure 6-15).

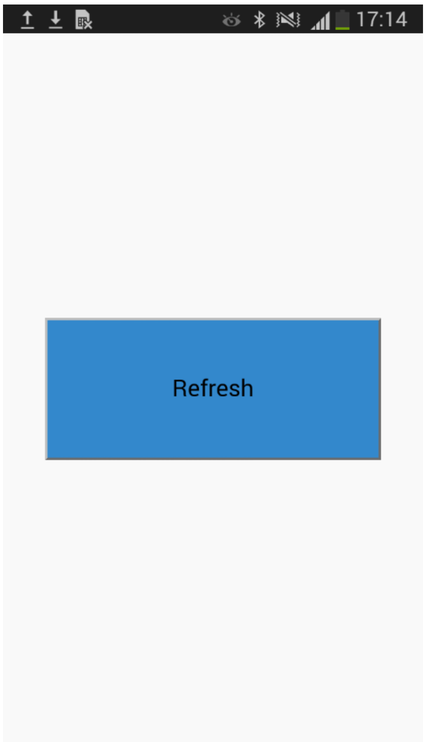


Figure 6-15 illustrating the Refresh screen of the smartphone application

The pop-up message provided information on possible faults and instructed users to contact the researcher if the problem persisted, so that the issue could be investigated. However, due to the nature of the heating algorithm, even successful data exchanges were potentially harmful if the same data was delivered more than once. For this purpose, pending query checks were also built in to prevent any activity until the query had reached a natural successful or unsuccessful end. These techniques made the application's functionality robust enough to be deployed to use by "real humans" with all their tendencies, habits and usage preferences.

6.3.2.2 Raspberry Pi Computers and sensors

The hardware units installed in participants' homes were Raspberry Pi model B computers combined with PiFace Digital I/O boards. This equipment was chosen as it was extremely flexible at a relatively small cost, facilitated a range of operating systems and possible programming languages and were widely used in the hobbyist community for online technical guidance. The Raspberry Pis were equipped with USB 2.0 wireless 802.11n Wi-Fi adapters to allow communication to the servers and heaters, as well as eliminate necessity for a large amount of Ethernet cables in the participants' homes. The motion and temperature sensors were integrated using the I/O board's digital ports, which added another hardware component, but meant that integration into code was extremely easy. A USB TEMPer1 sensor was used to measure temperature and Adafruit PIR motion sensor PPADA189 were used for capturing motion. Exploded view of the used hardware can be seen in Figure 6-16.

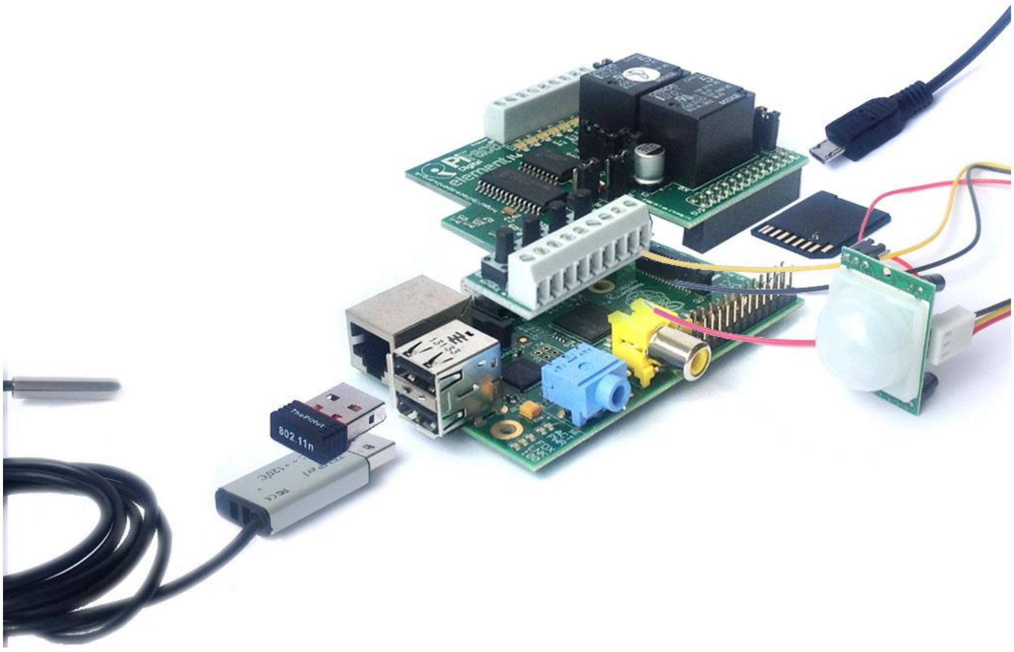


Figure 6-16 exploded view of the deployed hardware

WiFiPlug2 Wi-Fi-enabled plugs were chosen to control 2kW stand-alone convector heaters by Oypla, purchased via Amazon. The heaters featured several functions such as 3 temperature settings, a thermal control unit and more. However, on installation to the participating houses, all these settings were set to maximum and thereafter, control of the heaters handed to the Raspberry Pis via Wi-Fi plugs. An example set-up of the apparatus can be seen in Figure 6-17. Wi-Fi plugs were used as they were an off-the-shelf component that allowed the researcher to bypass many health and safety issues, which would have arisen when using a custom-built rig. As a point of caution for anyone intending to replicate the experiment or use the component, while these plugs came with an API, this was extremely poorly documented and there was a distinct lack of support from the manufacturers for the API.

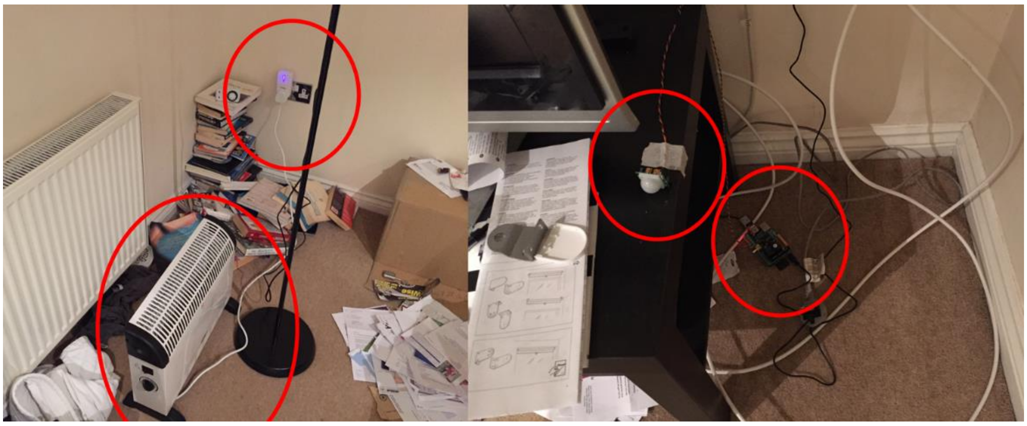


Figure 6-17 example fitting of the research equipment in Lounge of House 1, with Wi-Fi plug, heater, motion sensor and Raspberry Pi unit highlighted in red

The Raspberry Pi's software was designed to be as simplistic as possible to make the system error-proof. On start-up, the Pis used a cron job to initialise a python file containing all of the program's functionality, the general logic of which can be seen in Figure 6-18.

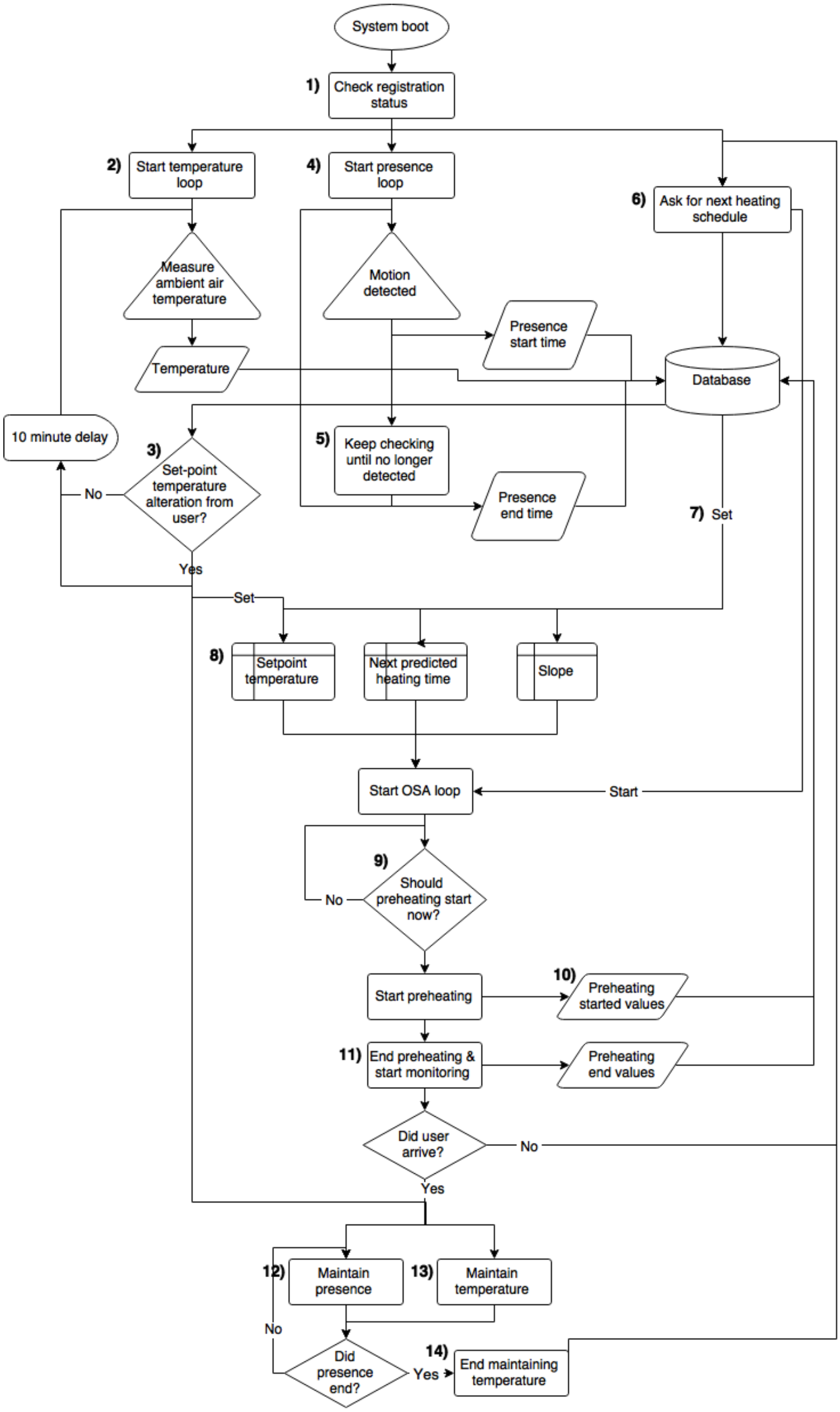


Figure 6-18 illustrating Raspberry Pi software logic flowchart

The Raspberry Pi computers were set up manually by the researcher with deployment information such as Wi-Fi passwords and hard-coded identifiers. Following this preparatory coding, the installation of the Pis was largely a matter of plug-and-play. On the very first boot on site, the auto start script called a registration function (item 1 in Figure 6-18), which identified the Pi on the server and allowed it to access data relevant to its room. Following this registration and allocation the Raspberry Pis were programmed to be fully self-sufficient. Two threaded endless loops were used to provide the two key pieces of data: temperature and presence.

Temperature loop

The temperature loop (item 2 in Figure 6-18) took a temperature measurement every 10 minutes and sent it to the server heater state (on or off). The server responded by handing the Pi its current temperature set point. If the returned value indicated an alteration by the user (item 3 in Figure 6-18) and the system was already in a planned heating cycle, the target temperature value was updated. If the system was not in a heating cycle, the set-point was updated and maintaining presence and temperature functions called.

Presence Loop

Following the initialisation of the presence loop (item 4 in Figure 6-18), the Raspberry Pi pinged motion sensor for movement continuously every two seconds. When motion was detected, the Pi contacted the server declaring the start or end of presence. Following the communication, the Pi entered a check window state (item 5 in Figure 6-18), wherein it checked every 2 seconds whether motion was still detected for the duration of two minutes. If motion was detected during this time, the Pi reset the window and it was treated as one continuous presence. If no motion was sensed for 2 minutes since previous detection, the Pi assumed that presence had ended and announced this to the server. Once this had occurred, the Pi returned to the beginning of the loop and started checking for the next presence duration.

If the start of presence happened to be in a period where the algorithm was not predicting the user to be present at that time the system kept checking if the presence persisted for ten minutes. If this was the case, the system contacted the server in order to raise the unexpected presence flag in the house table and trigger a push notification to prompt a response from the user asking whether they would like the heating to be turned on or not.

Heating and pre-heating the room

At the triggering of the program, a third loop was called, which handled the heating of the room for predicted presences. At the beginning of this loop, the Pi contacted the server to obtain the next predicted presence, the set-point temperature for that period, and a slope value from the slopes table (item 6 in Figure 6-6). These values were saved locally (item 7 in Figure 6-18) and triggered the optimum start algorithm, which used current time and temperature readings to calculate whether heaters should be turned on at that time in order for the temperature to reach desired levels by the time users were predicted to arrive. The equation used can be seen in (4).

$$t_{start} = t_{end} - \frac{T - T_{now}}{S} \quad (4)$$

For more on the slope calculation, please refer to the 5.2 Algorithm section. The software then compared the t_{start} value to current time (item 9 in Figure 6-18) to decide whether heaters should be on. If this was the case, heating function was called and preheating started.

At the beginning of the preheating, the Pi declared the start time and temperature to the server, where these would be used for subsequent slope calculation. If the transaction was successful, the Pi switched the heaters on and kept them on until temperature had reached the desired set-point temperature (T). Once this happened, the end time and temperature were sent to the server, re-calculation of the slope triggered, and a monitoring state (item 11 in Figure 6-18) entered. In this state the computer checked whether people were actually present in the room during the time that presence was predicted for. This state lasted the duration for which it took the local air temperature to decay to the T-1°C lower boundary and subsequently be raised by the system to the upper temperature of T+1°C. This method was incorporated to reflect the inertia of the specific household. The monitoring period was shorter for houses with an agile temperature change profile and slower for latent profiles. If no presence was detected during the monitoring period, the heaters were turned off and the whole process re-started by asking the database for the next predicted presence. However, if presence was detected during the monitoring period, maintaining heat and maintaining presence functions were called.

Maintaining heat (item 13 in Figure 6-18) meant that the system monitored air temperature in the room and maintained it between the upper (T+1°C) and lower (T-1°C) boundaries by switching the heaters on and off at respective times. The boundary values were constantly updated to reflect any changes that the user may have made from the control application (item 3 in Figure 6-18). This process was carried out as long as the maintain presence loop (item 12 in Figure 6-18) was active. In that loop the system kept monitoring the time period in which no presence was detected. If this period exceeded the length of two minutes, it was assumed that presence was ended. When this occurred (item 14 in Figure 6-18) the system turned the heaters of and started the process again by requesting the next predicted presence duration to heat for.

Error handling

As with most ‘real world’ research, there were a lot of factors that would influence the stability of the system, many of which were unpredictable and several that could easily be anticipated. It was assumed that the most detrimental error to the system was lack of internet connectivity. This assumption was based on the fact that highest severity risk - lack of electricity and thus power to the system - would also cripple the heating system as focus was on electric heating systems and could therefore be discarded.

Several measures were put in place in order to prevent limited internet connection from damaging the functionality of the system. Most importantly, users had over-riding control of the installed heaters and on a top level, could reject the heating system completely and revert to their own heating (see Appendix 7 - Field study information and consent forms). However, this was explained to be an extreme measure. Secondly, system functionality was divided between the server and Raspberry Pis, meaning that although data collection was impossible without internet connection on the Pis’ end, the data collected up to the point was safe. Similarly, after the Pis had received key information such as heating schedules, they were self-sufficient for most of the time. Therefore, linkages between the sides became most vulnerable periods. Error catches were built in to the Pi code at every connection to the server. These catches used a 3-tier system. On initial fail, the system waited 30 seconds and tried to perform the same action again. An email notification was also set up to deliver the researcher an email with the error message and the identity of the Pi that had experienced the error. This was seen as a method of covering minor outages and large amounts of concurrent traffic. If the second attempt failed, the system wrote and error to a local file and commanded a reboot of itself. This was seen as a fail-safe for system errors and longer outages as the system would keep doing this fail-safe & reboot loop until it eventually had internet. Reboot was seen as an optimal solution since after booting up, the system immediately sent requests for key data to resume activity on auto start.

Additionally, a third method was built in that allowed the researcher to access the Pi's remotely to view system logs and try to solve any issues. The Pis were set up to share a folder with the researcher's computer using BitTorrent Sync client to perform two functions. Firstly, the Pis kept a log of their actions and these logs were located in the folder so that the researcher could move logs away from the Pis daily to prevent running out of storage and have access to logs. Secondly, if a ssh.txt or vnc.txt file was synced to this folder, another automatically running script located the file and created a ssh or vnc tunnel to the researcher's computer allowing them to access the Pi and perform any necessary actions.

6.3.2.3 Algorithm

The heating control algorithm used was a duplicate of the logic presented in Chapter 5, recreated on the University of Nottingham server in PHP programming language. It was modified to plan one day of heating schedule in advance and was triggered at different times by users when adding or deleting away schedules to the database, and also every midnight by a trigger Pi that was set up in the researcher's office.

6.3.3 Data capture

The deployed technology acted as the primary method for data capture. Table 6-4 describes the captured data as various measures at different intervals for different reasons were captured.

Type of data (measure)	**Method of obtaining**	**Reason of data gathering**
Temperature (°C)	Taken by Raspberry Pi every 10 minutes using temperature sensor	Apparatus functioning Answering questions about thermal comfort
Presence (time start, time end)	Taken by Raspberry Pi when motion was detected using motion sensor	Apparatus functioning 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 Answering questions about algorithm functioning
Thermal sensation votes (number)	Obtained from user whenever the user chose to submit value	Apparatus functioning 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

Type of data (measure)	Method of obtaining	Reason of data gathering
System set point alterations (°C)	Obtained from user whenever the user chose to change the prevailing temperature in the room	Apparatus functioning
Away schedules (time values)	Obtained from user whenever the user chose to submit value	Apparatus functioning 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,	Answering questions about user experience

Type of data (measure)	Method of obtaining	Reason of data gathering
	or viewed a room overview in the smartphone application	

Table 6-4 detailing the quantitative data obtained during the field study experiment

In addition, the users were probed on several occasions using questionnaires, interviews and depictive explanation tools. Prior to the experiment's launch, an online-questionnaire (for more detail see Appendix 8 - Field study online questionnaire) was used to obtain the algorithm's training data from the users. This questionnaire asked the user to provide number and names of all rooms in their dwelling, the preferred temperatures for those rooms, and indicate in 1-hour slots the assumed presence in the rooms. Over the course of the experiment several interviews with participants were conducted to solicit their feedback regarding their experiences and ideas regarding the functionality of the heating system. The open-ended questions of all three interviews can be seen in Tables Table 6-5, Table 6-6 and Table 6-8. Household-specific questions derived from Google Analytics app usage data for the second and third interview can be seen in Table 6-7 and Table 6-9. For the first interview, the participants were asked to prepare a diagram that explained how they thought the heating system worked.

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?

Table 6-5 detailing the questions for field study Interview 1

Question Number	Question
1	Is there anything you would like to add [to the diagram] 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 6-7 below for full detail]

Table 6-6 detailing the 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 6-7 detailing the household-specific questions for field study Interview 2

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 6-9 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 spending 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 6-8 detailing the questions for field study Interview 3 (Debrief interview)

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?

Table 6-9 detailing the household-specific questions for field study Interview 3

6.3.4 Design

The experiment was a semi-longitudinal experiment lasting 5-6 months. The multitude of different collected data facilitated an explorative study design, rather than a strict independent-dependent variable, highly controlled set-up. Regardless, the experiment can be described to have used a between measures study design with two independent variables – smartphone application condition, and the heating strategy condition. Smartphone application condition referred to users' ability to see the feedback / feed-forward graph (see Figure 6-11 for graphic differentiation). Heating strategy referred to whether the heating control algorithm calculated to maximise users' comfort or minimise their discomfort. However, due to the 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 could not be performed. Rather, the conditions were observed individually and descriptive statistics used across conditions. Dependent variables were the thermal experience of the heating system, and the user experience of the heating system and control interface. Out of the total 4 conditions, only 3 were used due to the lack of participating households. The only condition that was not used was the maximise comfort – blind application condition. The rest of the used conditions are detailed above in Table 6-2.

6.3.5 Procedure

Prior to implementation, ethical approval for the technology intervention was gained from the University of Nottingham Faculty of Engineering Ethics Committee. The experiment took place over 6 months between February 2015 and July 2015 (inclusive). Prior to the commencement of the experiment, potential participants were asked several 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 subsequently, the obtained data was used to set up the experimental equipment specific to their house. 1-2 weeks after the deployment of the technology, Interview 1 was conducted with the participants. The second interview was conducted 2 months after deployment and the last interview was conducted on the day the equipment was collected. Throughout the duration of the experiment, check-up emails were sent to the participants to make sure everything was running as expected and to keep a dialogue with study participants. Every day, the researcher checked the time of the latest temperature reading on the experiment database to make sure the system was functioning properly. When delays occurred, the apparatus was restarted using built in remote troubleshooting capabilities. If the equipment was offline for longer periods and remote troubleshooting was not possible, the participant was contacted with a request to manually restart the equipment by removing and replacing the power cable. Participants were also sent reminder push notifications as means to prompt them to submit thermal comfort votes. The rate of push notifications decayed over the course of the experiment with a notification sent every two days in February, every three days in March and every four days until the end of the experiment thereafter. Following the collection of the equipment, participants were compensated with £20 Amazon shopping voucher per month of participation.

6.4 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, the relationships between some emerged interactions with the smartphone application and factors affecting those are explored and the heating system assessed. Qualitative data was coded using a selective coding approach focused around pre-determined themes, which were formulated around study questions (e.g. “interactions with interface”, “how they used the system”, “thermal experiences”, “experience of control”, “thermal behaviour”, “social aspects” etc.) combined with an axial coding approach to group emerging themes that were not accounted for. The qualitative interview data was used in parallel with quantitative data to make sense of the quantitative data and explain user experiences.

6.4.1 Evaluation of the deployed methodology

The study methodology highlighted the feasibility of a relatively low-technology, low-cost solution for investigating the use of a quasi-autonomous system in the wild. Overall the reliability of the system was satisfactory with 75.4% (see Table 6-10) Raspberry Pi uptime across all households. This was calculated using reported temperature readings which should have been recorded throughout the duration of the experiment in 10-minute intervals. Uptime was hindered by two severe disruptions during the 6-month deployment. These were caused by Wi-Fi-plug manufacturer's server downtime and each lasted less than a day. On those instances participants were notified and told to remove the plugs from power supply.

House	House 1	House 2	House 3
Uptime per house	87.5%	56.4%	82.3%
Total uptime	**75.4%**		

Table 6-10 uptime of deployed experimental equipment

Several smaller disruptions occurred due to errors from internet unavailability for Raspberry Pi computers or temperature sensor errors. These formed the bulk of errors and accumulatively affected certain households greatly. House 2 in particular experienced this issue as the house Wi-Fi was shared between neighbours and two rooms received very weak signal causing software errors. Those rooms recorded 45% uptime and the household as a whole 56.4% uptime. The majority of those errors were corrected by a failsafe described above in section 6.3.2.2 Raspberry Pi Computers and sensors. If there was no Wi-Fi, the Pi was unable to notify the researcher of a failure and such instances were then only detected by a daily routine check by the researcher, who subsequently contacted the participants and asked to perform a manual re-set by un-plugging and re-plugging the Pi to its power source. The potential downtime prior to detection and participant unavailability to perform restart, caused the long durations of downtime resulting in poor reliability. Majority of this down time was partial i.e. presence was recorded but not temperature, but on occasion the whole system was compromised. Other two households recorded 87.4% and 82.3% uptime, meaning that provided there were no issues with the internet connection, the system provided for a robust enough solution. This further highlights the ecological validity of the study – it is possible to design the best system, but without internet, it is bound to fail.

The smartphone application in itself was extremely reliable, only issues were encountered when users did not have an internet connection or if the heating system had experienced downtime and thus graphs in the application did not have any data to display. During system downtime, interface's apparent non-functionality, or even when the system was interpreted to behave erratically, the users would often contact the researcher:

"Generally okay. The only issues I have noticed is in the bedroom and kitchen in the last few days, but you asking to reset the Pis there explains that."

"No problem! I will reset. We told you just in case, because this morning we could see they were off while the app said they were not. I will let you know if this keeps happening."

However, the long deployment period still ensured these errors did not cripple the system entirely and it had sufficient data for functioning and ample data for the research. Some issues prevailed with logging interaction data as the Google Analytics plugin seemed to be unreliable at times. For example, some "view home screen" events were not logged as the user was automatically presented with the home screen and didn't press any button to get to it. Similarly, users were automatically presented with a room to view on launch and some "view room" events were not logged. Some of the missing data was retrieved by cleaning up logs after the conclusion of the experiment by applying simple logic – if a temperature change event occurred the users had to have been shown a room to alter, therefore a view room event was added to the data. Similar logic was applied to view home screen data.

Despite these shortcomings, the results prove that it is possible to build and deploy highly flexible, fully-functional autonomous systems from off-the-shelf components with a minute research team. It has been demonstrated that such systems can be robust enough to provide users with a virtually seamless experience of using a smart-home heating system in the most ecologically valid environment for smart homes (as per evolution vs revolution argument by Rodden and Benford, 2003 presented above). This experiment thus highlights the attainability of conducting ambient-intelligence smart-home research in real homes with function-specific equipment.

6.4.2 Emerged three behavior types

It was expected that some differences between the participating households in their use of the automated system would occur, reflecting the existing knowledge of user differences of classical heating systems. The results confirmed this and showed distinctly different thermal preferences and thermal adaptation behavioural patterns that emerged among the participating households. Exploration of those establishes an understanding of the collected data and sets the scene for exploring the users' experiences in more detail. The emergent user types of 'fashion user', 'frugal user' and 'everything's fine' user described here are 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.

6.4.2.1 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 altering clothing level or consuming hot/cold drinks were rarely utilised and subsequently, Carl was the heaviest user of both the interface and the heating system. The user reported varying their working-from-home behaviour and life patterns greatly around work demands creating an erratic presence profiles across rooms (Figure 6-19).

Figure 6-19 fashion user measured presence profiles for all weekdays (top) and weekends (bottom)

Long periods of time in late afternoons can be observed, where the user was recorded at 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 his personal habits made Carl aware of the system's intent to establish a schedule around his presence, which made 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 often 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 to the thermal sensation and the presence of a pre-existing alteration decision. These interactions delivered suitable conditions in the living quarters (Figure 6-20). As environment was matched to clothing choices, Carl was likely to feel different thermal sensations at same temperatures, resulting in a varied thermal sensation distribution (Figure 6-20) and causing the heating algorithm to continuously adapt to ensure the user's comfort. For example, the prevailing temperatures in the bathroom (orange line in Figure 6-20) showed that 75% of the whole experiment time, 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'.

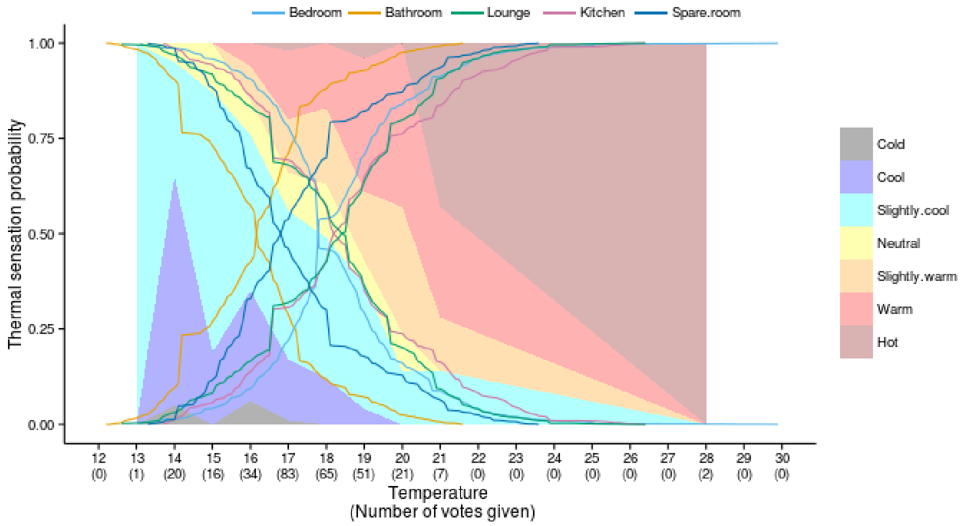


Figure 6-20 fashion user thermal sensation probability distribution based on user-given votes, with positive and negative accumulative temperature distributions fitted for all rooms

6.4.2.2 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 as Diane preferred higher temperatures and Paul 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.

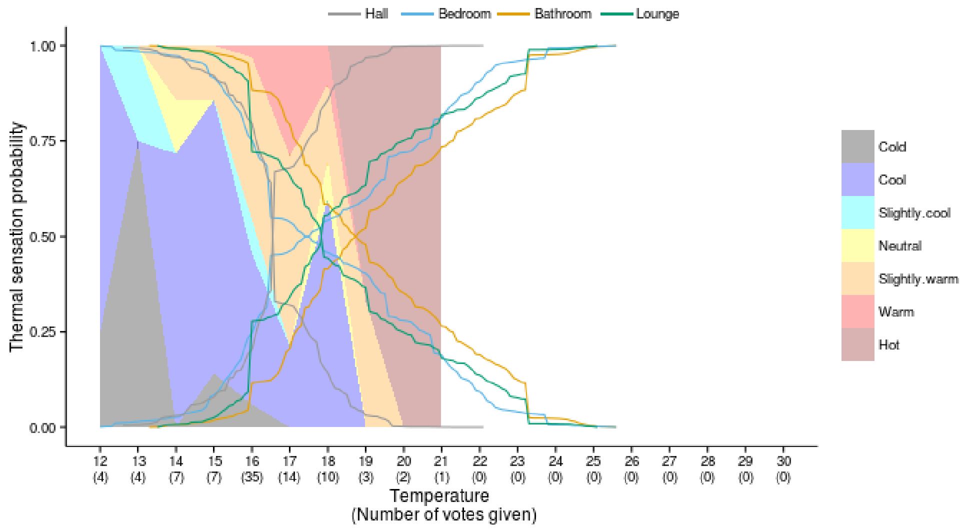


Figure 6-21 frugal user thermal sensation probability distribution based on user-given votes, with positive and negative accumulative temperature distributions fitted for all rooms

Prevailing temperatures were slightly higher than measured for fashion user, but frugal users had a very narrow range for neutral sensation (Figure 6-21), 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 (Figure 6-22 top), causing the algorithm having to adapt to various presence profiles. On weekends, the users preferred to spend more time at home, which also gave the algorithm various patterns for the ‘start of the 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.

Figure 6-22 frugal user measured presence profiles for all weekdays (top) and weekends (bottom)

6.4.2.3 The everything's fine user

These users (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 (Figure 6-23), 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).

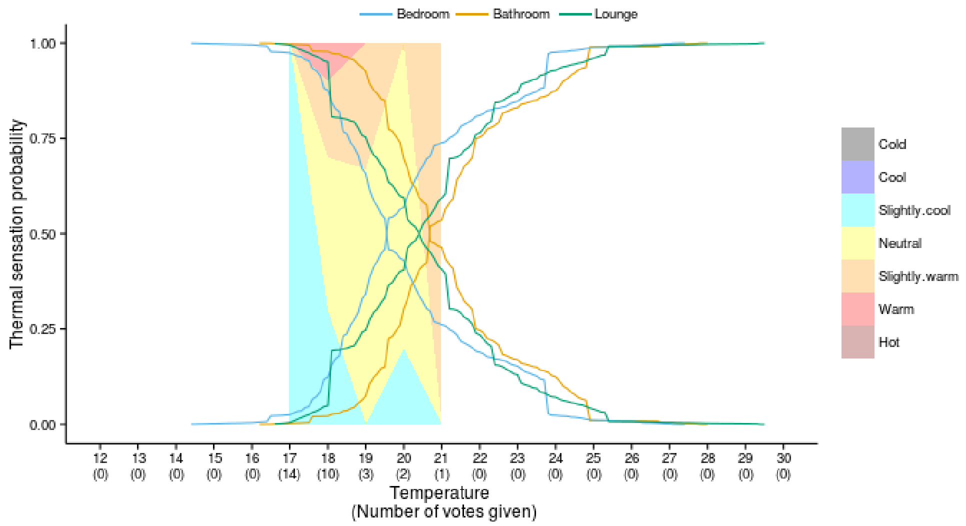


Figure 6-23 everything's fine user thermal sensation probability distribution based on user-given votes, with positive and negative accumulative temperature distributions fitted for all rooms

These users displayed the most dramatic difference between weekday and weekend presence (Figure 6-24), adhering to a strict out-of-home working schedule on weekdays, when highly active morning and afternoons contrasted with absence during working hours. On weekends (Figure 6-24 bottom), the users had different times of waking up, sometimes being out of the house, or spending weekends in. The algorithm had to adapt to these various behaviours and subsequent differences in needs for thermal comfort.

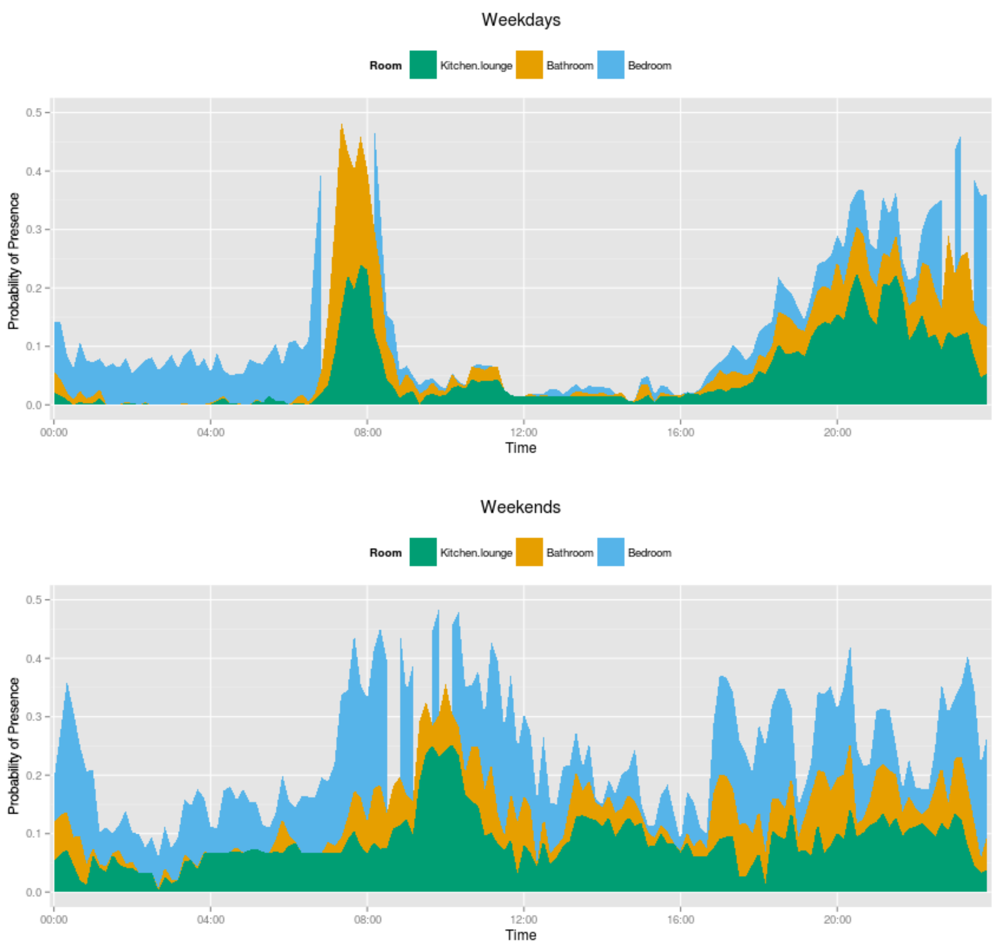


Figure 6-24 everything's fine user measured presence profiles for all weekdays (top) and weekends (bottom)

Long periods of 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.

6.4.2.4 Implications of emerged behaviours

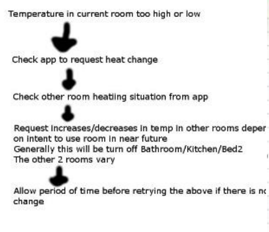
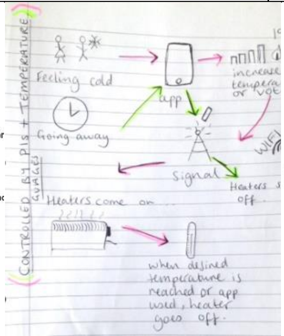
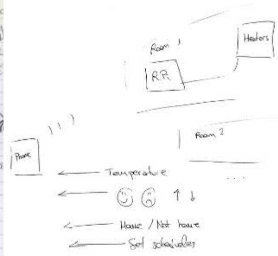
These results from a highly ecologically valid setting demonstrate that in the deployed three households the user behaviours regarding use of the system, thermal behaviour, and thermal preference varied greatly. Furthermore, the emerged behaviours did by no means represent a full set of possible behaviours, highlighting that domestic heating behaviour is indeed complex and highly personal. The described behaviour types showed that three households provided with virtually identical equipment displayed some similarities, but also vast differences in their equipment use behaviour, each adjusting the manner of use to their existing social, occupational, presence, and thermal adaptation habits. Subsequently we explore the user experiences further across the three behaviour types, answering questions formulated around specific themes.

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

6.4.3.1 Explaining heating system's operation & use strategies

The researcher expected users to anticipate automation capabilities from what little explanation was provided at the beginning of the experiment and for this to come through in users' explanations of the system. Furthermore, 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, the results contradicted this and showed little difference between 'blind' and 'visible' conditions in explaining the automation. This filtered through to the occupants' use strategies of the system.

Users' perceptions of the heating system and their use of it 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 6-11).

	Fashion user	Frugal User	Everything's fine user
User-generated diagram			
Researcher's explanation of diagram	Diagram started with their thermal discomfort, proceeding to explanations how their interactions are translated into environmental change.	Diagram started with their 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*	*"The heaters, after a while they'll go. For example if we put the*	None provided, heating system was described as a subservient only

	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]	*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]	to their commands through the application
Explanations of automation after told a computer	Suggested system was replicating their input.	*"It probably either learned our behaviour, so maybe if we were in and if it was below 16 degrees*	*"…the only thing I can guess, is that from the temperature and the answers that we give to the app.*

also made decisions	*"And then some level of variance depending on whether it could see me or not. Based on the motion"* [Carl]	*it would maybe learned that we were maybe would turn the heating on in that instance." [Diane]*	*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

Table 6-11 participants' explanations of heating system's operation and use strategies

The explanations provided in Table 6-11 were reported to be based to a certain degree 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 when they changed their daily routine. Such methods proved more useful that enhanced feedback / feed-forward graph for users in indicating automated system's functionality or capabilities and as such, no vast differences between the user-created diagrams of the 'blind' (frugal user) and 'visible' (fashion and everything's fine user) application version (Figure 6-11) users emerged.

Because of the users' low awareness of automation capabilities of the heating system, the heating system was used as a temporal solution. By that it is meant 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 that they did not obtain 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 at the beginning users relied heavily on guess-work made possible by opportunistic audible feedback from the Wi-Fi-plug 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 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.

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

User experience of control was analysed using interview data and user-submitted control votes. Figure 6-25 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).

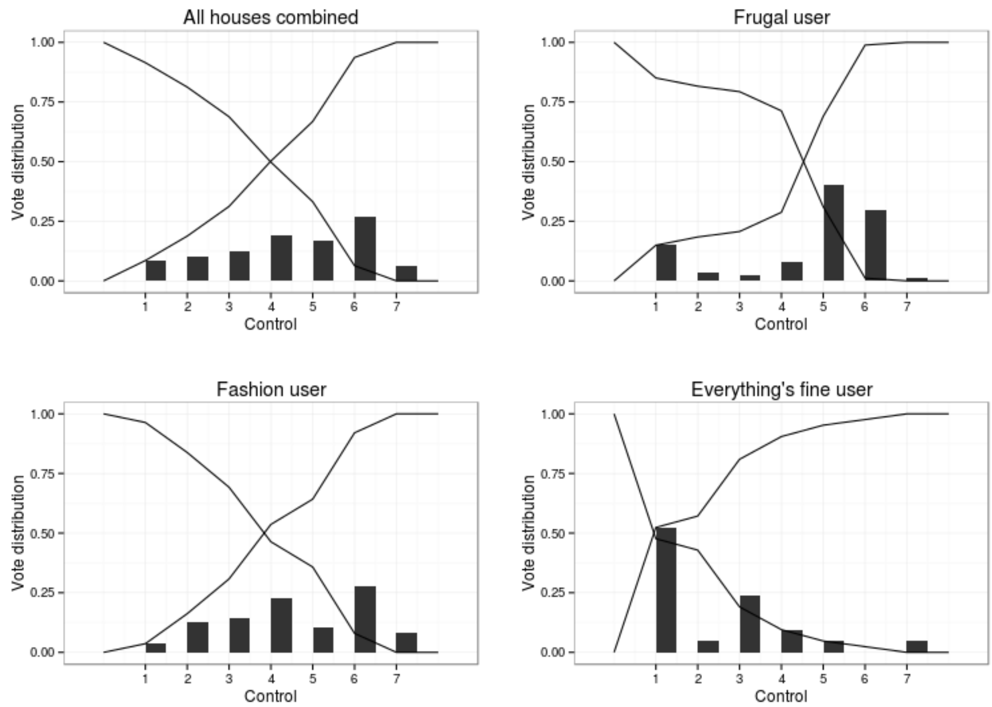


Figure 6-25 distribution of control votes for all houses (top-left), fashion user (bottom-left), frugal user (top right), and everything's fine user (bottom-right) from 1 – none to 7 – complete control, with cumulative distribution function in both directions.

The users explained their control experience and voting reasons as diverse, ranging from habit or interactions with the interface, 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 also making reference to specific instances during the deployment when the system acting 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 or something like that same with when I am in the living room and I would only put it on in the bedroom once I actually go to that room." [Paul]

Clearly, the user's experiences of situations in which their expectations did not meet the system functionality caused them to feel little control, however, over the course of the experiment, there was no consistent connection between system-predicted heating instances and low control votes (Figure

6-26), meaning that users either did not experience loss of control due to system-initiated heating. Figure 6-26 even shows that users were more likely to have a slightly higher perceived level of control during periods when planned heating was occurring than when it wasn't, suggesting that loss of control was more a result of a number of factors rather than system state alone.

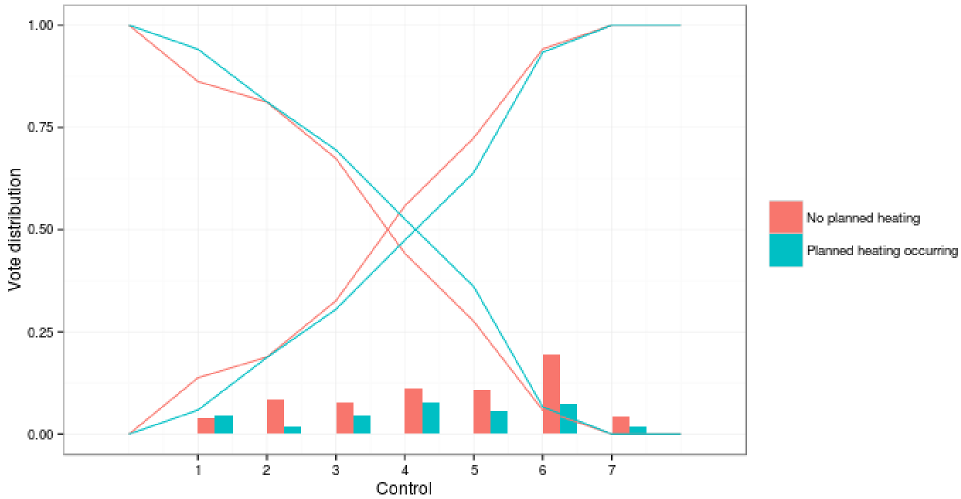


Figure 6-26 distribution of control votes, broken down by system state at the time of vote & cumulative distribution functions in both directions for either system state

Indeed, as data from interviews highlighted, other factors such as system responsiveness in combination with feedback played an important role. This relationship was further complicated by the multiple channels of obtaining information for users. The interface gave them feedback on their actions, but in addition users used environmental feedback, often prompting multiple interactions with the interface and highlighting an added intricacy in the aspect of control for quasi-automation heating system:

"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 multiple inputs of interface, environment, as well as lights and sounds from heaters to establish an understanding of the system state and how changes to that state either involving them or not, caused them to experience loss of control when the system state didn't match their expectation.

Similarly, users' thermal sensation was not a reliable indicator of loss of control, despite the fact that votes were often motivated by thermal discomfort – i.e. when users felt discomfort, they altered the system state and subsequently provided a vote. Figure 6-27 highlights the users' thermal sensation at the time a vote was given and shows that discomforting sensations dominated both high and low control experiences.

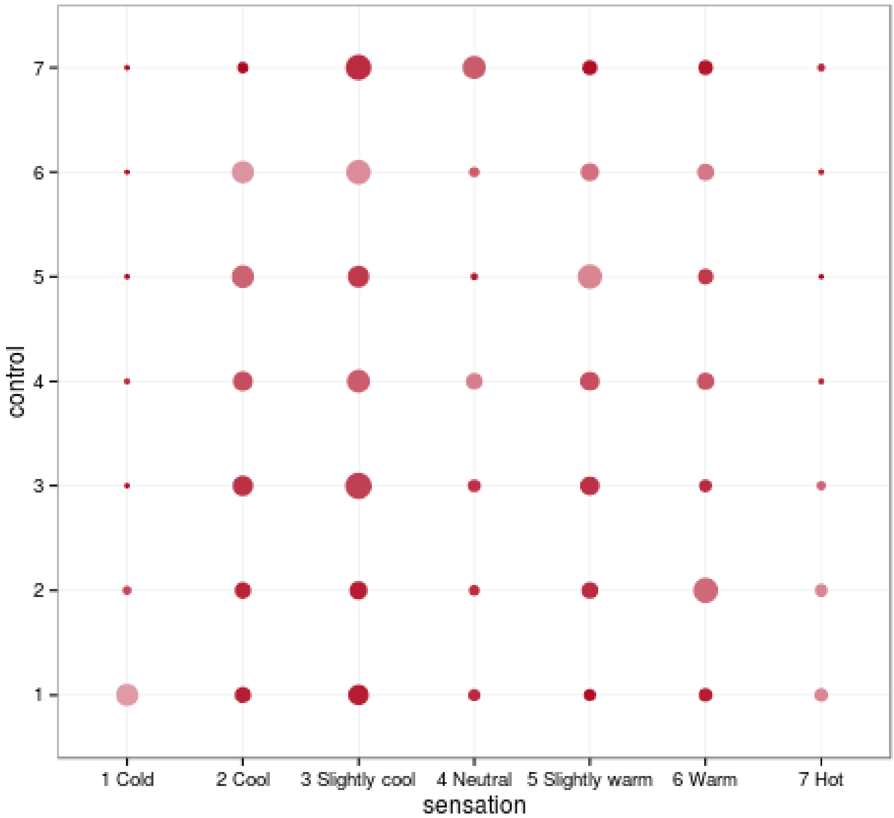


Figure 6-27 distribution of control votes, broken down by user's thermal sensation at the time of vote, size of node indicating probability of that sensation being felt and intensity of colour indicating the probability of that perceived control vote being given.

It was also noted that certain interface features revolving around delegating functionality to the heating system allowed users to increase the level of control they felt. These were particularly true for setting away schedules when users were away from home 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]

"Yeah, but 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 levels of familiarity with the automation could have inspired more trust in them, which could have allowed them to let the system act more autonomously without them experiencing a loss of control:

"…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? Well yes, probably I would have been... 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 for the heating system alone does not promote a user experience 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. This author therefore concludes that communicating rationale behind system functionality, and thermal behaviour, as well as responsiveness of the system in delivering feedback throughout the observable environment minimises the chances of mismatches in expectations occurring.

6.4.3.3 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 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, however, 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. In the 'frugal' household, the application was installed on three devices for two 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, the users also noted that generally they were very individual in their actions, as the users noted often not being together when making these decisions. However, this even lead to users being unaware of the other's alterations to the heating system state, 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, user reports highlighted that in some cases, the interface became a critical part in discussions when disagreements occurred. In the 'frugal' household, temperature feedback from the app was used to settle arguments and 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, which 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 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 that kind of … a shared element." [Diane]

However this shared element created an interesting situation for houseguests. The 'fashion' user occasionally had their partner visit and stay over for long weekends, which sometimes meant that 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]

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.

6.4.3.4 Unforeseen interactions that emerged from the application use

Several unforeseen behaviours emerged, which highlighted the unpredictable nature in which users may adapt their use of a 'connected' or 'smart' home. One such aspect was observed in the 'frugal' household where Paul often worked from home, which meant the heating system experienced variation in presence patterns and used push-notifications to solicit users' feedback. This, however, provoked interesting social nuances regarding personal location data protection and privacy issues:

"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 responses describing 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, the ability to monitor or control the house remotely also provoked interesting beneficial behaviours as Carl, the ‘fashion’ user reported utilising the 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 data that they did not have available to them before. The availability of such elements in the system enhances the user experience of them and increases their value above their function.

The results demonstrate potential problems and opportunities arising from technology monitoring presence and the social implications of the privacy of this information. Successful interface designs must navigate the issues retaining personal privacy while ensuring system efficiency or users’ understanding of the system functionality isn’t compromised.

6.4.4 Interactions with the smartphone control application

The researcher was interested in gaining an insight into the dominant interactions with a smartphone heater control interface that would prevail over long-term in-situ use. Three major use cases prevailed for the users – 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 and was motivated by a wish to make sure the heating stayed off during their 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.” [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]

These use cases emerged from participants’ descriptions of the way they used the application and were confirmed by interaction logs (Figure 6-28).

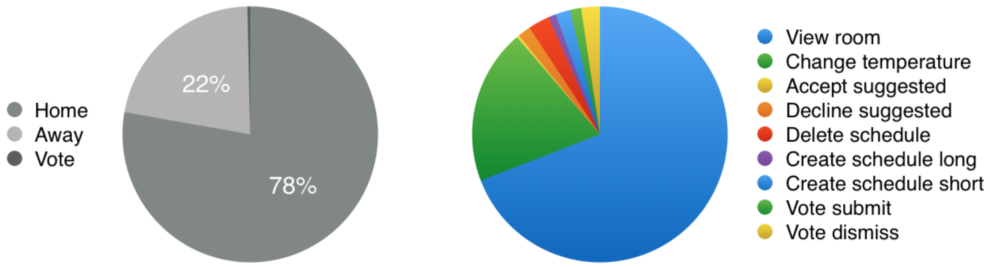


Figure 6-28 illustrating the interactions for viewed screens (left) and logged events (right) from all participants

Figure 6-28 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. Figure 6-28 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. The rest of the events were rather insignificant and users rarely utilised those functions. Interestingly, the ‘create long away schedule’ event was second lowest by occurrence, yet all three households mentioned its importance in the interviews.

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 yea so I adjust the room I am in, then adjust the other rooms if need be. 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. And normally we only put it on in the living room or in the bedroom. 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 Figure 6-29, which indicates the number of ‘view room’ events that occurred within a 10 minute 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. In addition, it emerged that few interactions led to a vote being submitted, indicating that explicitly providing feedback was not a natural part of the interaction.

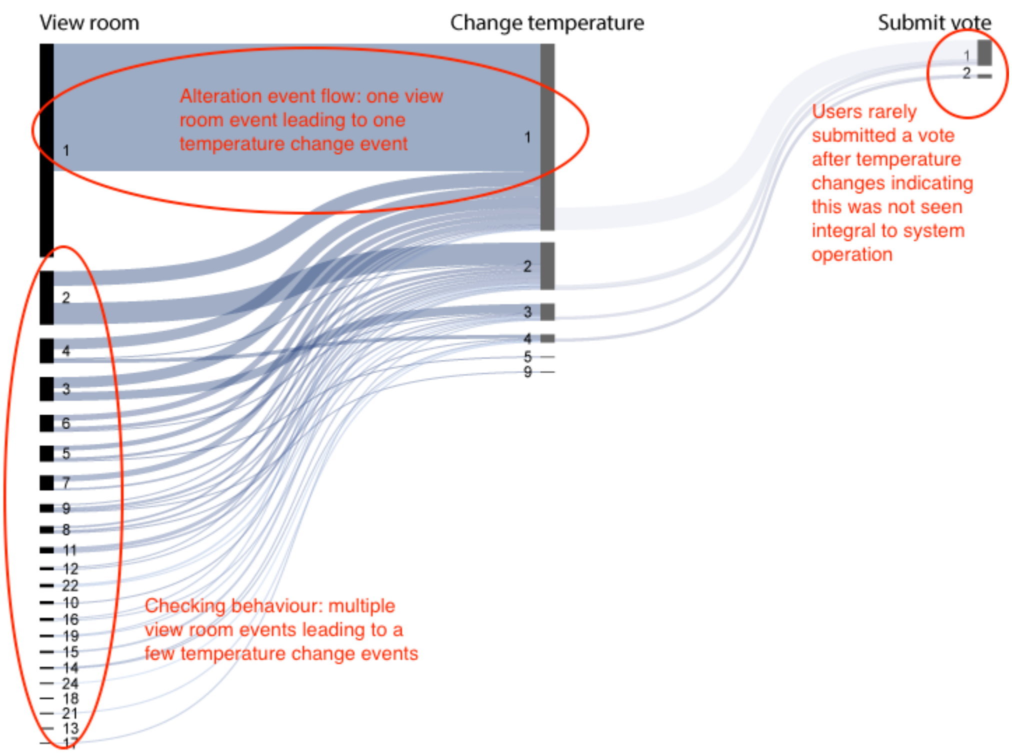


Figure 6-29 number of times an event occurred in a 10-minute time step, arranged in the dominant use case of viewing a room – changing the temperature – providing a thermal feedback vote thereafter.

However, analysis of the view room and change temperature events over time (Figure 6-30) showed that the checking behaviour was extremely 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 relatively similar levels. This was consistent with the users' explanations of how they utilised the system – means of controlling heating. In other words, initial learning period was substituted with more goal-orientated interactions.

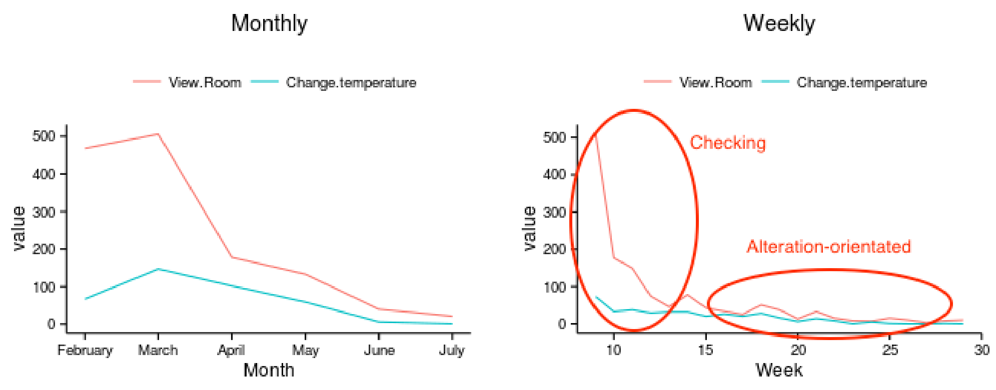


Figure 6-30 total number of View Room and Change Temperature events monthly and weekly over the course of the experiment

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 that can transit to a system state alteration behaviour depending on mismatches. The checking behaviour dominates during initial unfamiliarity with the system and is thereafter replaced by a more alteration-orientated interactions.

6.4.5 Were specific interactions with the system dependent on prevailing conditions?

In order to understand the 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 – users changing room temperature.

It was necessary to match the variety of data from different loggers (sensor data & user feedback votes logged directly in experiment database, app interactions logged via Google Analytics) to rid the data of mismatches. This was done by matching all received thermal feedback votes from all households to existing change temperature events in the same 10-minute time step where the vote fell. Only data with both matching entries (174 pairs in total) were used.

Interestingly, the temperature distribution (black lines) in Figure 6-31 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”.

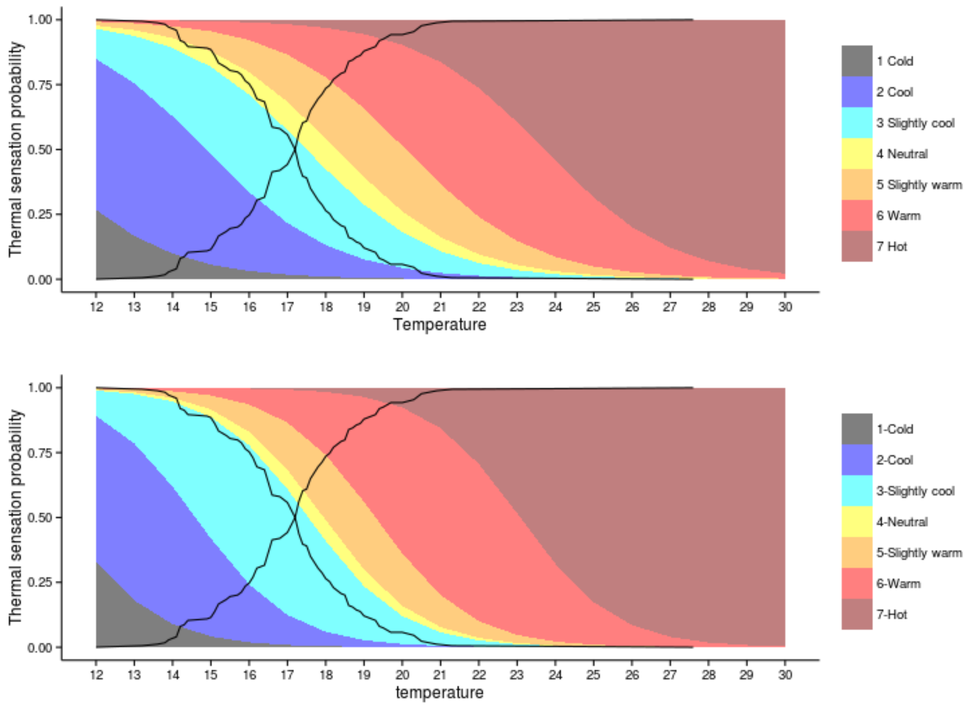


Figure 6-31 cumulative distribution functions for change temperature events plotted against thermal sensation probability distribution functions for all submitted votes (top) and votes given during temperature set-point changes (bottom)

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 (Figure 6-32), it emerged that the highest number occurred at "slightly warm" and "cool" sensations.

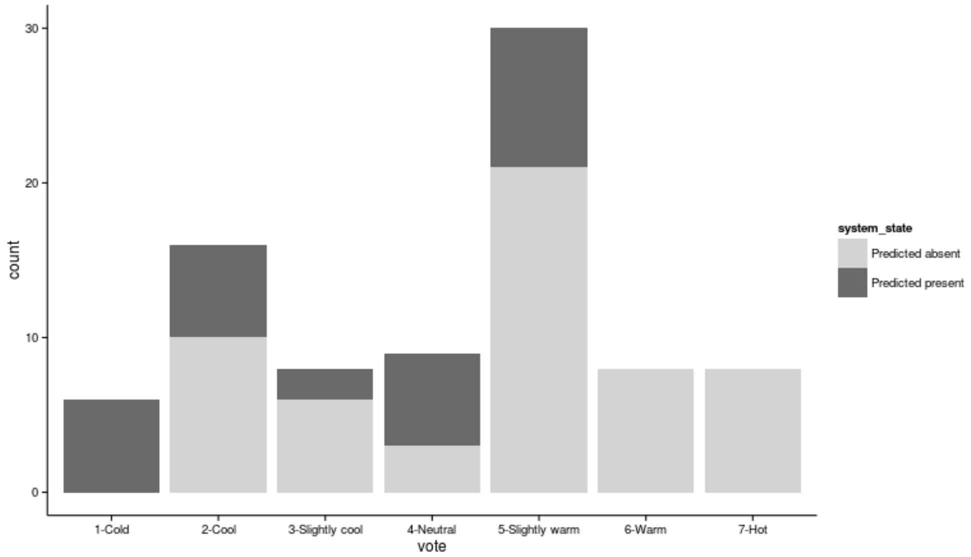


Figure 6-32 distribution of "change temperature" interactions by thermal sensation and predicted presence

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 sensation.

It has been demonstrated how users' vigilance around maintaining preferred conditions emerged as best indicator of likelihood to alter set-point temperature. Contrary to expectations, interactions based on large deviations from thermal comfort range were rarer than less drastic changes around the immediate periphery of the neutral sensation. This suggested "maintaining" comfort and "managing" automation output to be better predictors of interaction than "restoring" comfort and "correcting" automation. In addition, the results highlighted occupants' willingness to behave proactively alongside the system.

6.4.6 Dialogues with the system

An understanding of the users' experiences of dialogues with the system was analysed using interview data and interaction data for away schedules, unexpected presences and push-notification data.

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 for feedback on the environmental conditions through a push notification asking them to submit a thermal sensation vote. 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, highlighting that users were much likelier to perform this action when they initiated the interaction and required alteration on system state than if the system simply 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]

"…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. Over the period from February to August, an average of 6.8 push notifications per household per day were triggered by the system. These 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 gave them an enhanced feeling of control and made it easy to program periods away from the house. The interface also facilitated users to tell the system if they were out late on the day. However, it was noted by some users that this was not a natural interaction for them:

"It is the kind of thing where like yesterday I think I used it but 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, the moments of system proactivity in interaction should be tied to user motivations. It has been highlighted above that exercising override on heater state generates feelings of control in the user. Therefore, 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 for interactions and aim to maximise learning from user-initiated interactions. Similarly, it has been demonstrated that system proactivity without associated motivation from user fails to provide the system with necessary information.

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

All study participants reported to have had an enjoyable experience using the deployed system and highlighted several different reasons for this. 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 in the first place. In addition, him and ‘frugal’ user Diane noted how taking part in the experiment and using the deployed heating system 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 control interface.

Several households highlighted the fact that they enjoyed remote access to the home heating 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”* [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, it's much more friendly, 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 did not 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 were met. All users mentioned cost as a factor in their purchase decision, both from the point of view of installation, as well as savings delivered. Additionally, living in rented accommodation was a barrier to several participants, as well as home type – several users noted that since they lived in relatively small quarters, they felt they wouldn't maximise the potential of the system. Quite 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]

These results outline important factors for consideration when designing comprehensive user experiences for home heating system use.

6.4.8 Evaluation of the spatiotemporal heating algorithm

The heating algorithm was analysed from two points of view – firstly, by its output in delivering thermal comfort and energy saving for users; and secondly, by the performance of key parts within the algorithm that were responsible for providing the output.

6.4.8.1 Providing thermal comfort - user experiences of the two different heating strategies

Comparison of the maximise comfort and minimise discomfort heating strategies revealed that there was little difference between average sensation vote given (minimise discomfort 3.6, maximise comfort 3.9). However, analysis of the reported values of how users felt and wanted to feel at the time (Figure 6-33) between the two strategies showed that in both condition two dominant voting cases prevailed. In the first case, users reported a sensation of “cool” or “slightly cool” and they would have liked to have felt “neutral” or “slightly warm”. In the second case, users reported to have felt “slightly warm” or “warm” and would have liked to have felt a “neutral” or cooler sensation. Interestingly, the Maximise Comfort users had a higher probability of reporting thermal preference of “cold” at thermal sensations of “neutral”, “slightly warm”, or “warm” indicating that the suggested strategy rendered temperatures too high. In contrast, Minimise Discomfort strategy users were more likely to feel “cold”, but their preference at the time was the same as Maximise Comfort users’. It is worth keeping in mind that the Maximise Comfort strategy was only deployed in one house while Minimise Discomfort strategy was deployed in two.

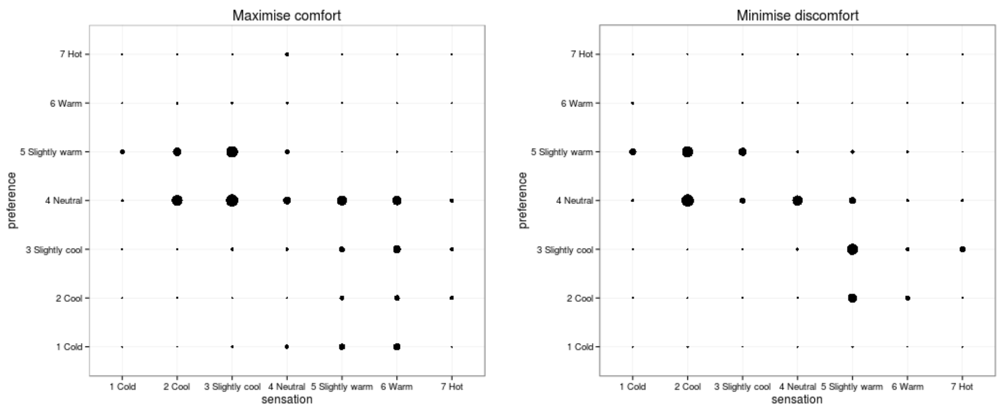


Figure 6-33 Thermal sensation – thermal preference probability distribution comparison between minimise discomfort and maximise comfort heating strategies

Furthermore, comparison between the thermal sensation probability distributions plotted against prevailing temperatures indicates that 2 out of 3 households were likely to experience comfortable temperatures for over 75% of the time (Figure 6-34).

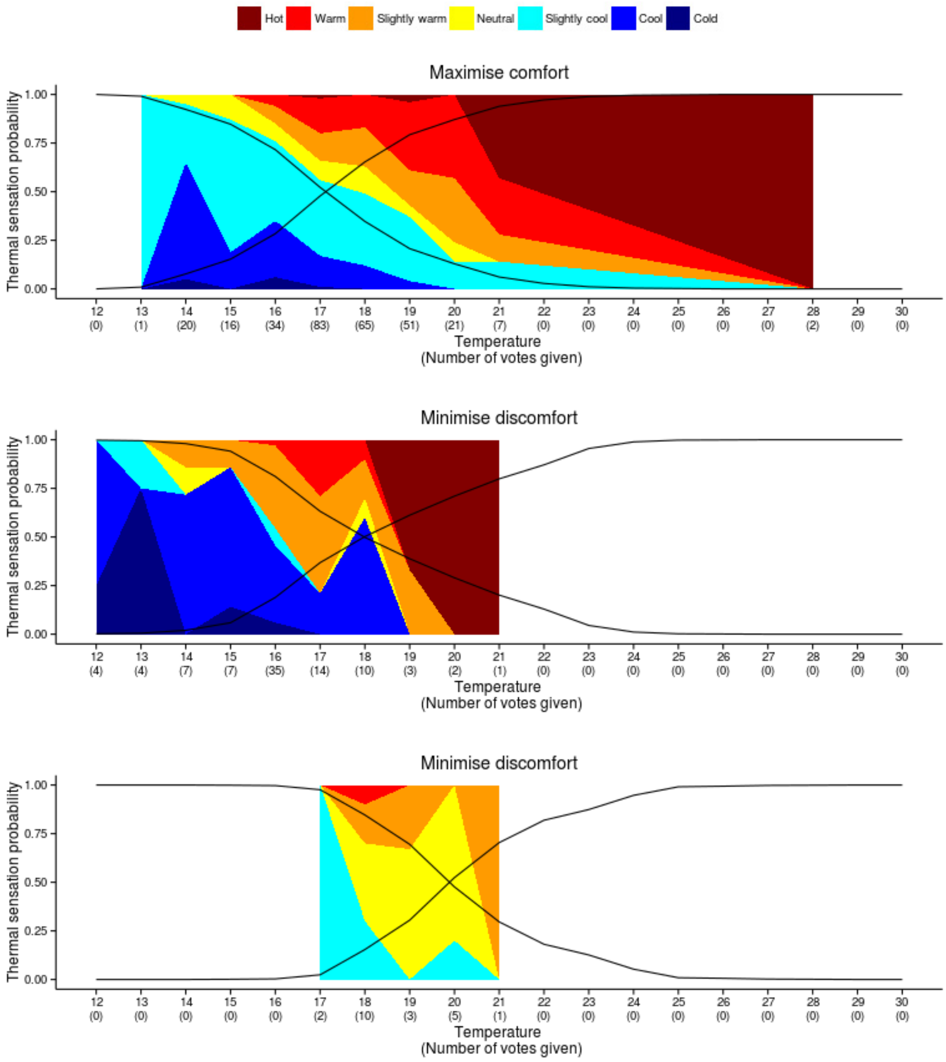


Figure 6-34 comparison of thermal sensation probability distributions with prevailing temperature positive and negative accumulative distribution functions (black) for participating households and their heating strategy (note variation in x-axis)

The ‘fashion’ and ‘everything’s fine’ users’ households (top & bottom on Figure 6-34) were very likely to be within their comfort range (slightly cool / neutral / slightly warm) for over 75% of the time. The ‘frugal’ users’ household (Figure 6-34 middle) was likely to experience “cold”, “warm” or “hot” sensations for the same percentage of time. It can be suggested that this was due to the users operation of the system – limiting the amount of time it was turned on in order to save cost, thus choosing to subject themselves to such conditions. Training the algorithm to these preferences meant that in the summer months, the prevailing conditions inaccurately reflected the users to be experiencing thermal discomfort by being too hot, when in reality this may not have been the case. Diminished engagement in sending thermal feedback votes could also amplify such results.

While the results require verification from a larger sample size, it can be concluded that there is potential for utilising minimise discomfort strategy as a nudging mechanism instead of maximising comfort heating strategy to provide comfort for users at lower temperatures.

6.4.8.2 Algorithm's ability to predict occupant presence and provide a spatiotemporal heating solution

The algorithm's ability to provide thermal comfort has already been addressed above and subsequently this section focuses on the aspects of predicting presence and utilising an optimum start algorithm for pre-heating rooms prior to occupants' arrival.

The recorded presence data and system functionality logs showed that the algorithm was able to predict the users' presence with a reasonable level of accuracy. Figure 6-35 - Figure 6-41 compare average predicted and measured presence profiles for every room in every household and highlight that the algorithm was able to create a fairly accurate pattern across the day.

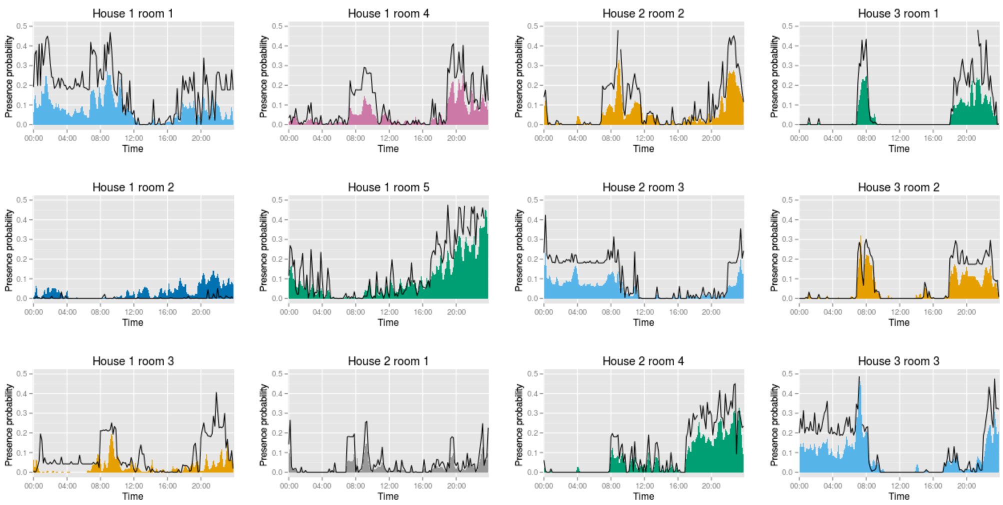


Figure 6-35 comparison of measured (solid) and predicted (line) average presence probability profiles in all rooms for all Mondays

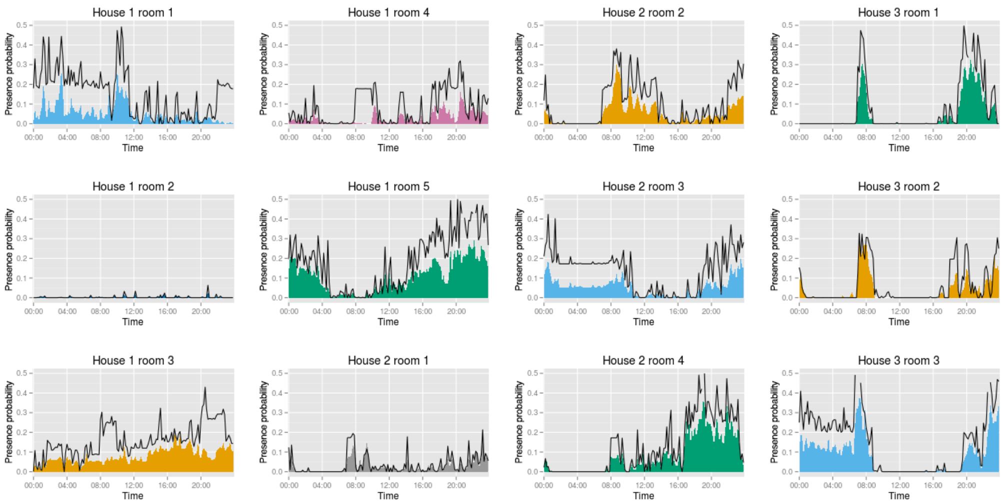


Figure 6-36 comparison of measured (solid) and predicted (line) average presence probability profiles in all rooms for all Tuesdays

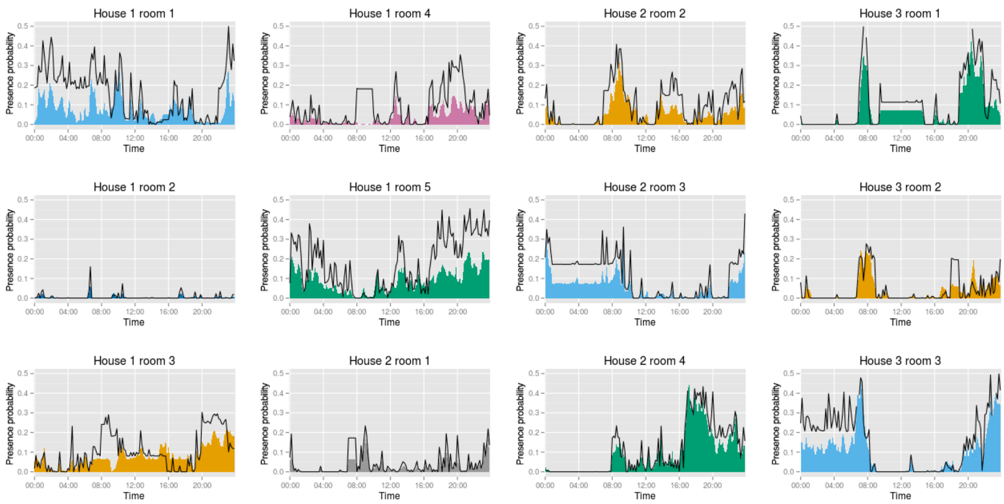


Figure 6-37 comparison of measured (solid) and predicted (line) average presence probability profiles in all rooms for all Wednesdays

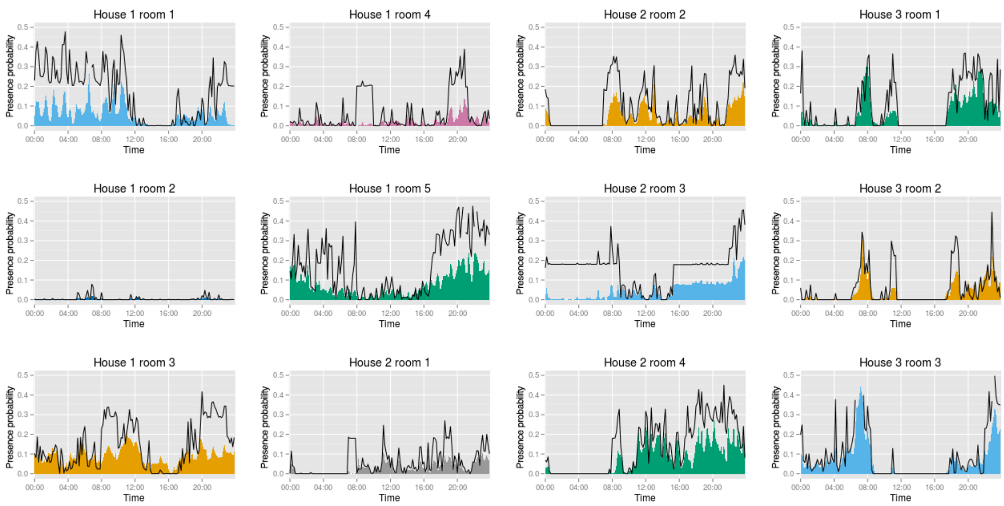


Figure 6-38 comparison of measured (solid) and predicted (line) average presence probability profiles in all rooms for all Thursdays

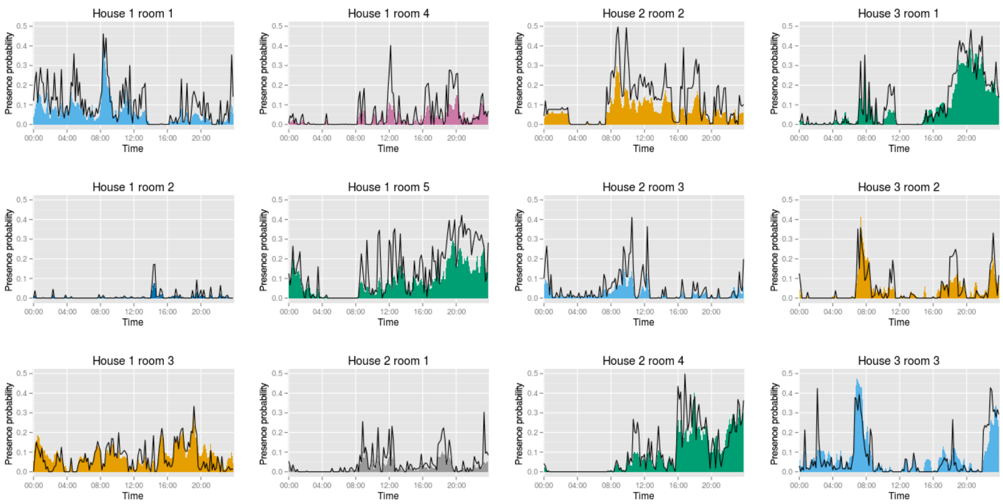


Figure 6-39 comparison of measured (solid) and predicted (line) average presence probability profiles in all rooms for all Fridays

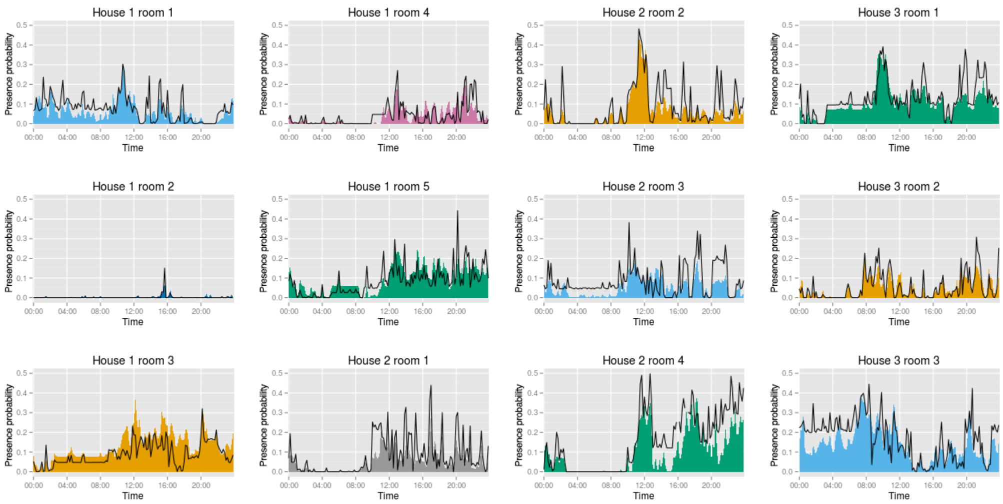


Figure 6-40 comparison of measured (solid) and predicted (line) average presence probability profiles in all rooms for all Saturdays

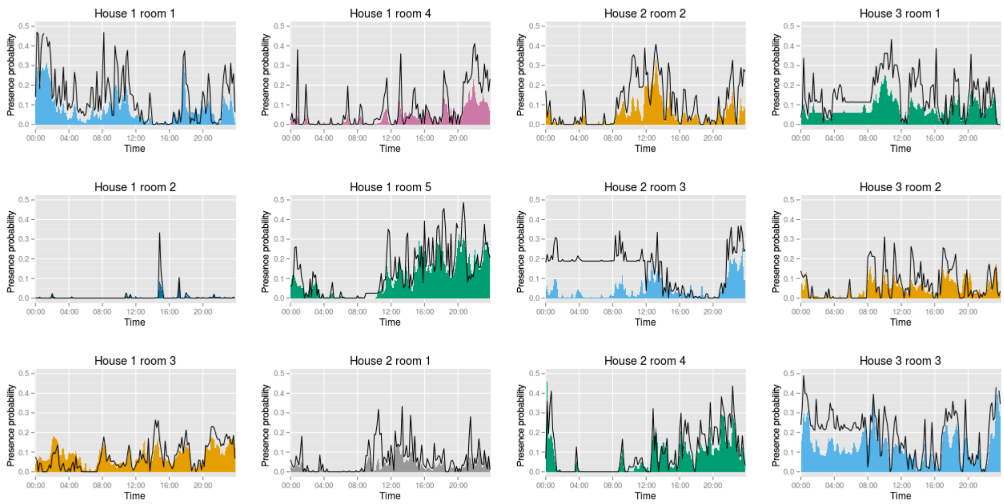


Figure 6-41 comparison of measured (solid) and predicted (line) average presence probability profiles in all rooms for all Sundays

The differences between the same room between days highlights that the algorithm was creating a presence profile specific to the day of the week, adapting itself to the users' different activities regardless of the day. The shapes of the predicted profiles are consistently accurate to the observed presence in the room, however, there seems to be a systematic magnitude error throughout, with the algorithm often over-estimating the likelihood of presence. If motion-sensors are used, this may not be an entirely bad thing as the sensors are likely to miss some time, when the user was present, however, if a more accurate sensor technology is to be used, such faults need to be accounted for. In addition, these magnitude errors could also be caused by a fault in the algorithm by which the algorithm ignored prediction calculations for periods of absence, but motion-sensor data was still being logged, causing a lower average presence profile.

Regardless, these results indicate that the algorithm performed up to expectation in predicting users' presence in rooms with regard to different days and users' differing activities.

6.4.8.3 Algorithm adjusting to its environment and pre-heating in anticipation of occupancy

The algorithm also included an optimum start algorithm (OSA) that aimed to calculate the most appropriate time to start pre-heating rooms for predicted presences. Figure 6-42 highlights the output 'slopes' of the OSA and reveals that rooms that were preheated a sufficient number of times. Houses 2 and 3 had 0-4 pre-heating instances per room which was not sufficient data for the OSA to adapt to the characteristics of the house. Data from rooms in House 1, however, showed how the algorithm adapted and subsequently calculated extremely similar slopes, yet still varying slightly (peaks at the left-hand side of x axis in Figure 6-42). This data highlights that the optimum start algorithm and pre-heating capability of the algorithm functioned as expected in adapting to the characteristics of the house and heat rooms prior to expected presences.

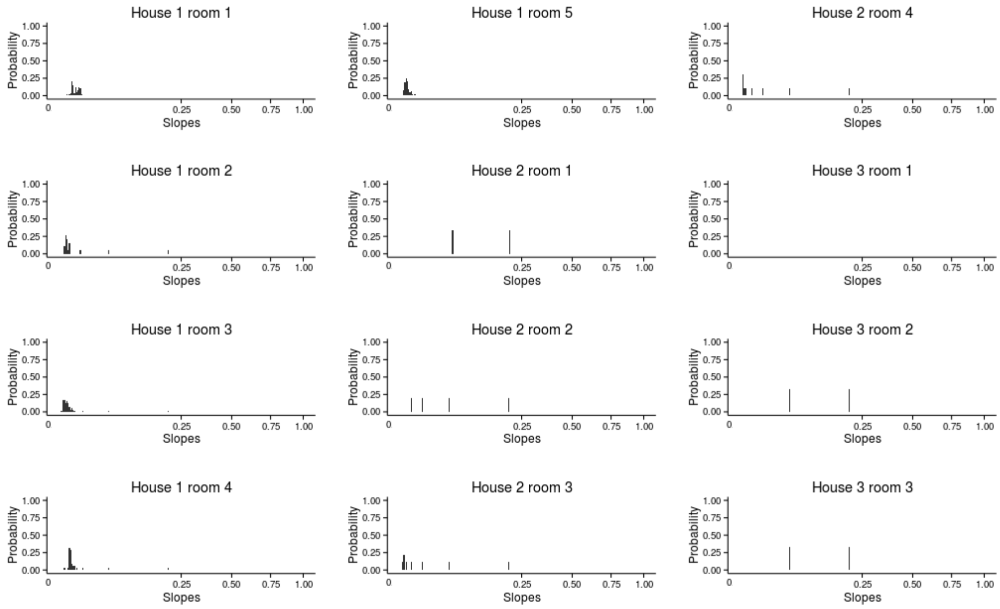


Figure 6-42 probability distribution of calculated slope values (x axis) from all individual rooms

These results highlight that the algorithm performed adequately in delivering a reasonable level of comfort to users while utilising presence prediction and pre-heating capabilities.

6.4.8.4 *What is the potential energy saving from spatiotemporal heating algorithm?*

Since no data was gathered regarding the participants' energy usage prior to the technological intervention, it was not possible to demonstrate any energy savings directly. However, several promising results emerged.

Firstly, when thermal neutrality set point temperature data feedback votes was compared to pre-experiment questionnaire data, it emerged that all households overestimated their preferred temperature by an average of 2.11°C (see Table 6-12 for full details).

	House 1	**House 2**	**House 3**
Average overestimation for household	1.71°C	4.29°C	0.32°C
Total overestimation	2.11°C		

Table 6-12 average over-estimations between comfort temperatures provided by users before experiment in comparison to during the experiment

These results suggest autonomous systems can potentially educate users regarding their thermal preferences in order to lower prevailing temperatures at homes. Furthermore, by treating user-defined temperature set points as a variable rather than a constant, these systems can automatically curtail energy use.

Secondly, heater switch-on logs revealed that across all three participating households and all rooms, the heaters were switched on for an average of 1 hour and 9 minutes (42min Everything's fine user, 2h 20min Fashion user, 25min Frugal user). These results were consistent to the Modern Electric house condition (based on house type and the heating system type) from the simulation activity performed in Chapter 5, where heating durations on times were 3h 45 min (EnergyStar configuration), 1h 32min (Maximise Comfort configuration), and 10min (Minimise Discomfort configuration). On average across the participating households, this duration was just under the Maximise Comfort configuration in the simulation and thus suggest that average 46 $kWhm^{-2}$ saving suggested in the simulation in comparison to an EnergyStar recommended programmable thermostat settings over half a year would be applicable.

6.5 Discussion

This section focuses on the wider implications of the results regarding research methodology, the spatiotemporal heating algorithm, and user experience.

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 the importance of exploring user experiences in a highly ecologically valid setting over a long period of time, which prevents the emergence of potential use strategies and interactions from the rich use context. This has been demonstrated through the emergence of unexpected home-security and inter-occupant ‘spying’ behaviours, which would not have emerged during a short deployment users’ extended familiarity with the system behaviour. Furthermore, the ‘spying’ behaviour also demonstrated the importance of data privacy. While commonly accepted that users’ data should only be accessible to them, we have shown how even if the data is kept personal to the users, it 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 parent being aware of their child’s presence in the house are acceptable. Furthermore, this raises the question whether such instances are the users’ social problem, 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, our spatiotemporal heating algorithm performed adequately when deployed, which similarly to the previous argument made, advocates for testing of other domestic algorithms in the wild, where these can be coupled with the user and their context-enriched inputs. This means that home automation algorithms can be approached from a holistic joint-cognitive systems view ensuring a pleasurable user experience.

Thirdly, emergence of three distinct user behaviour types have been described 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, this research does not attempt to classify behaviours, but explores 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. The 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, these factors have been shown not to be permanent, meaning that users primarily motivated cost, can at times act solely motivated by comfort and vice a versa.

Fourthly, several pieces of evidence have been presented 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, the results have highlighted how applying a mobile interface can cause disarray in operation of a shared space as multiple users can independently alter the system state. As the results showed, this disarray is subject to further complication by personal thermal preference, as well as the manner in which strategies to achieve thermal comfort are formed. Personal habits, economic and comfort priorities, and communication dynamics all affect decisions to interact with the heating system. The users' display of unexpected behaviours in the use of control interface as part of their interpersonal dialogue in the making of these decisions highlighted how availability of information and engagement with the system can alter not only heating decisions, but the communication process leading to the decisions.

Furthermore, the results highlight several implications regarding the user experience of quasi-autonomous home heating systems, which are arranged according to our conceptual model (Figure 6-43).

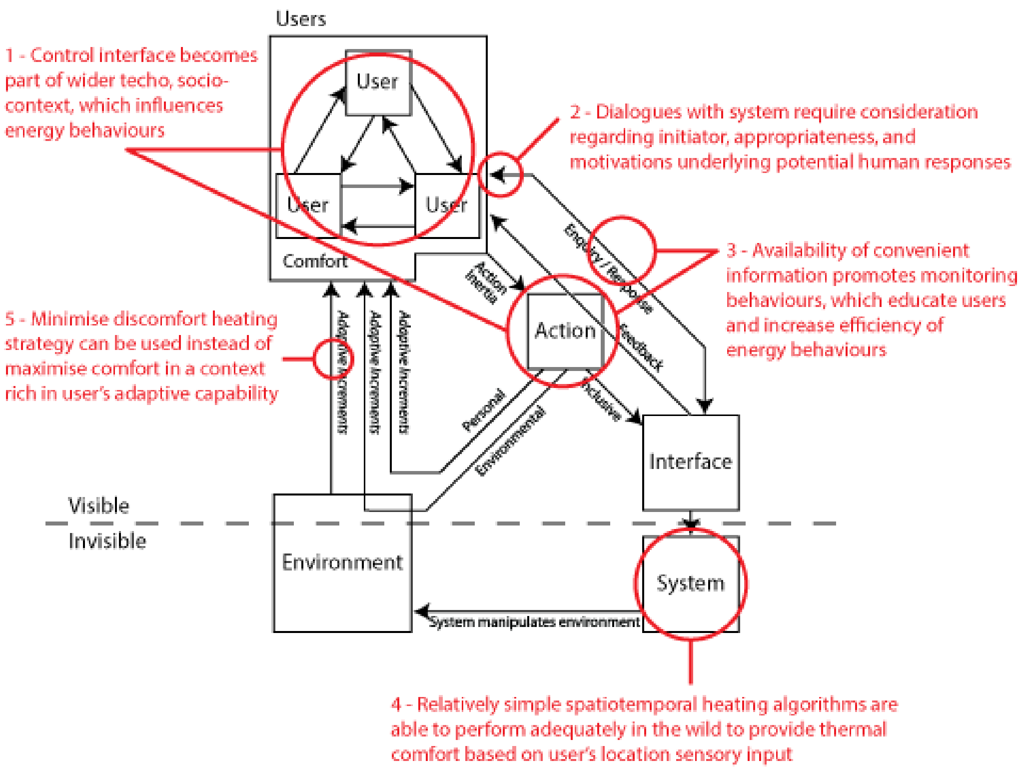


Figure 6-43 conceptual contributions and implications of field study results

As indicated under item 1 in Figure 6-43, the user interface becomes part of that social environment, influencing the social interactions and subsequent energy decisions. In addition, (item 3 in Figure 6-43) the 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 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 Figure 6-43).

This research has 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. The results have highlighted the need for assessing the essence of these dialogues in order to limit noise and prevent disengagement of users. This researcher proposes 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.

Lastly, (item 4 in Figure 6-43) the results demonstrated how a relatively simple heating algorithm could be utilised to provide a spatiotemporal heating solution aimed to provide thermal comfort while reducing energy consumption. Furthermore, (item 5 in Figure 6-43) in the experiment's limited sample, vast differences between the user experience of minimise discomfort and maximise comfort heating strategies did not emerge. While these claims require verification on a larger scale, these results suggest that in an environment rich in thermal adaptation possibilities and user over-ride of the heating system, minimise discomfort strategy could be utilised to lower the energy usage on domestic heating and nudge users towards a more sustainable energy behaviour. However, it was also noted that several potential improvements to the algorithm could be made. Namely, the algorithm could be more responsive, not acting on measured data at midnight to compile a schedule for the whole day, but rather find a most suitable dataset continuously throughout the day, similar to the data selection & prediction logic highlighted in (Scott et al., 2011). Secondly, users' explicit thermal feedback may not be a reliable source for thermal preference data. It should be endeavoured to decouple users' thermal sensation feedback from heater behaviour feedback. For example, users' interactions to switch heating off can be motivated by energy conservation rather than feeling too warm. Explicitly asking for motivational feedback would become excessively demanding of the user as the result have shown in terms of soliciting thermal feedback, suggesting that systems should aim to obtain much of their input information from naturally occurring interactions through inference. As mentioned, this approach needs to, however, be highly critical of users' motivations in order not to build a false image of the user and their preferences.

All of the aforementioned in combination with 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 desired. It is can be suggested that the users displayed a situated action pattern of behaviour (Suchman and Reconfigurations, 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. Therefore, this researcher suggests an entirely holistic approach focused on the interactions of users embedded within a context, to be central to the design of automated home heating and other systems.

6.6 Conclusions and future work

The experiences uncovered in this experiment 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. 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.

7 EMERGENT MODELS

7.1 Chapter overview

This chapter presents the emerging models from the activities described in Chapters 3, 4, 5, and 6 and utilises a rich picture analysis methodology. The aim of this activity is to construct a holistic view of the context of use of quasi-autonomous spatiotemporal home heating system, highlighting user experience design considerations, potential interactions with the heating system and its interface that may take place as well as the motivations behind them. Firstly, the applicability of the methodology is discussed, the emergent rich picture presented and discussed, and its implications presented.

7.2 Methodology

This activity utilised rich picture analysis, a method that is rooted in the Soft Systems Methodology (SSM) and sociotechnical approaches to system design (Mumford, 1985). Soft systems methodology can be classified as a business process modelling technique, of which there are many. It was chosen over others (key strength and weakness of each method highlighted respectively in brackets) including data flow diagrams (easy to understand / only flow of data is shown), role activity diagrams (supports communication / not possible to be decomposed), integrated definition for function modelling (shows inputs, outputs, control and mechanisms overview and details / tend to be interpreted only as a sequence of activities), or object oriented methods (enactable model to control and monitor processes / excessively large and detailed, fragmented information) due to the method's ability to support communication and understanding of the process, despite its lack of structure and particular notation (Aguilar-Savén, 2004).

The rich picture has been discussed to be a broad, high-grained view of the problem situation that depicts the primary stakeholders, their interrelationships, and concerns (Monk and Howard, 1998). Key components include structure, process, and concerns, with structure referring to aspects of the context that are slow to change including all people involved who are affected by an intervention system, process referring to the transformations that occur in the process of the work (e.g. flow of goods, documents, or data), and concerns referring to particular individual's motivations for using the system that result in the different perspectives each person has (Monk and Howard, 1998). The method was seen in particular to match the research's need to convey 1) broad scope, 2) highly detailed nature, and 3) focus on human experiences within the system. Subsequently, a rich picture of the environment within which automated home heating systems operate is presented.

7.3 Emergent model

The emergent model presented in Figure 7-1 plots the relationships between the knowledge generated in the studies discussed in previous chapters.

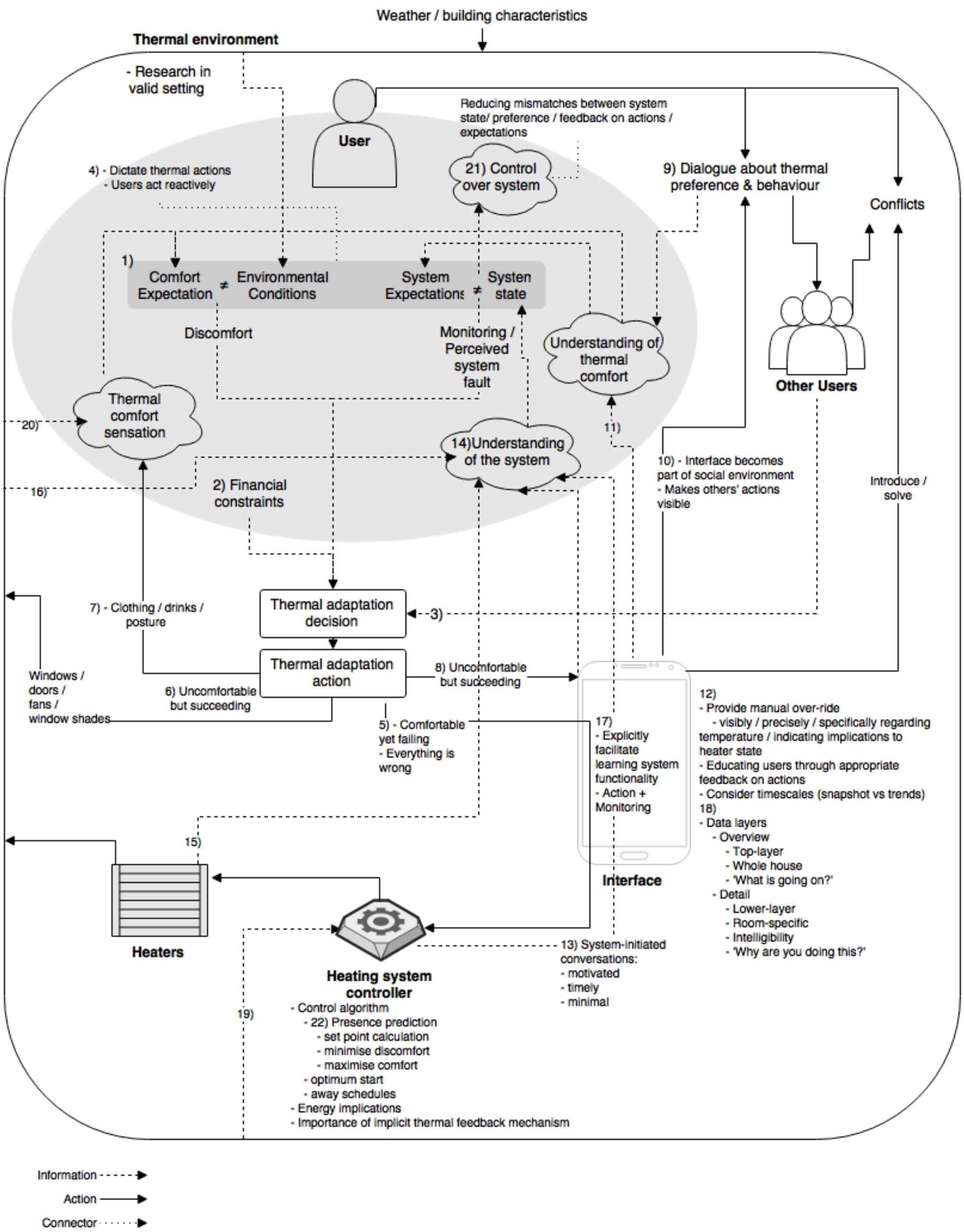


Figure 7-1 rich picture analysis of knowledge created in this research

Figure 7-1 details the user experience of heating system user, all elements affecting their interactions with it, and the multitude of factors in play within the broad home environment. The rich picture was loosely based on the mismatch-action model (item 1 in Figure 7-1) developed in Chapter 3 since the action routes were supported by subsequent studies. Mismatches between environmental conditions, system state, and user's expectations of those determined the action route taken, within the social and financial constraints

(2 & 3 in Figure 7-1). The user acted reactively in their interaction with the heating system or interface (4 in Figure 7-1) to eliminate discomfort or perceived system fault with the former being a stronger indicator of alterations to heating system state (5 in Figure 7-1). Other action routes included alteration the environment, personal adaptation, or system functionality enquiry (6, 7, or 8 respectively in Figure 7-1). Dialogue with other users regarding thermal behaviour (9 in Figure 7-1) was influenced by each user's understanding or preference of thermal comfort, as well as the interface, which became part of the social environment and the conflicts between them (10 in Figure 7-1). The conflicts and dialogues influenced user's understanding of thermal comfort and the actions they were thus likely to take to maintain their own comfort. User's understanding of thermal comfort was also influenced by the control interface, that educated the user regarding their thermal preference and the temperatures at which the user felt comfortable (11 in Figure 7-1). In addition, this education could be enhanced by appropriate feedback on user over-rides and the consequences of these actions (12 in Figure 7-1). The interface also had to exercise caution when instigating communication with the user (13 in Figure 7-1), primarily ensuring initiated communications were motivated, timely, and minimal. The interface was also the user's primary source of information regarding system functionality (14 in Figure 7-1, others sources including audible / visual / thermal feedback from heaters – 15, and feedback from the environment – 16), therefore being required to familiarise the user with system's functionality through action-based learning (17 in Figure 7-1). Following the learning, the interface was required to provide appropriate levels of information to the user based on the user's needs, which could broadly be categorised as need for establishing an overview of the state of the environment, and understanding problem-specific functionality to restore equilibrium (18 in Figure 7-1). These explanations played a major role in establishing an understanding for the user of the system's functionality. This in turn affected the user's expectations of the system, misalignment of which

to system state, alongside delayed feedback of user actions cause the user to experience reduced control over the heating system (21 in Figure 7-1).

The heating system control algorithm utilised the user and the environment (19 in Figure 7-1) to create a suitable thermal environment by controlling the heaters. It did so through predicting user presence, calculating a suitable set-point temperature, selecting optimum times for heaters to be switched on or off, and incorporating user-provided absence information. However, user thermal preference was a complex aspect to capture as interactions with the interface held dual-motivations of thermal preference and heater control, meaning that the system needed to infer preference implicitly. The control algorithm could nudge the energy behaviour by selecting a lower energy impact heating strategy without the significantly altering the user's thermal sensation (22 in Figure 7-1).

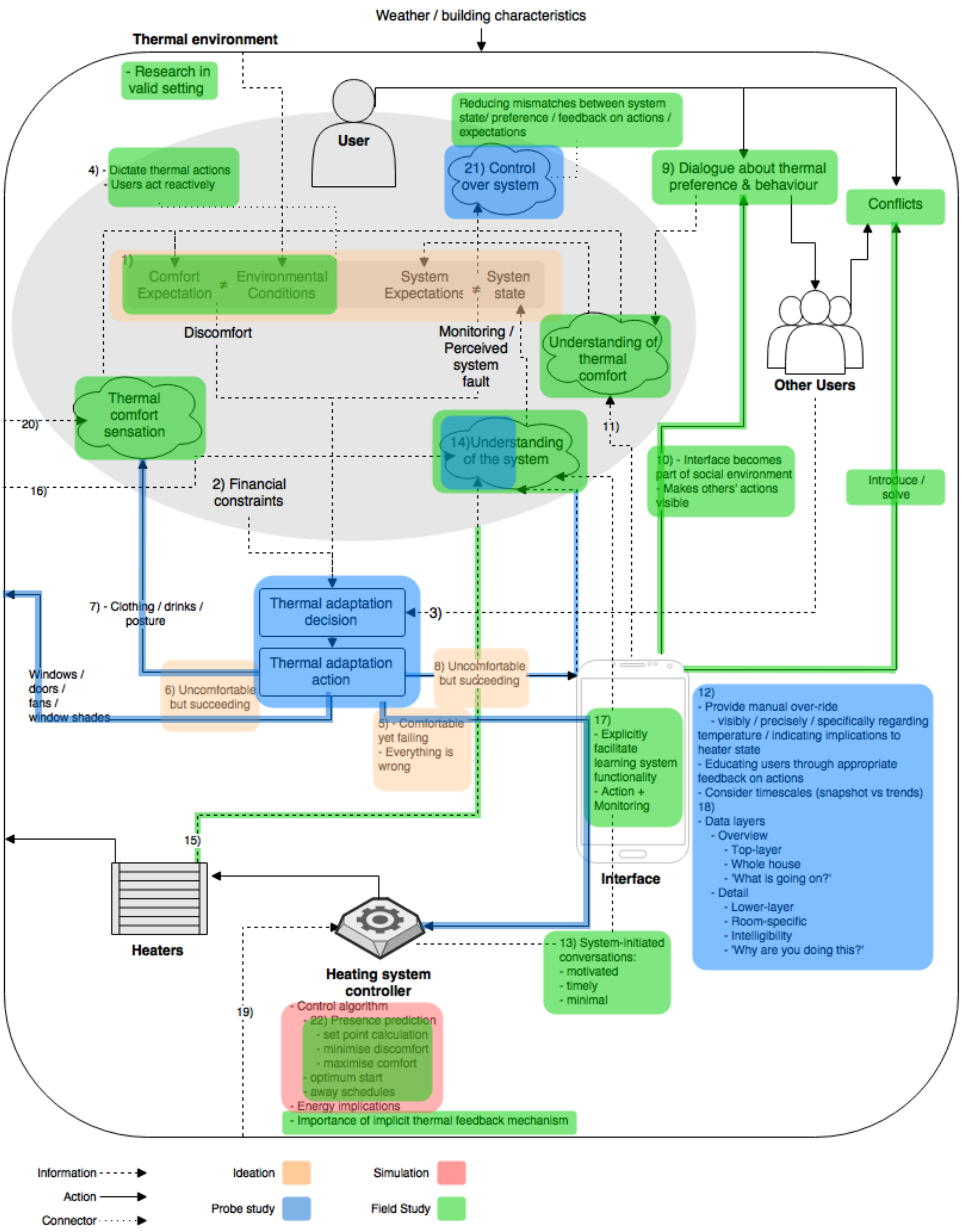


Figure 7-2 contributions of each activity to the rich picture

Figure 7-2 above highlights the contributions of each undertaken activity in the construction of the rich picture. This rich picture provided the detail and context required to draw design guidelines for interface design for home automation systems.

7.4 Design Guidelines

Key considerations from the rich picture were assembled to guide interface design for home automation systems. These merited a separate output for two distinct reasons. Firstly, everything discussed up to this point was viewed within the context of automated home heating systems. However, it was recognised that some aspects of the context and its implications to interface design reached beyond the automated application and were more fundamental to any system that could be described as ambient intelligent, autonomous, or ubiquitous. Secondly, the interface-focused activities and research contributions did not aim to propose an improved design artefact, but rather to inform design practice and as such are naturally broader in scope, making themselves easily extendable to an array of applications. Therefore, this section focuses on establishing key questions to be asked of designs and of designers in order to challenge them to consider aspects that if addressed, make for a successful user experience. In other words, the aim is not to tell designers what their proposed interface should be like, but rather to ask relatively open questions as means to provoke designers to pay attention to important elements. The questions are purposefully open, allowing designers to define parameters within the questions themselves, making the questions specific to the chosen application. The designer's subsequent ability to answer the questions positively would deliver a successful user experience. The seven design questions are displayed below, separated by a short discussion/explanation of each and an example provided where appropriate.

1) Does the interface facilitate appropriate manual over-ride?

    a. Should over-ride utilise specific or approximate input?

    b. Is feedback on the impact of user actions provided?

c. Is the over-ride impact on invisible parts of the system visualised to the user?

As with any automation, at times the users will need manual over-rides. It is the interface's responsibility to ensure that the manual over-ride does not compromise the automation's ability to reach its goal, nor to deny users control over the automation. This is a balancing act. E.g. if the automation is designed to provide energy saving, the manual over-ride must not become a way for the user to disengage for their energy behaviour.

2) Does the interface utilise appropriate information levels?

a. Does the interface allow users to achieve a quick overview of the current situation including all critical actors?

b. Does the interface explain system functional logic in sufficient detail?

i. What the system knows?

ii. How it knows it?

iii. What it is doing about it?

iv. Why it is doing that?

v. …?

Automated systems and ambient intelligence applications utilise complex thinking patterns to achieve their goals. Users' interactions must not be made cumbersome by vast amounts of detail, however, this is required when mismatches between system state and expectations of system state occur. e.g. can the interface answer user's questions of "What is happening in my house?" and "Why did it turn my lights on?"

3) Does the displayed information address the appropriate context?

a. What are the borders of physical spaces that the user is interested in?

Home automation can address various physical spaces. These spaces are influenced by various actors within them. When the user interacts with the interface, the interface needs to navigate the boundaries of these spaces to address the relevant content and context. E.g. should the interface adjust the displayed information or controls based on the user's location or other actions performed within the interface?

4) Does the interface explain system functionality in appropriate timescale?

a. Trends vs snapshot?

b. Does this vary for info levels or context?

c. Should trends be extrapolated into the future?

Automated systems often work in sequences of events and triggers to current activity may be rooted hours / days / weeks before, or the system's activity may not make sense without communicating events predicted to take place in the future. Such information would be lost in a snapshot of current system state. In is the interface's responsibility to display the relevant information in a suitable manner.

5) Are system-initiated dialogues with the user motivated, timely, and minimal?

a. Does the communication solve a critical problem for the user?

b. When does the dialogue need to take place to solve the problem and not disturb the user?

c. Is it possible to achieve a similar level of operation without requiring the dialogue?

If the interface possesses capabilities to initiate contact with the user, it is important to do so appropriately. It should be maintained that interacting with the interface is not the primary activity within the home space and users would wish to never have to concern themselves with the functionality of the automation. Any system-initiated dialogue must be critically assessed? E.g. if the interface can notify the user using any modality, what are the negative impacts of these notifications in any use / misuse case?

6) Does the interface educate and engage the user?

    a. Does the interface utilise a learn-by-doing approach?

    b. Does the interface employ suitable means of informing the user of their preferences?

    c. Does the user understand the short-term and long-term consequences of their interactions with the interface?

Introducing a new device to the home context requires users to develop a new mental model about the device's functionality. It is the interface's responsibility to teach the user to operate the interface in a most efficient way, while allowing the user to define what efficient means. E.g. is the user aware of all functionality at their disposal, or are they able to eliminate undesired functionality?

7) How does the interface alter the social dynamic between users' conflicting views?

It should be assumed that every interface alters the social interactions taking place at home in some way. Both positive and negative effects need to be considered, as well as potential actions that may follow conflicts between users regarding the interface. E.g. consider users not using the automated system the same way or having opposing preferences. What are the consequences of this?

If the designer can confidently say that their interface appropriately addresses all these seven questions, it is most likely that it will deliver a successful, pleasant, and meaningful user experience, whichever form it takes.

7.5 Conclusions

This chapter provided means of observing the automated home heating context, based upon the results of all the activities undertaken as part of this research. This was done utilising rich picture analysis, which adopted a broad view, factoring in a wide variety of actors influencing the interactions taking place, and provided detail regarding each of those actors and their relationships. In addition, interface design guidelines for similar applications was provided. The guidelines took a broad view, aiming to establish a method for provoking designers to focus on key qualities that would allow their designs to provide a successful user experience in this domain.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Chapter overview

This chapter reflects on the technological outputs of the research, sums up the research findings while referring back to the aims and objectives established at the outset, and makes recommendations for future research. Answers to research questions are highlighted and broader contributions to knowledge outlined. The chapter ends with a discussion of the limitations of this research through recommendations for future work and conclusions of what was presented.

8.2 Reflection on research technology and its context

At the beginning of this research, first ‘smart’ thermostats were entering commercial market place, notably the Nest learning thermostat (Nest, 2012) that played a role in inspiring this work. Subsequently, over the course of this research project, technological and societal advancements have rendered an increase in the adoption of such devices, as well as their capabilities, not prevalent at the outset. Therefore, it is of worth to place the heating system developed as part of this research within the commercial and academic state of the art context.

Commercially, several new products have entered the market and established brands have upgraded their products to include the advanced capabilities. Table 8-1 below compares the heating controller described in this work with the top ten ‘programmable thermostats’ for the year 2017 from a commonly used review and comparison website (toptenreviews.com, 2017). Several trends can be seen in Table 8-1, that broadly categorise the smart thermostat market at the time of writing. Firstly, it has become commonplace for heating controllers to be connected through Wi-Fi and include features including remote control, away features, and information about HVAC system or weather.

Feature	**Controller presented in this research**	**Nest Learning Thermostat (Nest, 2017)**	**Ecobee3 (Ecobee, 2017a)**	**Ecobee Smart SI (Ecobee, 2017b)**	**Honeywell Lyric Round (Honeywell, 2017a)**	**Honeywell Wi-Fi Smart (Honeywell, 2017b)**	**Carrier Cor (Carrier, 2016)**	**Radio Thermostat CT-80 (Radio Thermostat,**	**Emerson Sensi** (Emerson Electric, 2017)	**Lux GEO** (Lux, 2017)	**Venstar ColorTouch** (Venstar, 2017)
Controllable through mobile app	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Seven-day manual scheduling	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Away/Vacation Features	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Auto-Schedule by algorithm	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-	-	-
Instant Savings Feedback	-	Yes	Yes	Yes	Yes	-	Yes	Yes	-	-	-

Time to Target Temperature	-	Yes	-	-	-	-	-	-	-	-	-
HVAC system condition status monitoring	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Displaying outdoor weather conditions	-	Yes	Yes	Yes	Yes	Yes	Yes	-	Yes	-	Yes
Outdoor weather included in comfort algorithm	-	Yes	Yes	Yes	Yes	-	-	Yes	-	-	-
Humidity sensor integration	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-	-
Motion sensor integration	Yes	Yes	Yes	-	Yes	-	-	-	-	-	-
Geofencing to detect occupant leaving and returning	-	Yes	-	-	Yes	-	-	Yes	-	-	-

Zonal control	Yes	-	Yes	-	-	-	-	-	-	-	-
Dynamic temperature set point	Yes	-	-	-	-	-	-	-	-	-	-

Table 8-1 Comparison of commercial home heating systems with proposed controller

Secondly, it can be observed, that the more advanced models distinguish themselves through features that are yet to penetrate the mainstream such as automatic schedule generation, incorporation of weather data within the scheduling algorithm, presence data through motion sensors, or instantaneous feedback. And lastly, there are some really novel features like geofencing or zonal control, which are included in only a small number of controllers. The control system presented here falls on the border of the last two groups described, meaning, that it did not include some of the more basic features expected of a thermostat (e.g. 7-day manual scheduling or information about the HVAC system) or some of the more advanced features penetrating the mainstream (inclusion of outdoor weather data or geo-fencing). However, the research controller focused on features that are emerging (presence data integration through motion-sensors), or highly uncommon and experimental features (zonal control or dynamic set point calculation).

Indeed, the same trends can be seen in academic publications within the field. In a review to assess the quality of current knowledge on domestic heating controls, Lomas et al. (2016) classified and quantified literature on various control systems (see Figure 8-1) and highlighted that so far focus has been on more traditional control systems. However, as Peacock et al. (2017) have pointed out, the information deficit model (if provided information about their energy consumption, people will act predictably and reduce their consumption) has been debunked and most home energy management systems (HEMS) can be characterised by a lack of long-term engagement. Therefore, at the time of writing, latest HEMS have focused on researching the aspects of automated systems as these can outlast user disengagement. A study among the Nest thermostat users found difficulty in users understanding how the system worked and causing workarounds (Yang and Newman, 2013). The authors suggested exception flagging (implicit user input collected while allowing users to flag exceptional inputs), incidental intelligibility (intelligibility delivered opportunistically, in small, occasional, incidental interactions), and constrained engagement (interaction between user and system is necessarily sparse and peripheral yet continuous and long-lived) (Yang and Newman, 2013). Such studies align with the research presented and (and display the rich understanding gained from longitudinal experiences with the device, a cornerstone of this research) and bridge the gap between academia and industry's advancements.

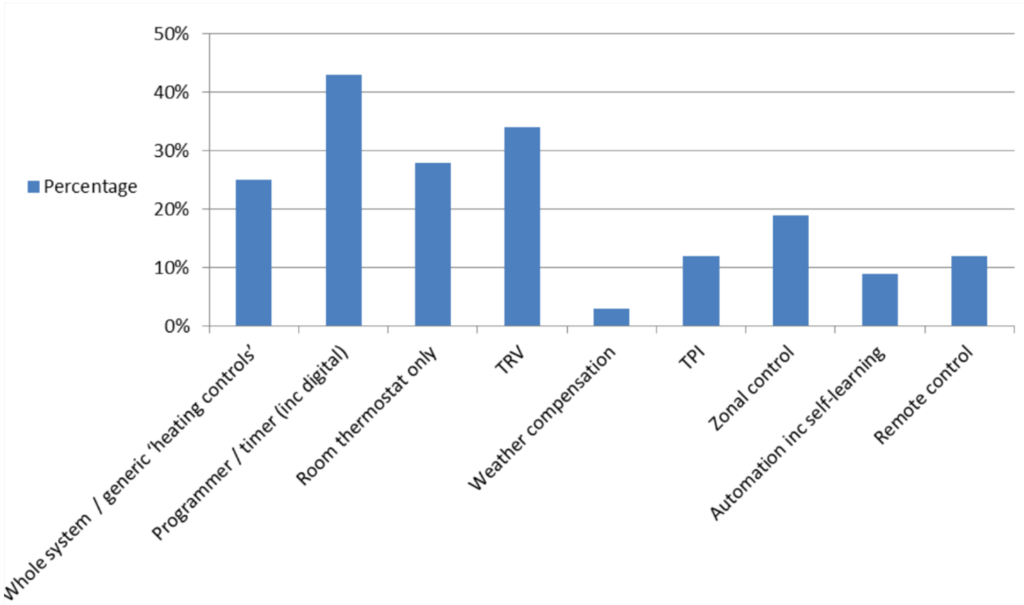


Figure 8-1 percentage of documents that focus on each of the heating controls (as seen in Lomas et al., 2016)

Similarly, other ideas presented in this work are now being researched elsewhere. Ghahramani et al. (2014) presented an interesting approach to HVAC control in an office building by selecting set point temperatures based on occupant votes, calculated using fuzzy logic. This and similar work (Nowak and Urbaniak, 2016) for classrooms highlight the research trends focused on agile and personalised heating controls at the time of writing.

The state-of-the-art at the time of writing described here and larger bodies of surrounding work described in Chapter 2 define this research's location in a research niche between large bodies of knowledge. In terms of commercially available products, the research has explored the experimental and "up-and-coming" features, while within the academic scope, it has asked recently prevailing questions in a so-far unexplored domain of domestic dwellings. In addition, this home context has been explored by combining the explored areas of presence prediction, thermal comfort prediction, and behavioural nudging in a unique combination.

8.3 Meeting the Aim and Objectives

The aims of this this research were established in Chapter 1, outlining the broad contributions of this work. More specific objectives in the form of research questions were established after an exploration of existing knowledge in Chapter 2 and these, alongside answers to them can be seen in Table 8-2 below.

Research question	**Answer**
Q1 - What is the context within which these interfaces are used?	The context of use for automated home heating system interfaces was initially answered utilising data visualisation techniques to create a conceptual model in Chapter 4 and subsequently elaborated upon using a rich picture approach in Chapter 8. The interfaces were used in a highly complex context with a multitude of actors. The environment was defined by the physical building space, which in the UK housing stock could be described as outdated and displaying poor performance. Within this space the interface had one or more users, each influencing each other through social interactions and each interacting with the interface based on the alignment of the environmental conditions and system state to their expectations of those elements. Interactions with the interface formed a minority of a vast range of activities. Users' navigation of the

	context and the information that the interface (primary, but not sole source of information regarding system functionality) displayed could be classified as situated action behaviour, utilising case-by-base observations of the environment to fulfil broad goals and not conforming to a sequence of carefully planned activities.
Q2 - To what extent can spatiotemporal automated heating minimise energy use while providing thermal comfort?	The spatiotemporal heating control algorithm's ability to deliver dual goals of thermal comfort and minimised energy use were answered in the simulation activity in Chapter 5. The results showed that the proposed control algorithm could on average deliver 46 $kWhm^{-2}$ saving across various configurations in in comparison to a standard programmable thermostat over the period of 180 days. This was possible without compromising on thermal comfort.
Q3 - How are different heating strategies experienced by users?	Question regarding users' experiences of heating strategies was answered in the field study in Chapter 6 and in the simulation in the Chapter 5. The results showed that to a great extent, users reported the same thermal experiences for the minimise discomfort and maximise comfort heating strategies. The lack of vast differences meant that the minimise discomfort strategy could be utilised instead of the maximise comfort, thus delivering 19.4 $kWhm^{-2}$ energy savings.
Q4 – How do visibility of	Visibility and intelligibility questions were answered in probe and field study activities in Chapters 5 and

feedback, and intelligibility affect the user experience involving understanding and control?	7, respectively. The results showed that intelligibility as well as 'why' explanations were extremely useful for users to establish an understanding on system functionality. However, it was shown that intelligibility should not be an interface design goal in itself, but rather fit in with broader UX design regarding data levels, context specificity, and timescales. Visibility of feedback on both user actions as well as intelligibility of system actions was important to users for maintaining control over system. However, it was also shown that experience of control did not diminish simply due to increased autonomy, or increase because of explanations, but rather originated from a variety of factors that could best be described as alignment of expectations and reality. Explanations affected this alignment by modifying the expectations.

Table 8-2 answering research questions

The research questions were answered through a number of different activities that followed a holistic design process path from research and initial concept work through to user involvement and different stages of prototyping leading to a longitudinal in-situ deployment. Table 8-3 summarises these activities as well as their individual contributions.

Activity	Aims of the activity	Contribution
Ideation	Establish an understanding of the complex architectural, technical, social context within which automated home heating systems are used.	Development of a data-driven conceptual model explaining the factors at play in the wider context of autonomous home heating systems and some potential interactions with the heating system that might take place. The model explained these interactions as resulting from different combinations of mismatches between perceived environmental conditions, comfort expectations, perceived system state, and user expectations of system behaviour.
Participatory design	Understand user values, motivations, and preferences, and include these in the design process.	Design criteria informing **field study** interface design and **rich picture analysis,** which was drawn from the assessment of 19 user-generated interface designs. Four interfaces that were modified and used as technology probes in **prototype analysis** activity.

Prototype analysis	Explore the role of different interface qualities and how these qualities affect the user experience of controlling the heating system via mock interfaces used as probes.	User interface design recommendations regarding user overrides, feedback on interactions, thermal feedback, data layers, and system explanations. Descriptions on how these design qualities can be utilised at different mismatches according to the **conceptual model developed in Ideation** activity to provide user experience rich in intelligibility. These were also used in **rich picture analysis** activity to draw design guidelines for autonomous home systems.
Simulation	Assess the developed heating control algorithm fitness for purpose in providing a spatiotemporal heating solution that reduces energy use without compromising on user thermal comfort.	Demonstrated the proposed home heating control algorithm's fitness for purpose in administering spatiotemporal heating control. Highlighted the algorithms ability to deliver an average 46 $kWhm^{-2}$ energy saving above EnergyStar recommended settings for programmable thermostats, and showed how a 'minimise discomfort' heating strategy can be used instead of a 'maximise comfort' strategy to further

		increase energy saving without compromising on occupant comfort.
Technology intervention in field study	Explore the thermal, social, and technical user experiences of the proposed automated heating system in situ over an elongated period of time.	Demonstration of the ability to achieve a fine degree of spatiotemporal heating control in the domestic setting and the effects of a quasi-autonomous system delivering this control on the wider socio-thermo-technical environment over a long period of time. Identified diverse heating system use behaviours and conceptualised these behaviours and the users' experiences in line with the conceptual model presented in **ideation** activity. Highlighted the potential for a quasi-autonomous system to nudge users towards energy-efficient behaviour by lowering set-point temperatures without compromising users' thermal comfort experiences.
Rich picture analysis	Construct a holistic view of the context of use of quasi-autonomous spatiotemporal home heating system,	Visually and conceptually explained the wide context of use for autonomous home heating systems, highlighting user interaction routes, design

	highlighting user experience design considerations, potential interactions with the heating system and its interface that may take place as well as the motivations behind them.	considerations, and knowledge transfers between human and machine actors. Provided design guidelines for autonomous or quasi-autonomous home systems reaching beyond the chosen heating domain.

Table 8-3 summary of the undertaken activities, their aims, and contributions

Summarised, this research provided methodological, empirical and theoretical knowledge contributions relevant for applied cognitive ergonomics, thermal comfort, and home automation research fields, as outlined in Chapter 1.

8.3.1 Methodological contributions

This research highlighted the attainability of relatively low-tech, off-the-shelf technology deployment in-situ for investigation of ambient intelligent sensor-based systems. It has been demonstrated that such technology can display adequate service uptime, creating a virtually seamless experience for the users. This in turn challenged the notion of user experience studies being confined to a laboratory setting with snapshot exposure times. By this it is meant that differences should be made between 'testing' an interface and 'assessing its user experience'. The latter referred to the users' longitudinal exposure to the technology in a highly ecologically valid setting. Such assessment allowed for un-foreseen nuances in UX and user behaviour to emerge, both of which would not prevail in a 'testing' session. This research has demonstrated that academia can utilise readily available open-source code libraries and low price-point services to create true-to-life smartphone application-based heating system control interfaces similar to those available on the market at the time of writing. Therefore, not only would such an approach increase the ecologic validity of the results, but also increase the research's impact by allowing results and methodologies to be easily transferred to industry.

Furthermore, the demonstrated methodology would also allow researchers to iterate interface designs and experimental parameters over the course of the longitudinal deployment, if need be. The distributed deployment allowed the researcher to make real-time decisions based on live data at every stage of the deployment, as well as ensure everything was in full working order. While such an approach would require a flexible study design, it does demonstrate academia's ability to utilise agile research methodologies similar to existing practice in industry (by that reference is made to the iterative processes visible in smartphone application production and deployment through different app store eco-systems).

8.3.2 Empirical contributions

This research presented a novel spatiotemporal heating control algorithm and confirmed the existing results from multiple pieces of work that automated spatiotemporal heating solutions are able to provide energy saving when compared to traditional programmable thermostats.

The presented algorithm included a novel aspect of treating set-point temperature as a variable. Through simulation and field study, this 'nudging' of user settings was demonstrated to deliver further energy saving, than straightforward compliance with user settings, without compromising on user's experience of comfort. The nudging ('minimise discomfort' strategy) was shown to be able to deliver 19.4 $kWhm^{-2}$ more energy saving than straightforward compliance ('maximise comfort' strategy) and a total of 46 $kWhm^{-2}$ energy saving in comparison to a standard programmable thermostat that included a set-back temperature over the period of 180 days.

8.3.3 Theoretical contributions

This research contributed to the theoretical understanding of thermal comfort behaviour. The complex context within which thermal behaviour takes place has been conceptualised in a cognitive ergonomics model, in which potential heating system interaction within the context have been explained and attributed to mismatches between user expectations and reality in both thermal comfort and system state. These mismatches have been demonstrated to cause the user to undertake a decision-making process in which they display a situated action type behaviour, analysing all influencing actors and subsequently choosing an appropriate adaptive action which may or may not include interactions with the control interface or alterations to the heating system functionality.

Through rich picture analysis, data from all performed activities has been compiled to generate a comprehensive account of the socio-thermo-technical environment of automated heating systems, highlighting users, social interactions, interface design qualities, heating system behaviour, physical factors, technical factors, and how these affect one another.

In addition, the research explored the way in which intelligibility and visibility affect user’s understanding, control and overall user experience, factors that influenced the chosen thermal adaptation actions. This work has demonstrated their position within the overall UX design in terms of data levels, context specificity, and timescales. Combining these results, interface design guidelines for relevant domains have been provided. These guidelines provide concise considerations for automated home systems designers beyond the domain of home heating. The research focused on design guidelines rather than proposing an improved design artefact because they allow for the creation of any number of artefacts that all, despite of their form or functionality, display qualities necessary in delivering a meaningful user experience. ‘Meaningful’, in this case referring to a user experience rich in understanding of the system logic and functionality, experience of control over it, one that educates the user regarding their thermal and energy actions, and engages them with their energy behaviour.

The research demonstrated automated heating systems' ability to become an active member in the thermal comfort and energy behaviours. By demonstrating that no significant difference in the user thermal experience between 'minimise discomfort' and 'maximise comfort' strategies existed, a new direction for proactive, more energy saving home heating algorithm design has been suggested. By that it is meant that algorithms can establish a dialogues with users regarding the impact of user-chosen settings, potentially, nudging users towards a more energy-efficient behaviour. This aspect has not been the dominant theme in home heating automation algorithm research and in accordance with the results presented in this research, merits further investigation.

8.4 Recommendations for Further Work

8.4.1 Improvements to current work

In many respects, the work presented here serves as a starting point for further research into user experience of automated heating controls. As such, the results are exploratory in nature, which means that validation of many would be beneficial. Primarily, a new paradigm has been introduced whereby the control algorithm becomes an active member in the thermal comfort discussion through the 'minimise discomfort' heating strategy. This is a highly intriguing finding, but the study of such heating strategies requires validation on a larger sample size and through strategy isolation as the sole independent variable. In addition, a replication study sample size should reflect the population breakdown and target archetypes highlighted in Chapter 3. Similarly, due to technical constraints imposed by this researchers lack of familiarity with the used technology at the outset of this research, direct measures of energy impact of the deployed heating control system were not included. A replication focussing on these aspects could validate the results regarding the potential of ‘minimise discomfort’ heating strategy for delivering energy saving without compromising occupant comfort.

Secondly, the time frame of this research meant that several activities occurred concurrently. This meant that the interface design deployed in the field study did not reflect the findings of the probe study, which had not finished while the interface had to be deployed in order to ensure the system was deployed during heating season. Therefore, a replication with a new interface design could be undertaken with a single control algorithm version, isolating interface features and thus utilising a more rigorous study design to discover potential causalities and correlations between interface qualities, system state, environmental conditions, and interactions these lead to.

Lastly, several minor improvements could be made to the control algorithm. By that it is meant that the proposed algorithm is seen as part of the iterative process, improving and delivering new knowledge at every iteration. For example, the algorithm could be more responsive both regard to the sensor hardware and presence prediction. Continuous updates based on measured presence could be performed to select the optimum dataset to reflect current behaviours and perform predictions to reflect occupant presence without the need to separate datasets by weekday. This would allow for the training as well as memory decay to be more responsive. Similarly, the thermal preference voting mechanism could be improved upon to separate heater state and thermal comfort orientated alterations.

8.4.2 Further research directions within the context of existing knowledge

The work presented here has contributed to knowledge at the intersection of Human-Computer Interaction (HCI) and thermal comfort fields. This intersecting area of research has so far been under-examined with regard to the domestic setting (extensive thermal comfort knowledge exists within the workplace), role of heating system interfaces (building controls and the human element have not been the focal point of heating system design, but have been studied in isolation to a great extent). This work has presented a conceptual model of the context within which home thermal comfort behaviour emerges. In addition, interactions and experiences of living with a quasi-autonomous home heating system have been highlighted and the possibility of describing interactions through situated action theory explained. However, at the time of writing, the selection of these moment-by-moment interactions is still largely described as a ‘black box’ by the HCI community, meaning that the factors influencing decisions have been accounted, but not explained. It would be of interest to the academic community (whose focus is on the intersection of HCI and thermal comfort) to provide a more rigorous (and empirical) account of the thermal behaviour decision-making process and subsequently, how interface design can affect these decisions. This would open the ‘black box’ and allow for energy providers, policy makers, and designers to navigate the situated action behaviour and allow energy-aware users to successfully fulfil their dual goals of comfort and effectiveness more often.

Secondly, it would be of interest to the same community to quantify the degree to which autonomous heating systems are able to nudge user preferences, this both with regard to proactivity, as well as temperature offset. Similarly, to existing knowledge of thermal adaptation empirical effect on comfort (see section 2.5.2.3 Fully Empirical Adaptive Model), understanding the degree to which an autonomous system can deviate from the “neutral” sensation before corrective interaction by the user is taken, would allow autonomous home heating systems to further maximise energy efficiency. And by extension, it would be of interest to holistically observe the conditions that prevail when certain interactions with any autonomous home heating system control interface are taken.

Addressing these two research areas would allow to construct a rigorous predictive model of domestic thermal comfort and energy behaviour, account for the complex factors influencing the behaviour at any given moment, and establish any causalities or correlations within the environment that autonomous systems can exploit or navigate. Achieving this would allow for he creating of robust autonomous spatiotemporal heating systems delivering a successful user experience.

8.5 Summary

This thesis presents research carried out to explore the user experience of automated home heating systems through a design process. It has utilised a mixed-methods approach in an iterative design process from ideation and data visualisation techniques to establish design agenda, through to iterative prototyping and deployment of a technology intervention. The insights and knowledge delivered will inform the design of future automated home heating systems and provide guidelines for the design of interfaces in the automated home domain for the delivery of effective user experiences.

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10 APPENDIXES

10.1 Appendix 1 - Full scale housing typology infographic

Legend

4.7t CO2 / annum	1 - One Adult aged 16-59
5.9t CO2 / annum	2 - Two adults aged 16-59
4.8t CO2 / annum	3 - Small family / lone parent
6.0t CO2 / annum	4 - Large family
5.6t CO2 / annum	5 - Large adult household
6.6t CO2 / annum	6 - Two adults one/both aged 60 or over
5.6t CO2 / annum	7 - One adult aged 60 or over

5.6t / dwelling / year	CH - Central heating
6.8t / dwelling / year	SH - Storage Heating
7.7t / dwelling / year	RH - Room Heating*

Circles:

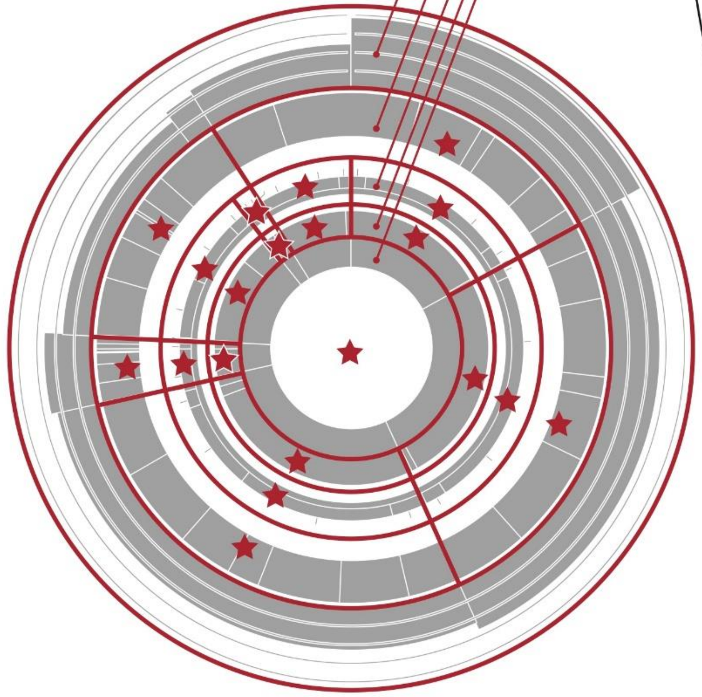
Total English housestock by dwelling type

Each dwelling type divided into segments based on systems used for heating

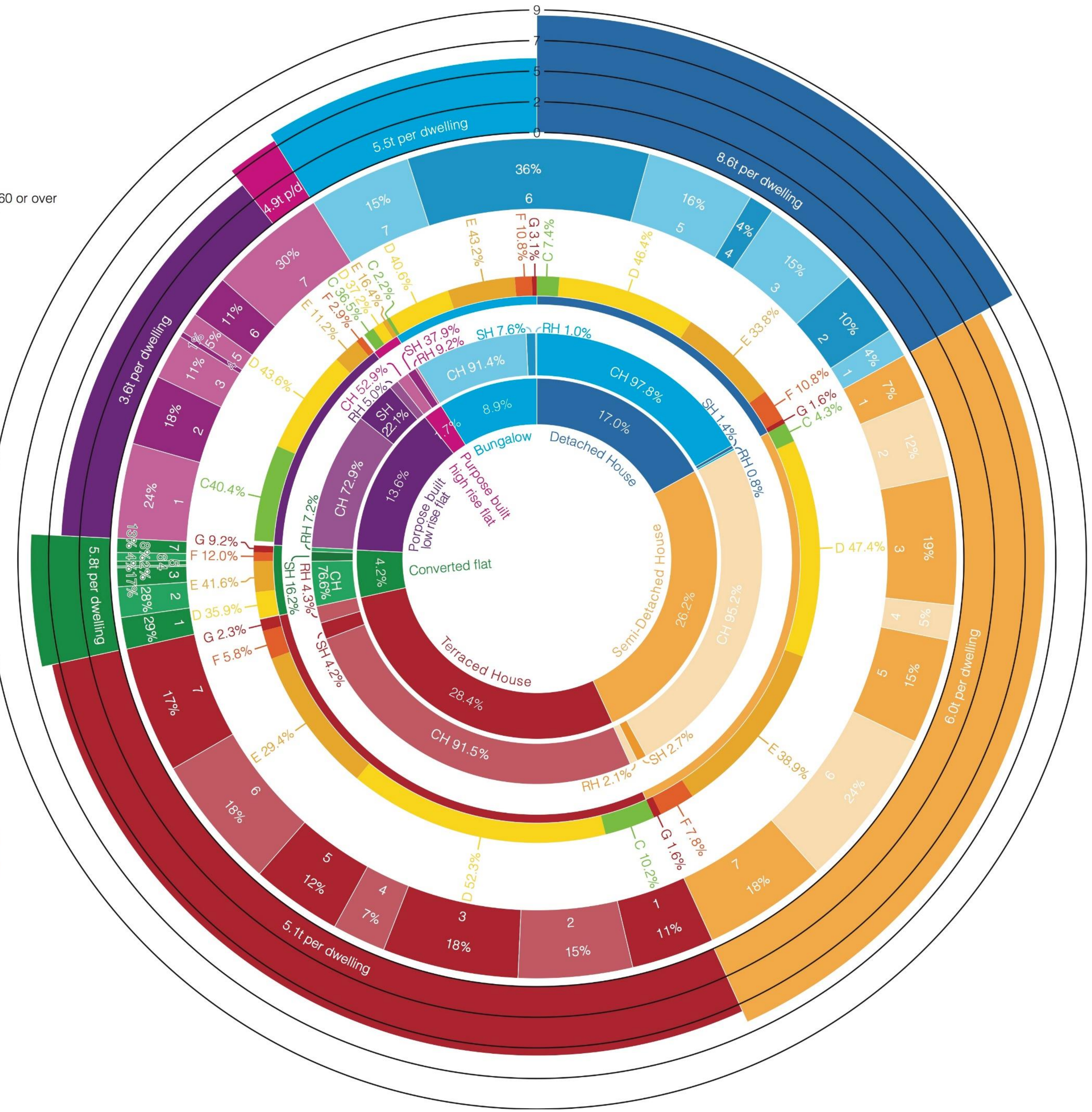
Each dwelling type divided into segments based on SAP rating band

Each dwelling type divided into segments based on occupant demographic classification**

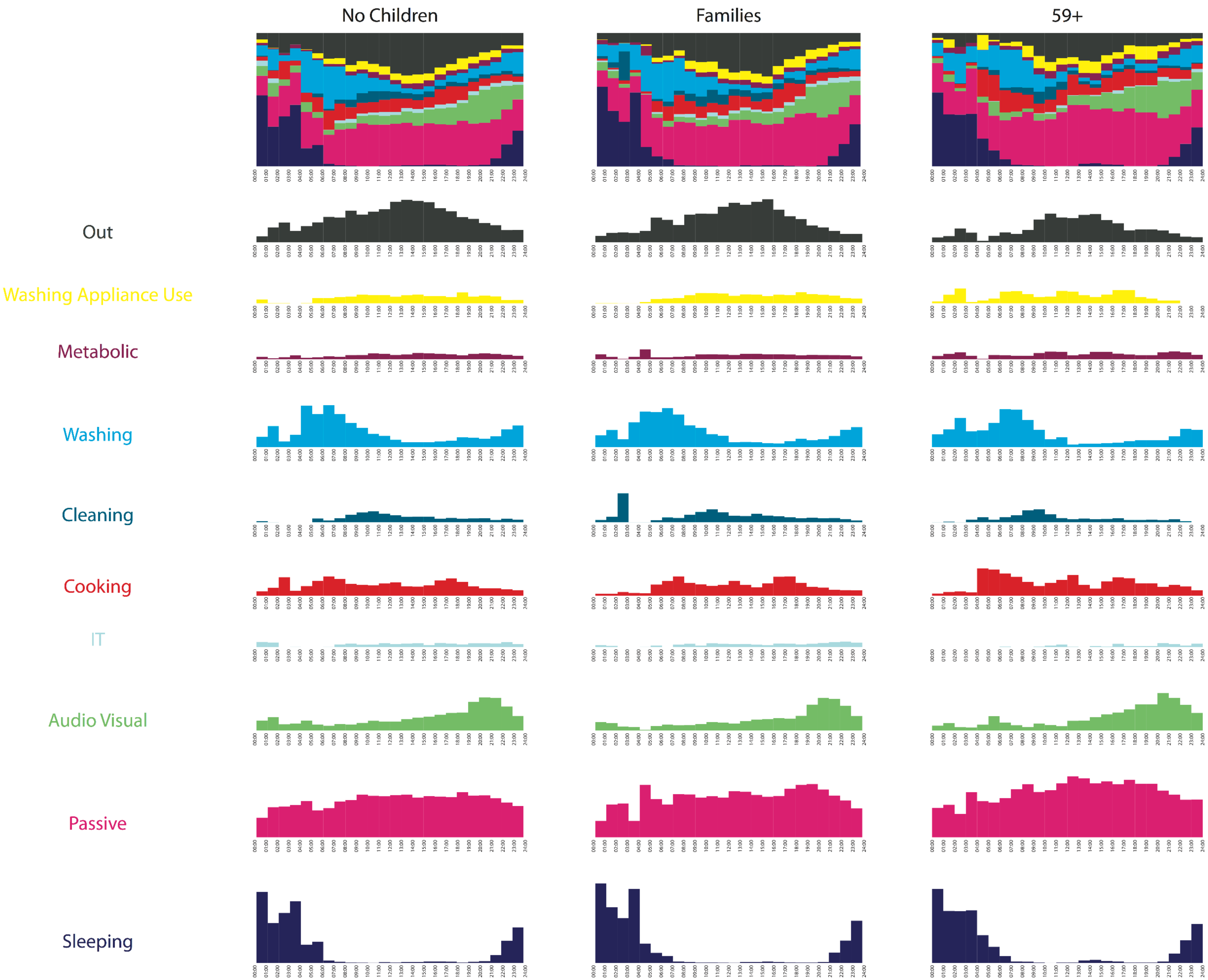
Annual carbon emissions of each dwelling type vased on mean ratings per dwelling within type, area of segment shows emissions per all buildings



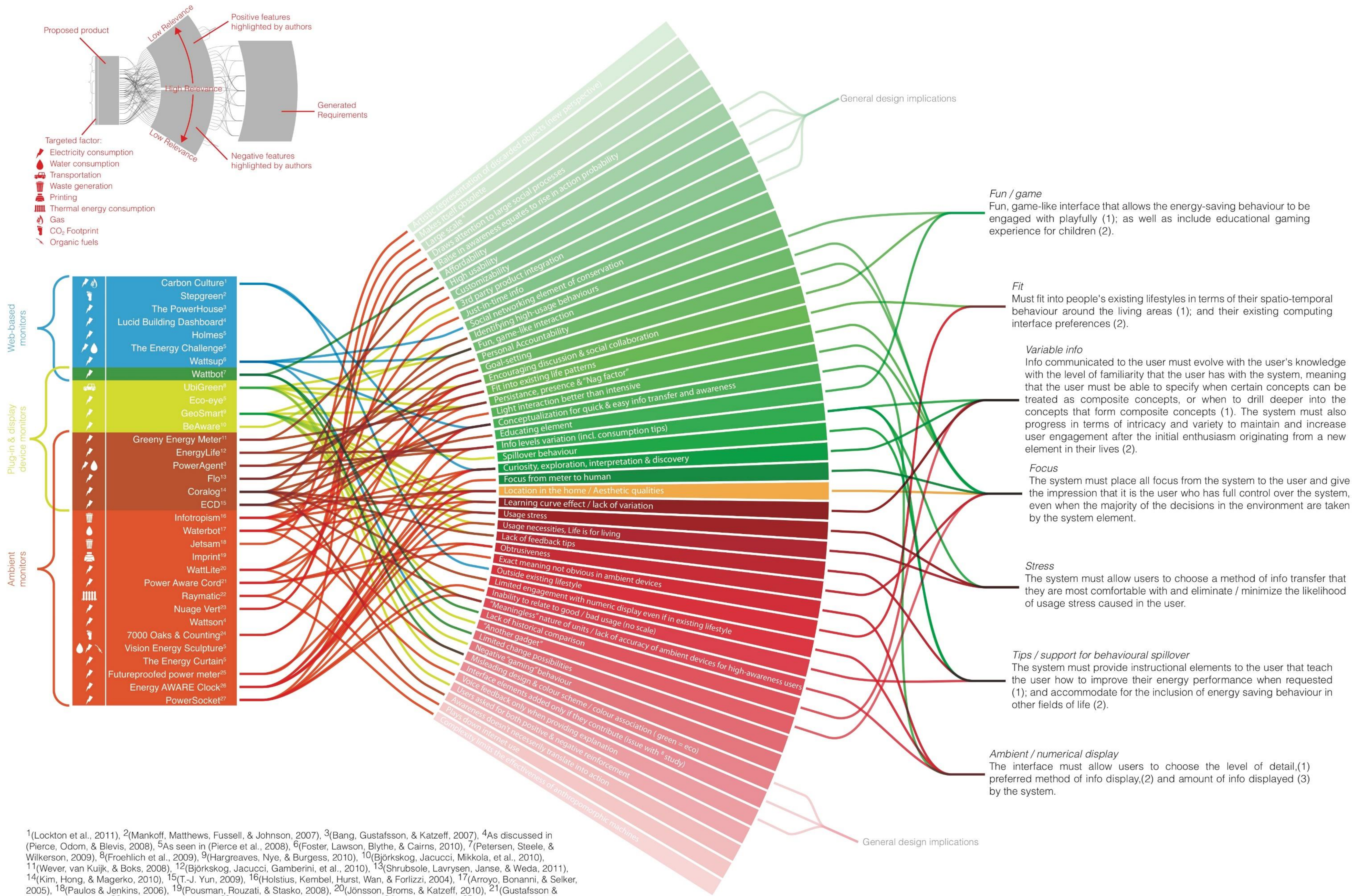
Each sector marked with ★ totals 100%



10.2 Appendix 2 - Full scale activities infographic

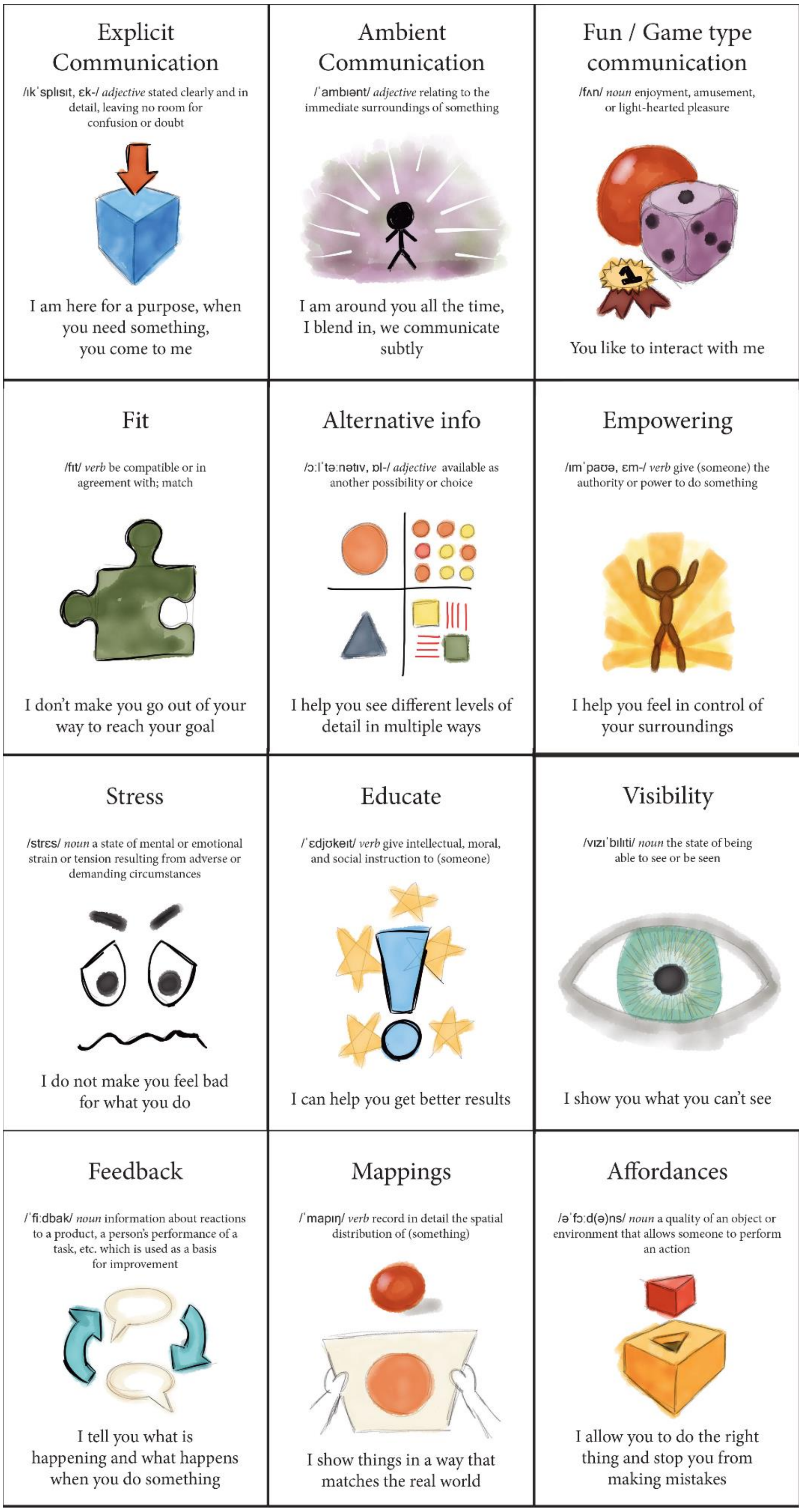


10.3 Appendix 3 - Full scale energy monitors infographic



1(Lockton et al., 2011), 2(Mankoff, Matthews, Fussell, & Johnson, 2007), 3(Bang, Gustafsson, & Katzeff, 2007), 4As discussed in (Pierce, Odom, & Blevis, 2008), 5As seen in (Pierce et al., 2008), 6(Foster, Lawson, Blythe, & Cairns, 2010), 7(Petersen, Steele, & Wilkerson, 2009), 8(Froehlich et al., 2009), 9(Hargreaves, Nye, & Burgess, 2010), 10(Björkskog, Jacucci, Mikkola, et al., 2010), 11(Wever, van Kuijk, & Boks, 2008), 12(Björkskog, Jacucci, Gamberini, et al., 2010), 13(Shrubsole, Lavrysen, Janse, & Weda, 2011), 14(Kim, Hong, & Magerko, 2010), 15(T.-J. Yun, 2009), 16(Holstius, Kembel, Hurst, Wan, & Forlizzi, 2004), 17(Arroyo, Bonanni, & Selker, 2005), 18(Paulos & Jenkins, 2006), 19(Pousman, Rouzati, & Stasko, 2008), 20(Jönsson, Broms, & Katzeff, 2010), 21(Gustafsson & Gyllenswärd, 2005), 22(R. Yun & Gross, 2011), 23(Evans, Hansen, & Hagedorn, 2009), 24(Holmes, 2007), 25(Jeremijenko, 2001), 26(Broms et al., 2010), 27(Heller & Borchers, 2011)

10.4 Appendix 4 - Ideation decks presented to participatory design participants



10.5 Appendix 5 - Interface probe study soundbites

Soundbite 1

"Welcome to this experiment. My name is Linda and I will take you through the experiment. You will be given 8 everyday scenarios in a home setting. Please imagine yourself as the person living in this home. The home has a heating system that is made up of two components. A smart heating system that makes decisions about the heating in your house, and is completely invisible to you. And an interface which allows you to communicate to the heating system. After each scenario, you will have the chance to interact with an interface. During this, you will be asked to speak out loud your thoughts and what you are doing. After the interaction, you will be asked to answer a few questions about it. I will be audio recording the session, and screen-capturing your interactions with the interfaces. You have the right to withdraw from the experiment at any time without needing to explain yourself. If you have any questions, please ask these now and my human counterpart will be happy to answer them."

Soundbite 2

"Thank you! If you agree to take part in this study, please sign the consent form handed to you by the researcher."

Soundbite 3

"Fantastic! Let's get started."

Soundbite 4

"Scenario 1. It is midday. You go to the living room to sit on the sofa and read a book. The room feels at a comfortable temperature to keep you warm as you sit in one place and read."

Soundbite 5

"Scenario 2. It is six PM. You have just finished cooking and sit down in the kitchen to have your dinner. Since you have been moving around a lot and the cooker has been on, the room feels very hot."

Soundbite 6

"Scenario 3. It is midday. You have guests coming over in a couple of hours' time and you are busy preparing the dinner party. Since there is quite a few guests coming, you decide to lay the table in the dining room even though the room is usually empty."

Soundbite 7

"Scenario 4. It is six PM. You are finishing dinner and decide to read a book in the study for a couple of hours since you don't feel up for doing anything else. But before, you must wash the dishes.'

Soundbite 8

"The interface you will now use is an orb that is placed in every room of the house. To mimic the way you would interact with the orb, use the ball the researcher hands you. To interact with the orb, simply squeeze it and the screen will show you what effect your actions have. If you wish to see the interface in a different room, just tell the researcher the name of the room, that you wish to see."

Soundbite 9

"Please interact with the interface and speak out loud what you are thinking as you do so."

Soundbite 10

"Please think out loud during the experiment."

Soundbite 11

“Have you finished using the interface?”

Soundbite 12

“Please answer the first questions on the iPad the researcher hands you. Do not press “continue” until I ask you to.”

Soundbite 13

“Please click continue and answer the remaining question. Do not press “continue” until I ask you to.”

Soundbite 14

“Please answer the following question. What was your aim in interacting with the interface?”

Soundbite 15

“Please answer the following questions. What did you like about this interface?”

Soundbite 16

“What did you not like about this interface?”

Soundbite 17

“Please click continue and answer the remaining questions. When you finish, please give the iPad back to the researcher.”

Soundbite 18

“I have two final questions for you. The heating system made it’s decisions about when and what temperature to heat based on two factors. What were those factors?”

Soundbite 19

“And how do you know this?”

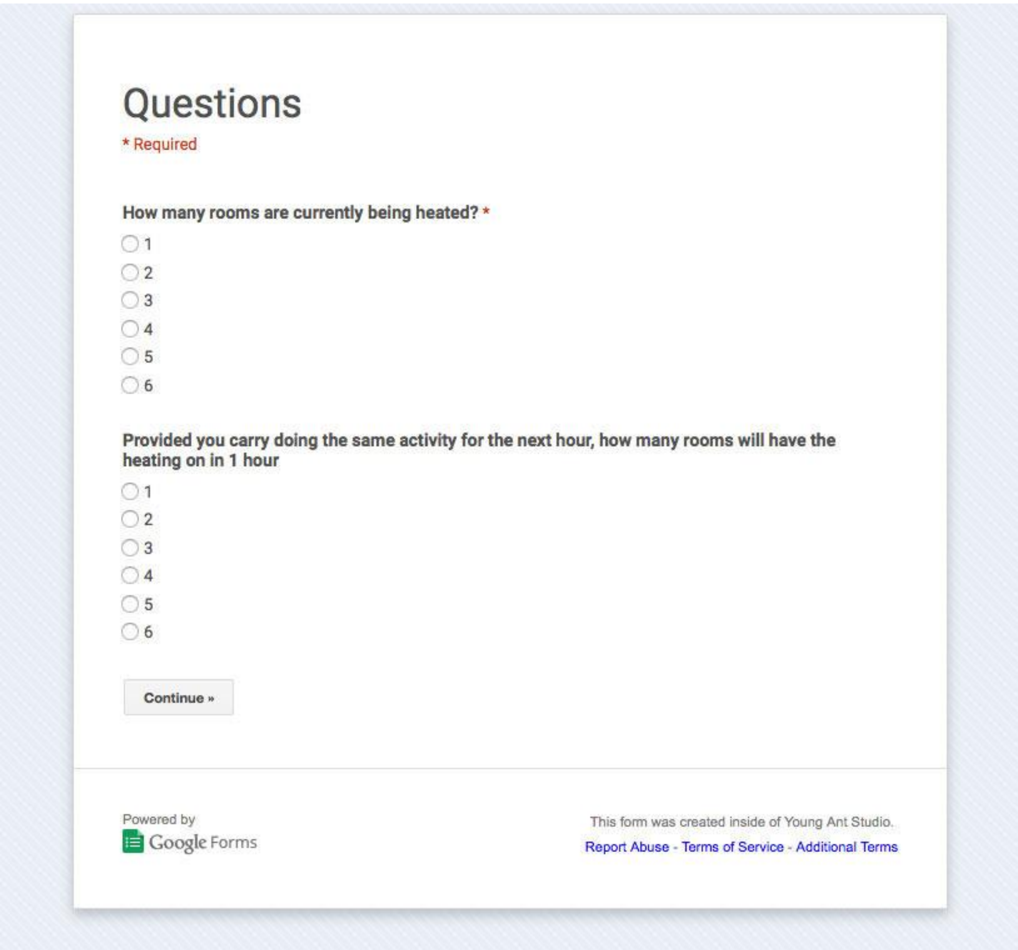
Soundbite 20

“This concludes the experiment. Thank you. The aims of this experiment were to investigate the role of intelligibility in ambient intelligent home heating systems and how this can be enhanced by different interface features. Intelligibility is an interface’s ability to tell its user what it knows, how it knows it and what it is doing about it. Thank you again for taking part and if you have any questions, please direct these to my human colleague.”

Soundbite 21

“Thank you”

10.6 Appendix 6 - Probe study multiple choice questions



Questions

* Required

How many rooms are currently being heated? *

- 1
- 2
- 3
- 4
- 5
- 6

Provided you carry doing the same activity for the next hour, how many rooms will have the heating on in 1 hour

- 1
- 2
- 3
- 4
- 5
- 6

Continue »

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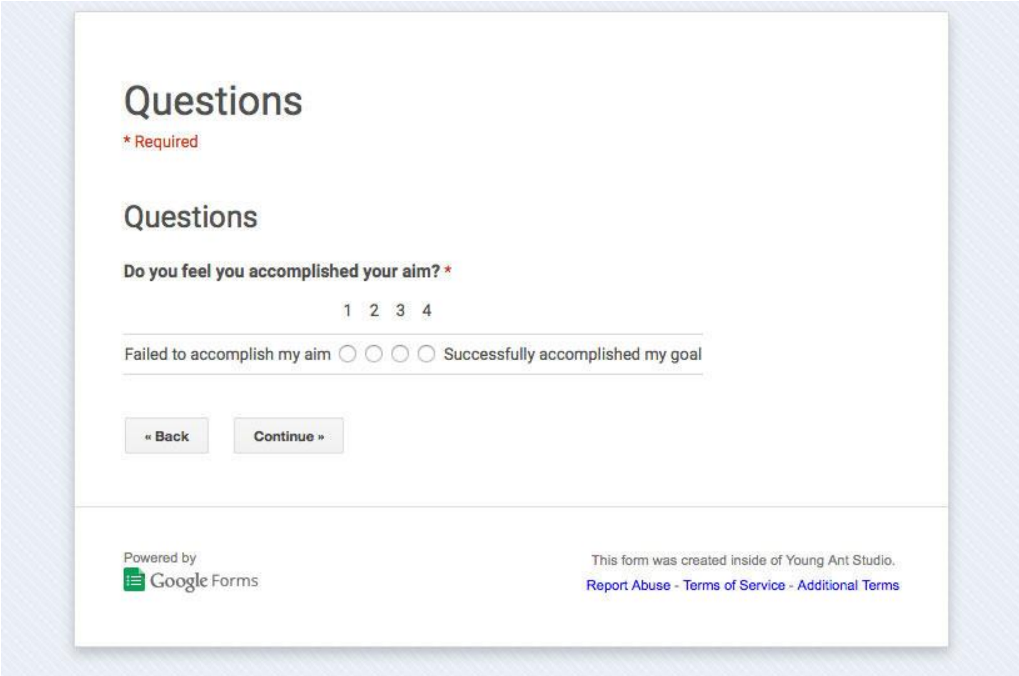

Questions

* Required

Questions

Do you feel you accomplished your aim? *

	1	2	3	4	
Failed to accomplish my aim	○	○	○	○	Successfully accomplished my goal

« Back   Continue »

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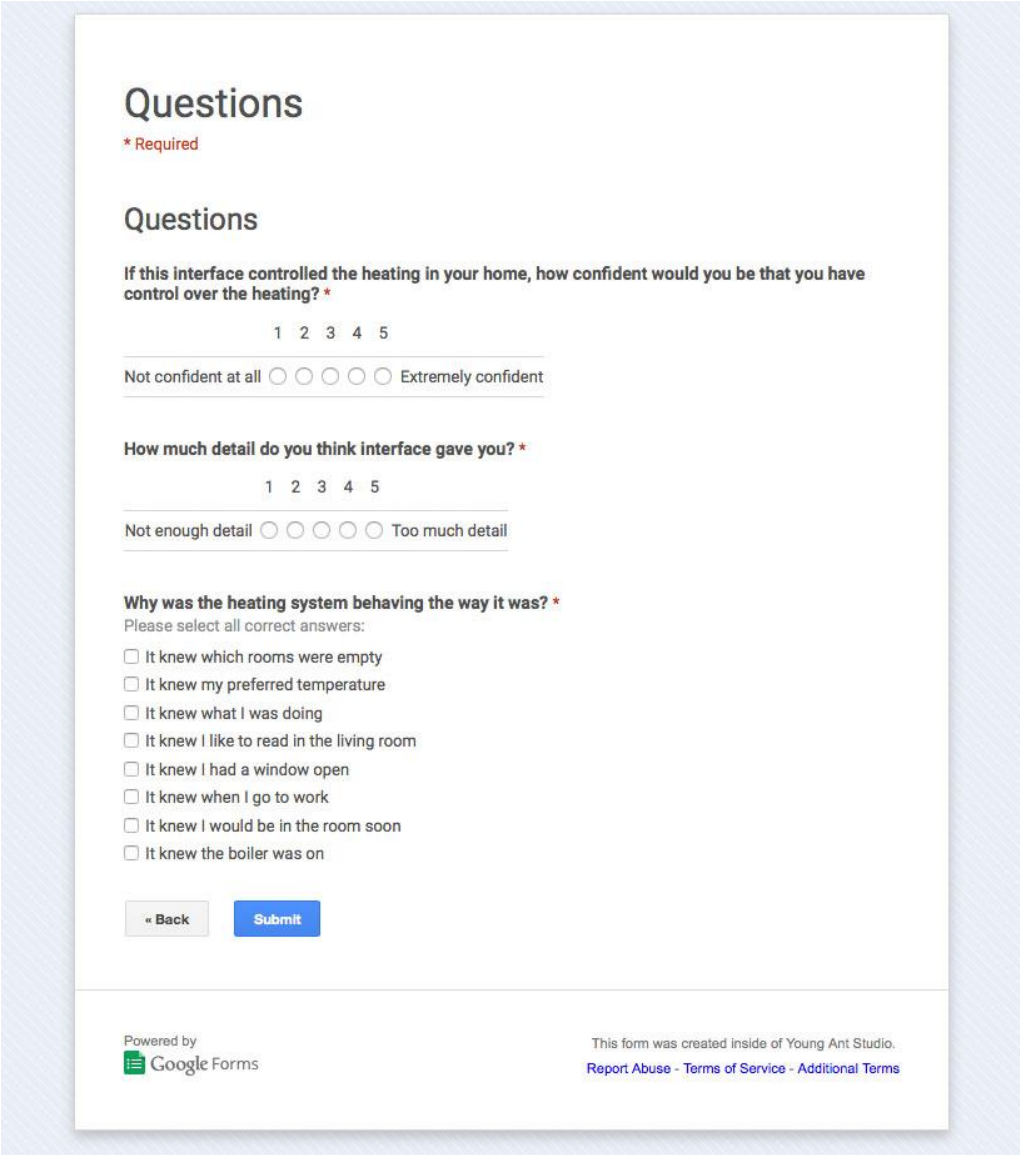

Questions

* Required

Questions

If this interface controlled the heating in your home, how confident would you be that you have control over the heating? *

1 2 3 4 5

Not confident at all ○ ○ ○ ○ ○ Extremely confident

How much detail do you think interface gave you? *

1 2 3 4 5

Not enough detail ○ ○ ○ ○ ○ Too much detail

Why was the heating system behaving the way it was? *

Please select all correct answers:

- ☐ It knew which rooms were empty
- ☐ It knew my preferred temperature
- ☐ It knew what I was doing
- ☐ It knew I like to read in the living room
- ☐ It knew I had a window open
- ☐ It knew when I go to work
- ☐ It knew I would be in the room soon
- ☐ It knew the boiler was on

« Back Submit

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10.7 Appendix 7 - Field study information and consent forms

PARTICIPANT CONSENT FORM

Project title	Automated home heating study
Researcher's name	Martin Kruusimagi
Supervisor's name	Professor Sarah Sharples, Professor Darren Robinson

- I have read the Participant Information Sheet and the nature and purpose of the research project has been explained to me. I understand and agree to take part.
- I understand the purpose of the research project and my involvement in it.
- I understand that I may withdraw from the research project at any stage and that this will not affect my status now or in the future.
- I understand that while information gained during the study may be published, I will not be identified and my personal results will remain confidential.
- I understand that any intentional damage or damage due to negligence to equipment placed in my home for the duration of the experiment is my liability.
- I understand that the equipment placed in my home records motion and temperature data without recoding any video and that data will be collected from my use of the provided smartphone application. Furthermore, I understand the installed equipment will affect the thermal environment inside my home and subsequently the occupants' thermal comfort.
- I understand that data will be stored as a digital copy on a University of Nottingham computer and only the researcher conducting this study and their supervision team will have access to it. The design artefacts will be photographed and digital copies stored in the same manner as audio-visual data. All data will be destroyed after the conclusion of this research project from the university laptop and will be submitted to the university on a USB storage device to be kept for 7 years, after which they be deleted.
- I understand that I may contact the researcher or supervisor if I require further information about the research, and that I may contact the School of Engineering Research Office, if I wish to make a complaint relating to my involvement in the research.
- I understand that under no circumstances shall The University of Nottingham or any of its representatives involved in the carrying out of any experiments be liable for any additional cost the intervention may cause to the participant's electricity and/or heating bill.
- I have been given access to, and have familiarised myself with user's manuals of the electric heaters placed in my residence.
- I accept all responsibility for the use and misuse of the electric heaters placed in my home, including, but not limited to environmental hazards such as covering heaters, placing flammable objects near heaters, etc.

- I understand that under no circumstances shall The University of Nottingham or any of its representatives involved in the carrying out of any experiments be liable for any damage caused by my use or misuse of electrical heating equipment.

Signed .... (research participant)

Print name .... **Date** ....

Contact details

Researcher: *psxmk2@nottingham.ac.uk*

Supervisor: *lazdr@nottingham.ac.uk*

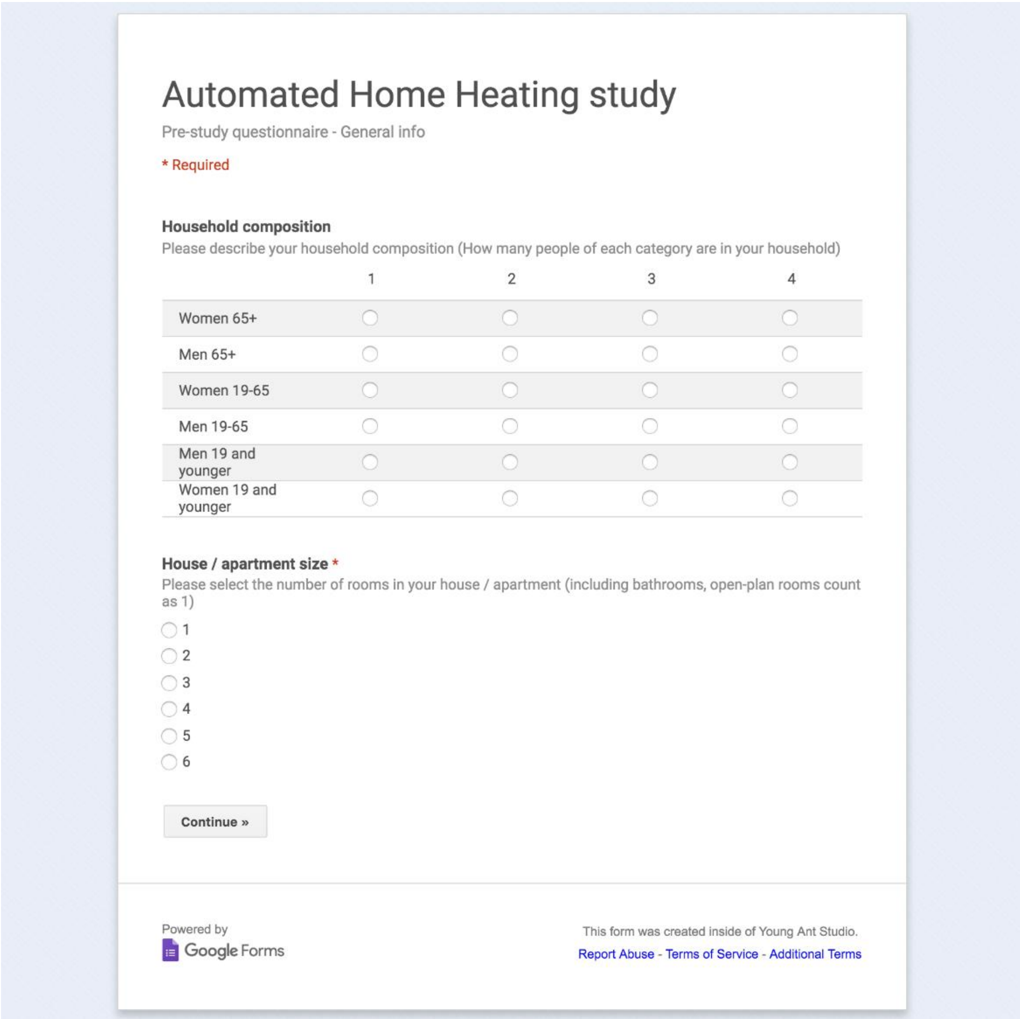
Supervisor: *epzscn@nottingham.ac.uk*

School of Engineering Research Office: tzjld@nottingham.ac.uk

PARTICIPANT INSTRUCTION SHEET – SYSTEM FAULTS & OTHER

- Damage
    - When any part of the system seems visibly damaged or dysfunctional, please contact the researcher immediately
- Internet connection
    - When your home internet is down, the system is unable to function. Fail safes have been built in, and the system recovers automatically from failures. However, if a disruption lasting a couple of hours or more occurs, please let the researcher know.
    - If the system seems to work incorrectly or display faults after an internet outage, please contact the researcher immediately.
- Discomfort
    - If at any stage you experience extreme discomfort due to excessive cold, please contact the researcher immediately to receive instructions how the issue can be fixed.
- Electrical outages
    - If your household experiences a long lasting electrical outage and your usual source for heating is not electricity, you may be able to switch to your usual heating method. If this is the case, please contact the researcher immediately to receive instructions on how to do this.
- Manual over-ride
    - If at any stage you alter the set-up of the heating system (this can include reverting to your conventional heating system) please notify the researcher immediately that this has occurred.
- Other
    - For any other issue, please contact the researcher.
- Contact details
    - Email: psxmk2@nottingham.ac.uk
    - Mobile phone: 07960 712 742

10.8 Appendix 8 - Field study online questionnaire



Automated Home Heating study

Pre-study questionnaire - General info

* Required

Household composition

Please describe your household composition (How many people of each category are in your household)

	1	2	3	4
Women 65+	○	○	○	○
Men 65+	○	○	○	○
Women 19-65	○	○	○	○
Men 19-65	○	○	○	○
Men 19 and younger	○	○	○	○
Women 19 and younger	○	○	○	○

House / apartment size *

Please select the number of rooms in your house / apartment (including bathrooms, open-plan rooms count as 1)

○ 1
○ 2
○ 3
○ 4
○ 5
○ 6

Continue »

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Automated Home Heating study

* Required

Room overview

Please enter details to describe each room in your house / apartment

Room name *

Please give a name to this room (e.g. lounge, bedroom, bathroom, en-suite, etc)

Room usage on weekdays (Mon - Fri) *

Please tick the appropriate boxes to indicate when at least 1 person is usually in this room

- ☐ 00:00 - 01:00
- ☐ 01:00 - 02:00
- ☐ 02:00 - 03:00
- ☐ 03:00 - 04:00
- ☐ 04:00 - 05:00
- ☐ 05:00 - 06:00
- ☐ 06:00 - 07:00
- ☐ 07:00 - 08:00
- ☐ 08:00 - 09:00
- ☐ 09:00 - 10:00
- ☐ 10:00 - 11:00
- ☐ 11:00 - 12:00
- ☐ 12:00 - 13:00
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- ☐ 19:00 - 20:00
- ☐ 20:00 - 21:00
- ☐ 21:00 - 22:00
- ☐ 22:00 - 23:00
- ☐ 23:00 - 24:00

Room usage on weekends (Sat & Sun) *

Please tick the appropriate boxes to indicate when at least 1 person is usually in this room

- ☐ 00:00 - 01:00
- ☐ 01:00 - 02:00
- ☐ 02:00 - 03:00
- ☐ 03:00 - 04:00
- ☐ 04:00 - 05:00
- ☐ 05:00 - 06:00
- ☐ 06:00 - 07:00
- ☐ 07:00 - 08:00
- ☐ 08:00 - 09:00
- ☐ 09:00 - 10:00
- ☐ 10:00 - 11:00
- ☐ 11:00 - 12:00
- ☐ 12:00 - 13:00
- ☐ 13:00 - 14:00
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- ☐ 18:00 - 19:00
- ☐ 19:00 - 20:00
- ☐ 20:00 - 21:00
- ☐ 21:00 - 22:00
- ☐ 22:00 - 23:00
- ☐ 23:00 - 24:00

Room temperature *

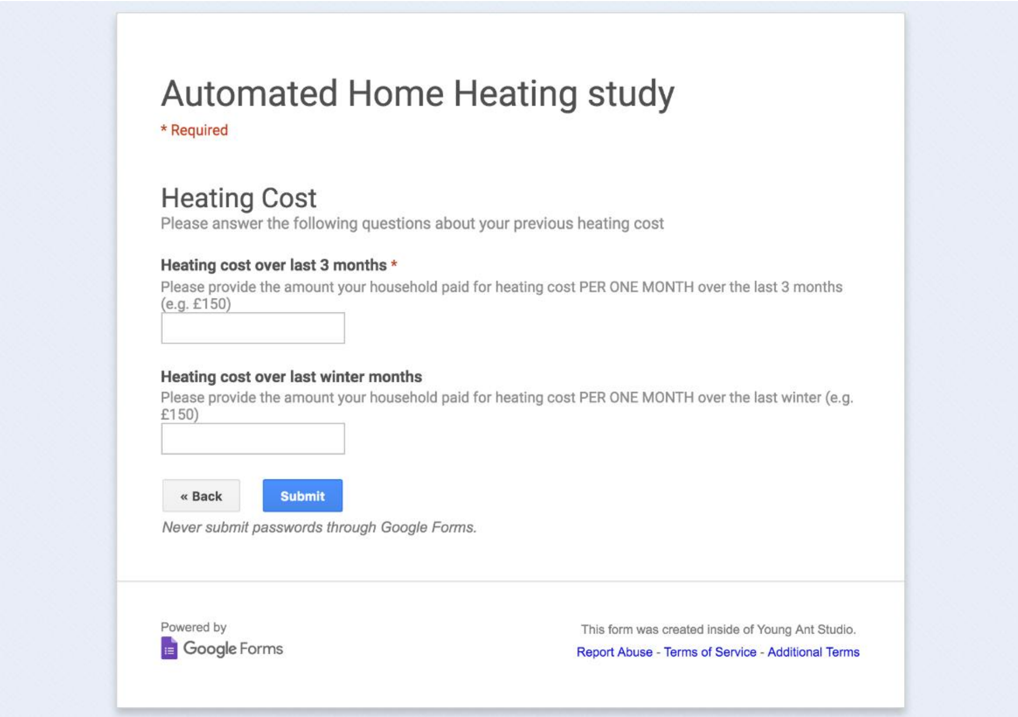
Please give a value of your preferred room temperature for this room (e.g. 20 C)

Other rooms *

Do you have other rooms in your house / apartment that you have not yet provided an overview for

- ○ Yes
- ○ No

« Back   Continue »



Automated Home Heating study

* Required

Heating Cost

Please answer the following questions about your previous heating cost

Heating cost over last 3 months *

Please provide the amount your household paid for heating cost PER ONE MONTH over the last 3 months (e.g. £150)

Heating cost over last winter months

Please provide the amount your household paid for heating cost PER ONE MONTH over the last winter (e.g. £150)

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