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UNIVERSITY OF SOUTHAMPTON

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**Mental Models: understanding domestic energy systems and user  
behaviour.**

by

**Kirsten Magrethe Anita Revell**

Thesis for the degree of Doctor of Philosophy

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## **ABSTRACT**

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Human Factors

Thesis for the degree of Doctor of Philosophy

### **MENTAL MODELS: UNDERSTANDING DOMESTIC ENERGY SYSTEMS AND USER BEHAVIOUR.**

Kirsten Magrethe Anita Revell

Energy consumption due to domestic heating is a major contributor to climate change. Kempton (1986) proposed that 'Mental Models' of thermostat controls could be linked to energy wasting behaviour. Mental models can be thought of as 'pictures in the mind' that help users understand and operate systems. This thesis explored if changes to the heating interface design could influence the mental model held, to promote appropriate behaviour with heating controls.

Consideration of bias is essential when undertaking research into mental models. The 'Tree-Rings' framework was developed to address this, resulting in the creation of the 'Quick Association Check' (QuACK); a method for capturing and analysing mental models and behaviour related to heating controls. QuACK was initially applied to a case study of 6 householders. This revealed a 'systems level' approach was necessary to understand behaviour strategies, in contrast to Kempton's single device focus. Differences in mental models explained differences in self-reported behaviour. Misunderstandings of how heating controls worked together and the influence of thermodynamics on boiler activation, explained variations in consumption between households.

Norman's (1983) '7 stages of activity' was used to produce a design specification for a 'control panel' style heating interface. This focused on correcting key misunderstandings in householders' mental models, that hindered appropriate behaviour. A home heating simulation was developed to allow the design to be compared with a typical presentation of heating controls. The new interface significantly improved the appropriateness of users' mental models at the system and device levels. More appropriate behaviour was found with specific controls and the duration of goal achievement was significantly increased. These findings have implications for strategies to reduce domestic consumption through behaviour change, and provide insights that can be used to improve the design of home heating interfaces.



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## DECLARATION OF AUTHORSHIP

I, Kirsten Magrethe Anita Revell

declare that the thesis entitled

Mental Models: understanding domestic energy systems and user behaviour.

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
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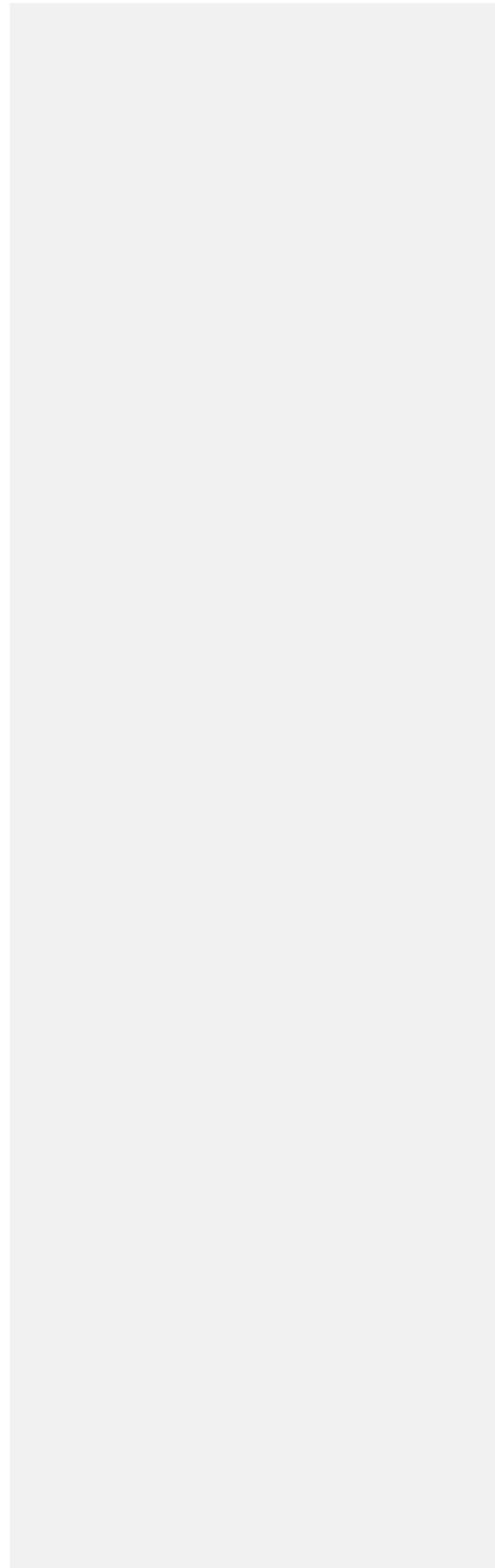
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## Definitions and Abbreviations

C(M(t))	Scientists' conceptualisation of users mental model of target system
C(t)	Conceptual model of target system
CUMM	Compatible User Mental Model
DCM	Designer's Conceptual Model
ECL	Efficient Cause Lattice
EPSRC	Engineering & Physical Sciences Research Council
FCL	Formal Cause Lattice
FiCL	Final Cause Lattice
HCI	Human Computer Interaction
MaCL	Material Cause Lattice
MCL	Mental Cause Lattice
MM	Mental Model
M(t)	Users mental model of target system
PSL	Physical System Lattice
QuACK	Quick Association Check
t	Target system
TRV	Thermostatic Radiator Valve
UCM	User's Conceptual Model
UMM	User Mental Model

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# 1. Introduction

## 1.1 Background

The UK has legislated to cut greenhouse gas emissions by 80% by 2050 (Climate Change Act 2008). A key element in achieving the proposed reduction in CO<sub>2</sub> emissions is the need to support domestic consumers in both reducing their demand for energy and improving the efficiency with which they use it. These consumers currently have the least visibility regarding their energy use, but they collectively contribute over 25% of total UK carbon emissions (The UK Low Carbon Transition Plan). A significant contribution to the variability of domestic energy use across buildings is due to behavioural differences of the householders (Lutzenhiser & Bender 2008).

This PhD formed part of a broader project, Intelligent Agents for Home Energy Management, funded by EPSRC, which was a collaboration between Electronics and Computer Science, Sustainable Energy Research Group, and [the Transportation Research Group](#). Using innovative digital technologies, the broader project combined a thermal model of the home, a model of the householders' energy use, a cognitive model of behaviour change, and sophisticated prediction and optimisation algorithms, with the aim to reduce domestic energy demand by more than 20% (IAHEM impact plan). The research undertaken for this thesis used the concept of mental models to contribute towards the goal of a 'cognitive model of behaviour change' linked to 'a model of householders energy use'. Since home heating is responsible for 58% of domestic energy use, the key focus was on users' mental models of the home heating thermostat.

Mental models are thought to be representations of the physical world (Veldhuyzen and Stassen 1976, Johnson-Laird 1983, Rasmussen 1983), constructs that can explain human behaviour (Wickens 1984, Kempton 1986) and internal mechanisms allowing users to understand, explain, operate and predict the states of systems (Fraib 1943, Kieras and Bovair 1984, Rouse and Morris 1986, Hanisch et al. 1991). The notion of mental models has proved attractive for many domains: For Psychology, when considering cognitive processing (Johnson-Laird 1983, Bainbridge 1992); in interface design (Williges

## Chapter 1 - Introduction

1987, Norman 2002, Jenkins et al. 2010); to promote usability (Norman 2002, Mack and Sharples 2009, Jenkins et al. 2011); and for the Human Factors domain, to enhance performance (Stanton and Young 2005, Stanton and Baber 2008, Grote et al. 2010, Bourbousson et al. 2011) and reduce error (Moray 1990a, Stanton and Baber 2008, Rafferty et al. 2010). A mental models approach can therefore tackle behaviour change from a variety of perspectives, extending the reach of the findings.

### 1.2 Aims and Objectives / Purpose

This research focused on how the concept of mental models can be applied in design to elicit behaviour change that results in increased achievement of home heating goals (such as reduced waste and improved comfort). This research will also contribute to methodology regarding the extraction and application of mental models. Success would allow the notion of mental models to be applied across domains when behaviour change was sought, and would validate its use as a design tool.

#### 1.2.1 Overall Hypothesis ([Hypothesis 4](#))

'By making changes to device design, it is possible to influence peoples' mental models of domestic devices, and associated patterns of domestic device use, to increase achievement of home heating goals'

#### 1.2.2 Sub Hypotheses

The overall hypotheses can be broken down into the following sub-hypotheses:

- 1- [Hypothesis 1](#): Users' Mental Models of Devices influences their Pattern of Device Use
- 2- [Hypothesis 2](#): Patterns of Device Use influences the Amount of Energy Consumed over Time.
- 3- [Hypothesis 3](#): The Device Design influences Mental Models of those Devices.

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Knowledge of existing Mental Models of Devices can be used in Device Design to encourage Patterns of Device Use that increase goal achievement (e.g. balance between comfort and consumption).

The relationship between these sub-hypotheses is represented in Figure 1, which is informed by the work of Kempton (1986). The research assumes a causal relationship can be found between the different components (Energy consuming domestic devices, Mental models of devices, Patterns of device use, and Energy consumption over time) and that changes in the design of devices can instigate changes in behaviour.

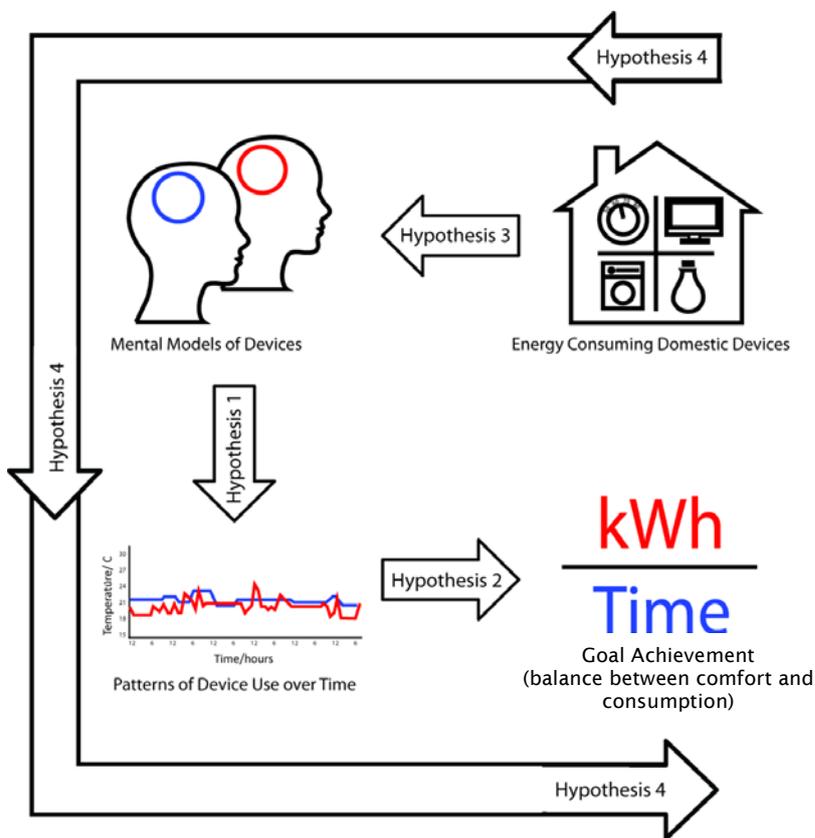


Figure 1- Relationship between sub-hypotheses and research components

### 1.3 Outline of thesis

This thesis is organised in nine chapters, starting with an introduction which describes the background to the work and outlines the main research objectives (Chapter 1). Each of the remaining chapters is briefly introduced in the following sections: [A participant list is provided in Appendix 12 to highlight the source of data contributing to different studies](#)

#### 1.3.1 Chapter 2 - Models of models: filtering and bias rings in depiction of knowledge structures and their implications for design

Chapter 2 investigates the barriers to be overcome in order to apply the notion of mental models pragmatically. Literature from Psychology, Human Computer Interaction (HCI) and Human Factors sources was reviewed to determine the utility of “mental models” as a design tool. This chapter identified bias as a major impediment to pragmatic application and concluded that definition and methods of construction and access need to be sufficiently specified. This chapter develops a graphical method to compare existing research in mental models, highlighting similarities, differences and ambiguities. This ‘tree-rings’ method was applied to the types of mental models described in the work of Kempton (1986) and Payne (1991) to illustrate fundamental differences in the notion.

#### 1.3.2 Chapter 3 - Case studies of mental models in home heat control: Searching for feedback, valve, timer and switch theories

Chapter 3 was inspired by the work of Kempton (1986) who identified 2 common mental models [of home heating](#) held by householders of the home heating thermostat: 1) A ‘feedback’ model that was a simplified but correct version of the way the device worked that could lead to energy systematically wasted, and 2) a ‘valve’ model that misunderstood the way the device functioned, but could result in energy saving. An intergroup case study is presented that investigated present day mental models of thermostat function, that differ significantly from actual functioning. These models were categorized according to Kempton’s (1986) valve and feedback shared theories, and others from the literature. Distinct, inaccurate mental models of the heating system, as well as thermostat devices in isolation, are described,

and their relationship to self-reported behaviour is described in support of Hypothesis 1 (Figure 1). This chapter highlights the need to consider the mental models of the heating system in terms of an integrated set of control devices, and to consider user's goals and expectations of the system benefit.

### **1.3.3 Chapter 4 - The development of the Quick Association Check (QuACK) for exploring the relationship between mental models and behaviour patterns of home heating systems**

Simple application methods, that allow exploration of a link between users mental models of a device, and their behaviour with that device, are scarce in the literature. This chapter describes the development of the Quick Association Check (QuACK) - a semi-structured interview with paper-based activities and templates. QuACK collects data, verified by the user, relating to: 1) typical behaviour patterns when operating home heating, and 2) mental model descriptions of home heating function. The aim of QuACK was to produce a quick, resource light, method to explore association between mental models and behaviour patterns with home heating to support studies targeted at Hypothesis 1 (Figure 1). QuACK was developed with consideration of bias from the outset, using the tree-ring method described in Chapter 2. The outputs from a single case study are used to illustrate the method and the process of analysis and the potential ways that QuACK could inform energy reducing strategies, is discussed.

### **1.3.4 Chapter 5 - When energy saving advice leads to more, rather than less, consumption**

Where Chapter 3 explored differences in mental models of the thermostat, Chapter 5 considers householders that share the same model. A case study of 3 households that held a 'Feedback' mental model of the home heating thermostat as defined by Kempton (1986), was undertaken to understand the driver behind differences in their home heating strategies, and the effect on energy consumption. This chapter provides evidence in support of Hypotheses 1 & 2 (Figure 1). 5 different data sources were used for analysis, comprising; 1) boiler on durations, 2) thermostat set point adjustments, 3) self-reported strategies with home heating controls, 4) user mental model descriptions of the home heating system & 5) Interview transcripts. This chapter found that

## Chapter 1 - Introduction

differences in user mental models of home heating at the system level explained differences in the strategies chosen at the control device level, building on the conclusions from Chapter 3. Differences in boiler on periods were found to relate to limitations of Kempton's (1986) 'Feedback' mental model. The implications for energy consuming strategies are discussed.

### **1.3.5 Chapter 6 - Mind the Gap: A case study of the gulf of evaluation and execution of home heating systems**

This chapter applies Norman's (1983) idea of the 'Gulf of Evaluation and Execution' to the home heating domain. The mental model from a home heating expert is used as a representation of the 'Design Model' of the system. How the mental models of novice home heating users differ from this design model represents Norman's (1986) Gulf. A design specification is developed based on common omissions and misunderstandings found in novice users. This chapter highlights how broader variables (missing from a Feedback mental model), such as household thermodynamics, would facilitate a user mental model of home heating that enables appropriate behaviour with controls. How a typical home heating interface at a system and device level impedes a compatible user mental model to the design model, is explored to identify where design strategies can help bridge this gulf. This chapter provides a methodology to facilitate investigation of hypotheses 3 and 4 (Figure 1).

### **1.3.6 Chapter 7 - Using interface design to promote a compatible user mental model of home heating and pilot of experiment to test the resulting design.**

Chapter 7 builds on Chapter 6 by taking the design specification produced to bridge the Gulf of Evaluation and Execution experienced by domestic users of heating systems, and applying it to the design of a home heating control panel. This chapter uses design principles, recommended by Norman (2002) and Manktelow and Jones (1987) to evoke mental models in the user. The intention in this chapter was to create a 'mental model promoting interface' that could form part of an experiment that compared performance, behaviour and models evoked, with a more traditional interface, to test hypotheses 3 & 4 (Figure 1). The focus was on key devices (Thermostat, Programmer,

Thermostatic Radiator Valves (TRVs) and Boost Button) and their relationship with boiler activation and radiator output. This chapter shows concept developments for the redesign of [key](#) devices to promote appropriate functional models. At the system level a redesign of the layout of key devices is shown to promote a mental model with appropriate integration between devices. The results of [a](#) changes to the design of the control panel interface are shown following a pilot of the experiment.

### **1.3.7 Chapter 8 - Mental Model Interface Design – putting users in control of their home heating systems.**

Chapter 8 reports the design and results of an experiment using a home heating simulation to test hypothesis 4, that interface design can influence the achievement of home heating goals by encouraging appropriate behaviour, through the evocation of appropriate user mental models. Using the design concepts developed in Chapter 7, two interfaces were developed to compare a mental model promoting ‘control panel’ with a more traditional home heating setup. This chapter reveals the benefits of a mental model driven design in terms of home heating goal achievement, behaviour with heating controls, and evocation of appropriate mental models at the device and system level. This chapter also discusses limitations of the study.

### **1.3.8 Chapter 9: Conclusions**

Chapter 9 summaries the key findings from this research, followed by a discussion of the core issues underlying the research. Key recommendations are made and areas for future work are presented.

## **1.4 Contribution to Literature**

[This thesis has made a contribution in 3 key ways: First it has provided generic methodologies relating to the investigation and application of mental models, in the form of the tree-rings framework to consider layers of bias to encourage commensurability of findings \(chapter 2\), and application of Norman’s Gulf of Evaluation and Execution \(chapter 6\) at the ‘mental model’ level to aid design strategies. Secondly, it has developed \(chapter 4\), and applied \(chapters 3,5 & 6\) , a home heating specific methodology for capturing and analysing mental](#)

## Chapter 1 - Introduction

model descriptions and associated behaviour, at the device and system level. Finally, home heating specific findings that further the body of knowledge have been identified: specifically that system level analysis is necessary for behaviour change strategies (chapters 3,4,5 & 6), that gaps in user mental models go some considerable way to explaining energy consuming behaviour (chapters 3 & 5), and importantly, that interface design can alter the mental model held, *without prior training*, to effect users' behaviour with controls (chapter 8). The implications of these findings are far reaching not only when considering potential domestic energy savings to mitigate climate change, but for any domain where technology has been designed for performance goals, yet requires active control by users, as well as understanding of broader variables, to fulfil conservation and efficiency goals. The work presented in this thesis contributes to the literature by providing generic methods that can be applied to the notion of mental models. The Tree-rings method enables specificity in definition of knowledge structures, prompts identification and mitigation of bias in mental model research and supports commensurability from a novel perspective. In addition, this thesis focussed on the underlying mental model 'scaffolding' when applying Norman's (1983) 7 stages of activity to offer a different approach for building a design specification to bridge Norman's (1983) Gulf of Evaluation and Execution. This thesis also provided a home heating specific methodology with the development of the Quick Association Check (QuACK). This method enables descriptions of users' mental models and associated behaviour, to be captured as the device and system level, in an output ready for analysis. It also provides a method of analysis that allows categorization with respect to existing types of model and behaviour patterns that exist in the literature. The method is quick, resource light, and flexible in its application and analysis. The method has been constructed with a semi-structured interview, paper-based templates and instructions for analyst, to ensure its repeatability. This method will be useful seeking insights into the thought processes and behaviour related to home heating. This method could also be revised to suit other scenarios where behaviour change is sought, extending its reach. Specific finding relating to the home heating domain have been identified in this theses. These include the extent of omissions of home heating controls in users' mental models and the correlation with omissions from behaviour strategies. The integration of controls in householders strategies demanding that a 'systems' view needs to

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Kirsten M A Revell

~~be adopted to understand home heating behaviour, and the need for the impact of broader variables to be communicated to householders for optimal heating control to be possible.~~



## 2. Models of models: filtering and bias rings in depiction of knowledge structures and their implications for design

### 2.1 Introduction

[This Chapter focuses on the nature of the key concept of this thesis, the notion of the 'mental model' itself. It looks at the characteristics of mental models as described in the literature, and considers how the choice of methodology and perspective of definition, effect confidence in the validity of the captured knowledge structure. The insights gained in this chapter inform the approach taken to test hypothesis 1 and 3 described in the introduction in section 1.2. To determine if users' mental models of devices, influences their pattern of device use \(Hypothesis 1\), it is necessary to understand what constitutes a 'mental model' associated with behaviour. To determine if device design influences mental models of devices \(Hypothesis 3\), it is necessary to understand the mechanisms by which mental models are formed, and the barriers to access that enable changes in mental models to be observed.](#)

Mental models are thought to be representations of the physical world (Veldhuyzen and Stassen 1976, Johnson-Laird 1983, Rasmussen 1983), constructs that can explain human behaviour (Wickens 1984, Kempton 1986) and internal mechanisms allowing users to understand, explain, operate and predict the states of systems ( Craik 1943, Kieras and Bovair 1984, Rouse and Morris 1986, Hanisch et al. 1991, Gentner & Stevens, 1983).

The notion of mental models has proved attractive for many domains: For Psychology, when considering cognitive processing (Johnson-Laird 1983, Bainbridge 1992); in interface design (Williges 1987, Carroll & Olson, 1987, Norman 2002, Jenkins et al. 2010); to promote usability (Norman 2002, Mack and Sharples 2009, Jenkins et al. 2011); and for the Human Factors domain, to enhance performance (Stanton and Young 2005, Stanton and Baber 2008, Grote et al. 2010, Bourbousson et al. 2011) and reduce error (Moray 1990a, Stanton and Baber 2008, Rafferty et al. 2010). For the successful application of this notion, clarity in its meaning and guidance in its use is vital. However, the

Chapter 2 – Models of Models: filtering and bias rings in depiction of knowledge structures and their implications for design

lack of consensus in this field, brought to light by Wilson and Rutherford (1989) over 20 years ago, remains unresolved.

It is proposed that for successful application of the notion of mental models (e.g. in device design), that the accurate capture of the model held by the agent of interest (e.g. device user) is key. In the literature, a pragmatic means of considering the deviation in accuracy from the model source to the recipient is absent. When comparing different notions of the term 'mental model', existing reviews of the literature have provided useful textual categorizations and high level frameworks, which go some way towards the goal of commensurability (see Richardson & Ball (2009) for a comprehensive review, 2009). The literature does not sufficiently emphasise the relationship between the type of notion, the methodology of capture and the risk of bias.

This review, therefore, has two aims: firstly, to compare and contrast the work of major research figures in the field and secondly, through the development of an adaptable framework, emphasize the importance of characterizing mental model content accurately based on a) the risk of bias resulting from the methodology undertaken and b) the perspective (in terms of model source and type) from which mental models are considered. [unaffected](#)

To achieve these aims, this chapter will first contrast the theories of Johnson-Laird (1983), Moray (1990) and Bainbridge (1992) who offer distinctly different concepts of mental models as inferred knowledge. The critical elements found will form the basis for an adaptable framework to demonstrate the second aim. Next, the role of cognitive bias in mental models research will be considered and the understanding, in this thesis, of 'filtering information', will be described with a view to further developing the framework using the case study of Kempton (1986). Following this, the different perspectives by which major researchers in the field define mental models, and the methodology with which they have undertaken research will be compared schematically using the framework, to illustrate similarities and differences. Finally, the use of the framework to compare two notions of mental models offered by Kempton (1986) and Payne (1991) to illustrate how the schematics can be deconstructed to help specify both the perspective from which data is gathered and the risk of bias in interpretation of the source model.

This chapter is considering mental models formed by an individual and accessed by another individual. As such, it does not address related notions such as ‘shared mental models’ or ‘team mental models’. Brewer’s (1987 c.f. Stanton (2000)) distinction that “schemas are generic mental structures underlying knowledge and skill, whilst mental models are inferred representations of a specific state of affairs” [to be may be](#) helpful when reading this chapter.

### 2.1.1 The concept of mental models as inferred knowledge in cognitive processing

This section will compare three different approaches to the role of mental models in cognitive processing, proposed by Johnson-Laird (1983), Bainbridge (1992) and Moray (1990b). These theorists are chosen to show that despite considerable differences in approach, focus and context, fundamental ideas are common. The aim of this section is to emphasise mental models as one of a range of mental constructs and highlight the importance of the role played by background knowledge.

The term ‘knowledge structure’ is taken from Wilson & Rutherford (1989) to describe the descriptions analysts make of a user’s understanding. A concise definition of a mental model is absent in the work under appraisal, with the notion conveyed by the theorists, partly by comparison to alternate constructs. To aid the readers understanding, Table 1 summarises the different categories of knowledge structures common to these theorists. The role and interaction of these structures will be expanded upon in the following section, considering each theorist in turn.

A summary comparing these ideas will then be undertaken, culminating in a graphical representation comparing these knowledge structures and related processes, which will form the basis of an adaptable framework that is built upon in part two of this chapter.

Table 1 - Table to categorise and compare the types of knowledge structures proposed by Johnson-Laird (1983), Moray (1990b) and Bainbridge (1992)

Theorist	Knowledge Structure
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Chapter 2 – Models of Models: filtering and bias rings in depiction of knowledge structures and their implications for design

	<b>Inferred</b>	<b>Background</b>	<b>Other</b>
Johnson-Laird (1983)	Mental Model	World Model	Propositional Representations
Bainbridge (1992)	Working Storage	Knowledge Base	Meta Knowledge
Moray (1990b)	Mental Causal Models	Physical Systems Lattice	n/a

**2.1.1.1 Johnson-Laird (1983)**

Johnson-Laird (1983) took a linguistic approach to the study of mental models, to understand the role they played in inference and reasoning. Johnson-Laird (1983, 1989, 2005) rejected formal logic as the driver for reasoning, showing instead that the manipulation of mental models makes it possible to reason without logic.

Johnson-Laird (1983) presented a building block approach to knowledge structures. Information is initially encoded as ‘Propositional Representations’, which themselves, do not allow the user to go beyond the data in the proposition (Manktelow and Jones, 1987). Johnson-Laird (1983) introduced the concept of ‘procedural semantics’ as the mechanism which determined if a propositional representation would remain in that form, or be combined into the ‘higher’ structure of a ‘mental model’. These, according to Johnson-Laird (1983, 1989, 2005) do allow users to go beyond the data, experiencing events by proxy to make inferences, predictions and ultimately, decide what action to take as a result (Manktelow and Jones, 1987).

Johnson-Laird (1983) explicitly described seven procedures which are required to create and test a mental model. All procedures state reference to a type of knowledge structure termed a ‘Model of the World’ (Johnson-Laird: 1983, 1989, 2005). Manktelow and Jones (1987) interpret the first five procedures as ‘general’. These provide the function of determining prior experience of the representation, amending the world model with new information, combining previous separate models based on new interrelated information, and

establishing the truth of a proposition. Manktelow and Jones (1987) interpret the final two procedures as recursive, with the function of checking back through the mental model with reference to the world model to see if it is flawed, amending or changing to a better model if necessary.

Johnson-Laird (1989) considers the creation of the mental model as a structure for comprehension and inference in general, for all agents who use language, but does not preclude its application in other domains. Whilst he particularly focused on classical syllogisms, he made clear that his theory was intended as a general explanation of thought (Manktelow and Jones 1987). Johnson-Laird's focus was on the interaction between any two agents via language. This differs from the following theorists whose focus is on a user interacting with a device or system.

#### **2.1.1.2 Bainbridge (1992)**

Focusing on operators of complex systems, with a view to understanding cognitive skill, Bainbridge (1992) considered the way the term Mental Model is used in cognitive processing too general. She offered 3 distinct ways the term makes a contribution: 1) Knowledge base – described as knowledge of the permanent or potential characteristics of some part of the external world; 2) Working storage – described as temporary inferred knowledge about the present or predicted state of the external world (equivalent to Johnson-Laird's (1983) notion of mental models); and 3) Meta-knowledge – described as knowledge of the outcomes and properties of the user's own behaviour. Bainbridge (1992) describes the knowledge base as equivalent to long-term memory, and proposed this is responsible for inference and prediction. The working storage, is interpreted as a knowledge structure of inferred knowledge, derived from the knowledge base in form that the user can work with in the current context. Bainbridge (1992) identifies that for cognitive skill, knowledge bases should be sufficiently developed to infer states and anticipate events, and meta-knowledge should be fully developed.

Bainbridge (1992) proposes 'processing modules' as the mechanism that meets particular cognitive goals. She hypothesised that multiple processing modules work simultaneously at different levels, responding to different strategies chosen by the operator to fulfil particular goals. The information needed is actively sought out, either in existing knowledge bases, the

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environment, or through further processing. The modules communicate with each other via working storage, with answers to lower level goals becoming input to fulfil higher level goals.

Like Johnson-Laird (1983), Bainbridge (1992) emphasises the recursive nature of the process, and considers reference to background knowledge as key. In addition, she highlights information in the world as an important information source.

Bainbridge's (1992) focus, unlike Johnson-Laird (1983), addressed how operators seek out answers to specific goals. The emphasis on operator strategies, may be specific to users of complex systems, since evident in Moray's (1990b) theory.

#### 2.1.1.3 Moray (1990)

Moray (1990b) used lattice theory to represent mental models held by an operator of complex systems. He presented an elegant approach to cognitive processing, based on operators selecting a strategy associated with one of Aristotle's four causal hypotheses. Moray (1990b) provides the following example to distinguish between causes;

“...when considering a switch causing a pump to operate, he (the operator) may consider; A *formal* cause (because it is in the 'on' position), a *material* cause (because it closes a pair of contacts), an *efficient* cause (because it allows current to flow through the pump), or a *final* cause (because cooling is required).” (p.579)

Moray (1990b) suggested that a Mental Cause Lattice (MCL) existed for each cause, resulting in a Formal Cause Lattice (FCL), Material Cause Lattice (MaCL), Efficient Cause Lattice (ECL) and a Final Cause Lattice (FiCL). Each lattice was considered a hierarchy, with the high level goal at the top, and extremely detailed information at the lowest level.

The chosen strategy activates cognitive processing within a specific MCL, allowing the operator to travel up and down the hierarchy in the lattice, and between lattices where one MCL links to an alternate MCL. The latter case

represents the operator switching strategies to find a particular bit of information.

Moray (1990b) proposed each MCL is derived from a shared 'Physical System' lattice (PSL). This is based on physical relations between parts of the system based on experience or system specifications. He proposed that the relationship between these groups, and from each group to the PSL, is via 'holomorphic mappings' which play a significant part in the explanation and reduction of errors. For example, inaccuracies in the PSL would be carried into the MCLs. This one-way relationship differs from the recursive process proposed by Johnson-Laird (1983) and Bainbridge (1992).

It is proposed by the author, that each of the four MCL are equivalent to internal knowledge structures which allow inference and prediction in the sense of Johnson-Laird (1983), and can be used as 'working storage' as identified by Bainbridge (1992). These MCLs also reference some sort of 'background' knowledge structure in the form of the PSL.

Moray (1990b) focused on troubleshooting problems in complex systems and was concerned with how 'answers' are found. Like Bainbridge (1992) the importance of goals and strategies is marked.

#### 2.1.1.4 Summary of comparison of theories of Cognitive Processing.

It is clear from the preceding discussion, that what can be termed 'background knowledge' in the form of 'knowledge base, PSL' or 'world model', plays a vital role in cognitive processing, both as an information source and reference for inferred knowledge structures such as 'mental models', 'working storage' or 'MCLs'. Bainbridge (1992) requires background knowledge to be 'sufficient' whilst Moray (1990b) stresses the importance of its accuracy.

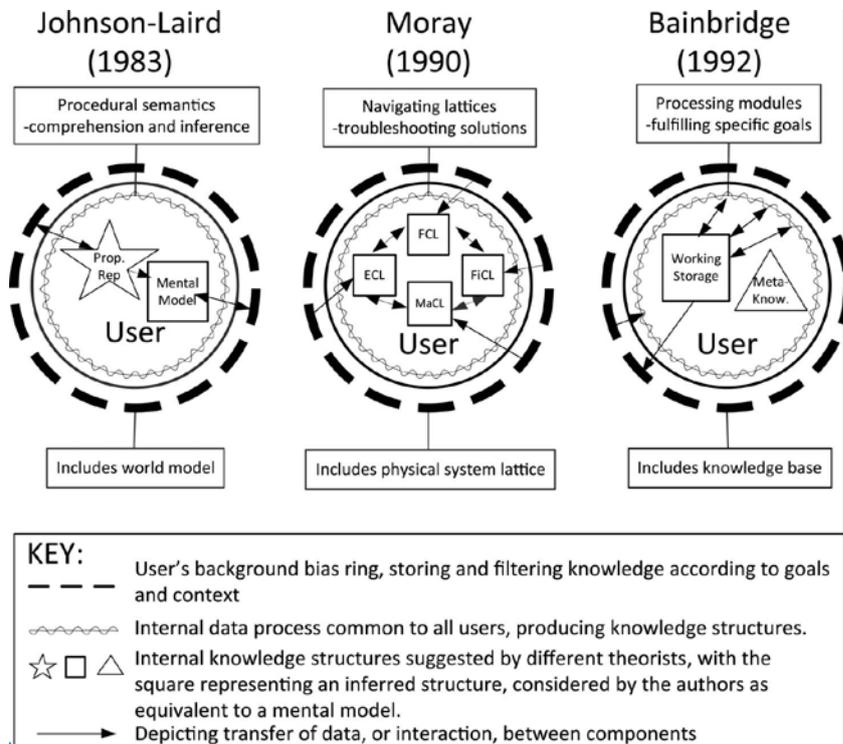
Figure 2 provides a schematic of the three theories discussed, to visually emphasise the similarities and differences. The area within the solid circle includes the processes and types of knowledge structures common to all people. The broken ring surrounding this represents people's background' which will vary based on experience and includes the various types of 'background knowledge'. This is termed the 'background bias ring', in this thesis, as differences in its content will 'bias' the inferred knowledge structure.

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We can see from Figure 2 that Johnson-Laird (1983) and Bainbridge (1992) emphasize a recursive nature to the relationship between background knowledge and inferred knowledge structures that support inference and prediction, but also include additional knowledge structures which play different roles. Moray (1990b) describes a one-way relationship and does not present additional knowledge structures, but instead 4 ‘inferred’ knowledge structures based on different causal strategies between which the operator can switch.

The different functional focus by different theorists suggests that different methods of processing may come into play in different contexts, meaning the theories discussed may all be relevant to an ‘umbrella’ theory related to multiple contexts. Johnson-Laird’s (1983) focus on linguistics highlights the importance of communication between agents, which has relevance to any domain where linguistic communication occurs (both verbally and textually). Moray’s (1990b) focus on operators holding an accurate model of the relationships found in physical systems is relevant for interaction between humans and devices. Bainbridge broadens the concept by relating the background knowledge to any relevant elements in the ‘external world’.

Whichever theorist is most applicable in a particular domain or context, it is clear that background knowledge is important in the construction of inferred knowledge structures which allow inference (what is termed in this thesis as “mental models”). As such, the significance of background knowledge and how it interacts with mental models warrants further understanding if the notion of mental models are to be applied pragmatically.



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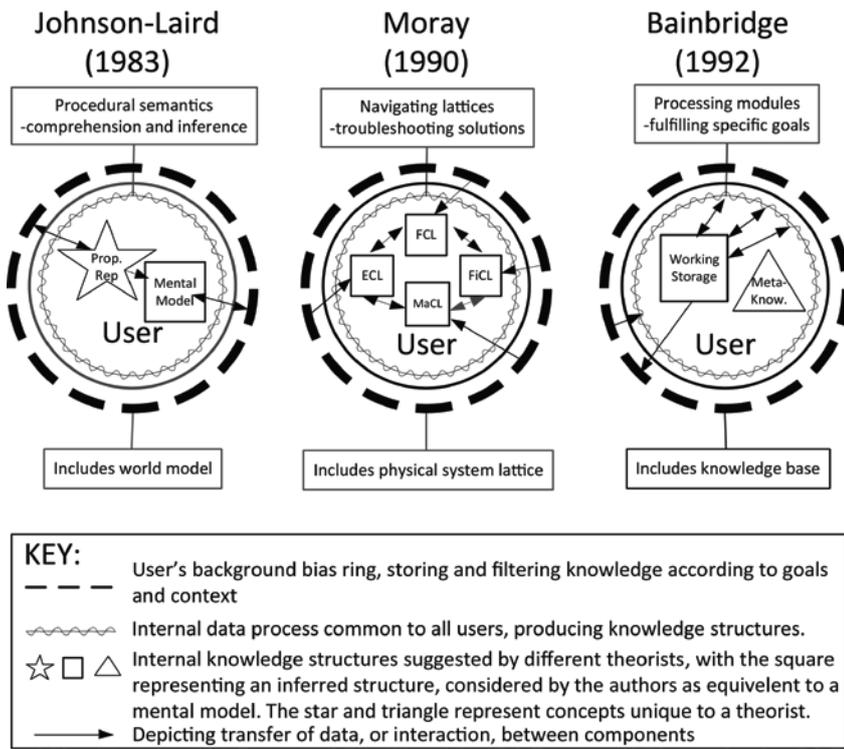


Figure 2 - Illustrating the way different theorists place mental models in relation to other knowledge structures.

## 2.2 The importance of accuracy in mental model descriptions – the development of an adaptable framework

In this section we will be developing a framework from the schematic shown in Figure 2, which identified the influence of 'background knowledge' on the content of inferred knowledge structures. Variations in background knowledge therefore bias the mental model constructed. It is suggested the same affect occurs when an analyst attempts to access a mental model, with their 'background knowledge' influencing the way data is interpreted. This view follows from that stated by the argument put forward by Wilson & Rutherford

(1989) that an analyst's intention to access a user's mental model, can result in the erroneous conclusion, that their description is evidence of its capture. The following framework intends to emphasise the difficulties in accurately capturing (or constructing) a mental model, due to inherent biases in the methods for communicating mental models. The first part of this section will briefly describe cognitive bias and its existing role in mental model research. The meaning in this thesis of the terms 'filtering' and 'bias in interpretation' follow as the key concepts in the proposed framework. The second section will use the case study of Kempton (1986) to illustrate the layers of bias inherent in methodologies chosen to access internal constructs. The third part will consider the perspectives from which mental models are considered, illustrating the intended points by use of the framework.

### **2.2.1 Bias and Filtering when constructing or accessing mental models**

Bias can be defined as "An inclination toward a position or conclusion; a prejudice." (Reber, 1985) Tversky and Kahneman introduced the notion of cognitive bias in 1974 in their seminal chapter which emphasised how heuristics are employed when people need to make judgements under uncertainty. They highlighted 1) representativeness, 2) availability of scenarios, and 3) adjustment from an anchor as three highly economical 'rules of thumb' heuristics that are usually effective, but lead to systematic and predictable errors.

A major emphasis in the subject of 'bias' in the mental model literature has been on 'belief bias', the effect of believability of an outcome on whether it is accepted as true (for example, Oakhill et al., 1989, Klauer et al., 2000, Klauer & Musch, 2005, Quayle & Ball, 2000, Santamari et al. 1996). Other biases have receiving attention include negative conclusion bias (Evans et al. 1995), matching bias, and the effects of temporal order and suppositional bias (Ormerod et al., 1993), bias in metapositional reasoning, (Schroyens et al., 2010), social, contextual and group biases (Jones & Roelofsmaa, 2010). With the exception of Jones & Roelofsmaa (2010), who consider 'shared mental models' in teams, the goal of the literature has been to test mental model theory derived from Johnson-Laird (1983) on its ability to explain bias effects found in experimental data, with a view to amend, extend, or abandon with alternate theories (Evans et al. 1995, Oakhill & Johnson-Laird, 1989, Newstead

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et al., 1992, Newstead and Evans, 1993, Quayle & Ball, 2000, Schroyens et al., 2010, Ormerod et al., 1983, Oakhill et al., 1989, Klauer et al., 2000, Klauer & Musch, 2005, Santamari et al., 1996)

Kahneman & Tversky (1982:201) class the deliberate manipulation of mental models as an important and distinct ‘simulation heuristic’ used particularly in: 1) prediction, 2) assessing the probability of a specified event, 3) assenting conditioned probabilities, 4) counterfactual assessments, 5) assessments of causality. Whilst emphasizing how other types of heuristic may interact with and affect the construction of mental models, they do not consider it necessary that mental simulation theory incorporate an explanation of these effects (Tversky and Kahneman, 1982). In this chapter, the same sentiment is adopted and recognition of the ‘risk of bias’ to mental models research in general, rather than the explanation of specific bias types within a particular mental model theory is the main concern.

To illustrate the importance of considering bias in mental model research, this chapter focuses on three broad categories: 1) The result of experience when interacting with the world (background bias), 2) that which comes into play when interacting simultaneously with another agent (social bias) and 3) when interacting separately, through some form of cognitive artefact (cognitive artefact bias). The first category is based on the conclusion from the previous section that differences in agents’ backgrounds influence the nature of inferred knowledge structures (derived from Johnson-Laird, 1983, Moray, 1990, Bainbridge, 1992). The second category builds upon Johnson-Laird’s emphasis on linguistics and therefore communication. The latter, extends from this to represent non-synchronous communication, which, by not allowing immediate interaction to check understanding is considered to be particularly prone to bias in interpretation.

The framework offered will propose a set of ‘tree-rings’ surrounding each agent (i.e. the user, analyst, instructor, intelligent device etc.), as depicted in Figure 3. These rings represent the agents’ background (in terms of experience and knowledge), their social interactions (including communication and behaviour) and where relevant, their use of cognitive artefacts for communication or as an information source. The background ring is closest to

the agent, and will always be present. The social and cognitive artefact rings may be present in various configurations depending on the type of interactions in which the agent is involved. The rings are represented as dashed lines to signify 'filters' allowing selected information to pass to the agent. The arrows portray different ways in which information from the world is treated by the combined effect of the filters. The key point to note, is that information intake is not treated as the dichotomy of accepted or rejected, but according to its consistency with existing or alternative knowledge structures. The implication is that inconsistent information may not be rejected, but merely treated differently to consistent information. Assumed (rather than perceived) information, consistent with the existing knowledge structure, is also reflected as an input for the construction of functioning mental models. Different treatments of information is likely to affect the clarity of the input when forming knowledge structures (represented by different arrow styles in Figure 3).

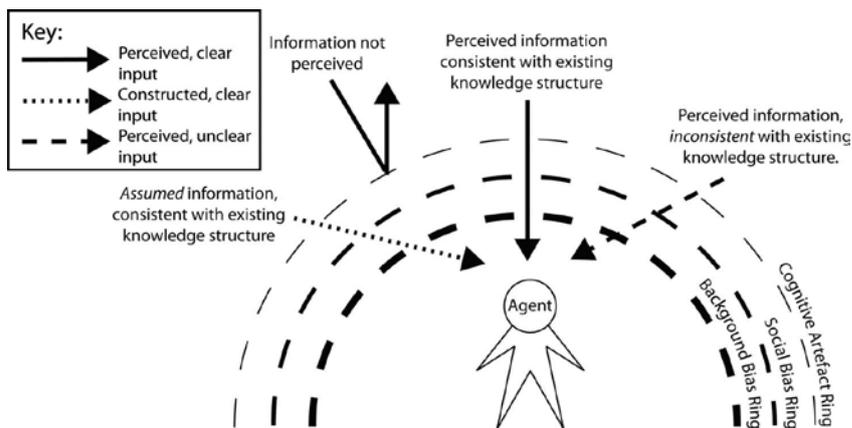


Figure 3 - Depicting how information in the world can be filtered in different ways.

As shown in the previous section in the theories of Bainbridge (1992) and Moray (1990) the idea of goals and strategies plays a significant role in resulting inferred models. In different contexts, or when the agent has different aims, the ways information should be interpreted to form a functioning mental model, will therefore differ. This implies that the filters vary accordingly. It is suggested that this difference represents the combined

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influence of cognitive biases relevant to that context, and provides a generic term to account for these variations as ‘bias in interpretation’ (henceforth termed ‘bias’).

Consider the analogy of a bowl with a ball of putty pressed off-centre, causing an imbalance or ‘bias’. The bowl can be considered the background or social bias ring, with the putty representing the agent’s bias, formed by his goal in a particular context. As the size and position of the putty in the bowl, determines the angle of imbalance, so too the amount and kind of background and social experience, determine the strength and direction of the agent’s bias.

Figure 4 (a) shows a bowl with no bias, whereby thought, action or behaviour are steered equally in all directions. Figure 4 (b) shows the effect of strong bias, steering thought, behaviour and perception in a single direction. Since the focus of this review is on mental models, the bias discussed will be related to ‘thought’. It should be made clear, however, that the interaction between perception, thought and behaviour, is considered implicit.

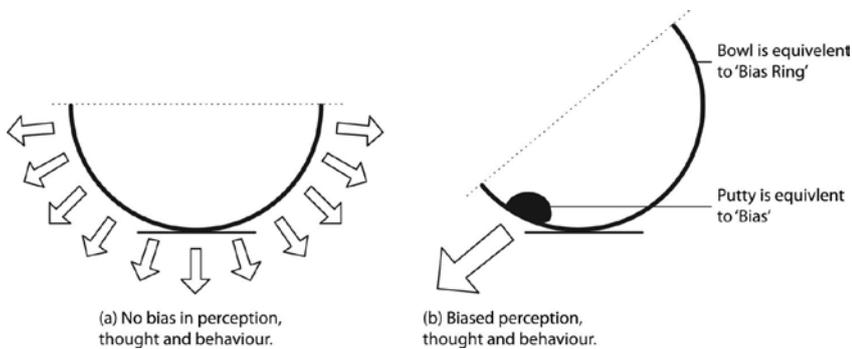


Figure 4 - Providing an analogy for 'Bias rings'.

It is assumed that each ring contains various biases, differing according to an agent’s experience. Selection of a particular ‘filter’ is based on the agent’s particular goal within the perceived context (see Figure 5 (a)). A sole background ring exists for each agent, containing a set of biases that connect to corresponding social rings. The choice of social bias is similarly based on context and aims, filtering thought and behaviour from the agent, as well as

the perception of information from the world (Figure 5 (b) and (c)). The cognitive artefact ring is a special case of 'pre-filtered' information, arising from the background and social rings of the creator, and extends the chain in Figure 5 (d).

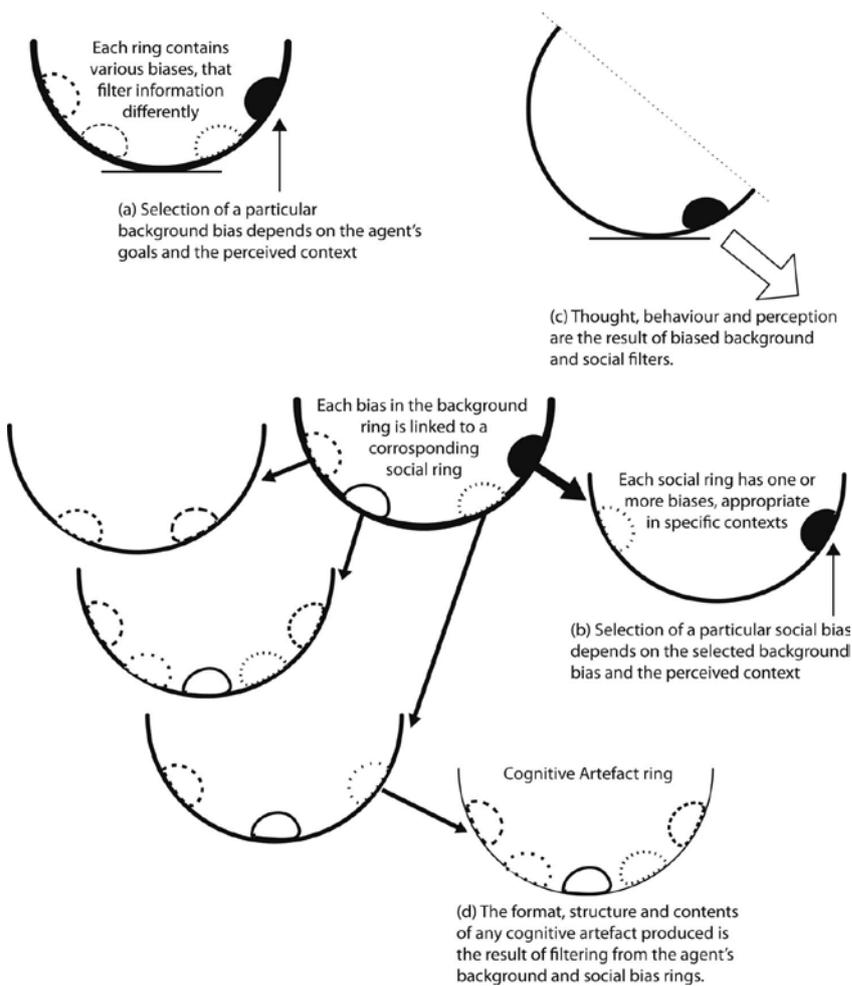


Figure 5 - Proposing the interaction between bias rings and filters.

The aim of this section was not to evaluate in depth mechanisms to explain the bias in specific types of reasoning, but rather offer a high level mechanism that complements the idea of 'filtering' to emphasise the need to consider 'risk of bias' in mental models research. In each individual context, specific biases will

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apply and these will need to be understood within that context and chosen methodology. The framework developed, is designed to depict the ‘risk’ of bias, as well as emphasise the perspective form which mental model structures are being considered, with a view to allowing commensurability in mental models research.

### **2.2.2 Accuracy of mental model content – a case study of Kempton (1986) illustrating the impact of methodology**

Kempton (1986) identified two different ‘folk’ theories of domestic heat control (‘valve’ and ‘feedback’), interpreting data collected by in-depth interviews with users. Kempton (1986) suggested that a user’s adopted folk theory for a device was the *driver* for their behaviour when interacting with the device. He argued that acknowledging this link could have practical applications in understanding and predicting behaviour that affects energy consumption. Having identified the considerable burden of domestic heating use on energy consumption, Kempton (1986) implied this could be reduced by ensuring users have the most energy efficient folk theory of home heat control.

Kempton (1986)’s study of home heating is chosen as an example to illustrate the impact of methodology on bias in mental models for three reasons. Firstly, as the area of study (energy consuming behaviour) reflects the interest of this thesis, secondly, because he is clear in his description of methodology adopted and finally, because the claims he makes about ‘folk theory’ are equivalent to the potential associated with the term ‘mental model’ as an inferred knowledge structure from which inferences and predictions can be made. Focusing on Kempton (1986) therefore provides an opportunity to consider ‘folk theory’ in the context of mental model theory whilst developing the proposed framework.

Kempton (1986) paraphrased four findings of McCloskey (1983) regarding the folk theory of motion, as follows, to illustrate the basis on which he uses the term. The reference to institutionalized physics can ostensibly be substituted with the established ‘expert theory’ dependent on context.

“folk theory.... (1) is based on everyday experience, (2) varies among individuals, although important elements are shared, (3) is inconsistent

with principles of institutionalized physics.... and (4) persists in the face of formal physics training.” (p.77)

Figure 6 depicts Kempton as the ‘Analyst’ and represents 2 users as ‘subjects’, who have individual models of the operation of a home thermostat, but some key shared elements identified by the analyst. From this depiction, it is not possible to determine if the shared elements are part of a ‘folk’ theory, as only part (2) of McCloskey’s (1983) four findings is established. A shared ‘amateur’ theory is suggested as an alternative that does not fulfil findings (3) and (4).

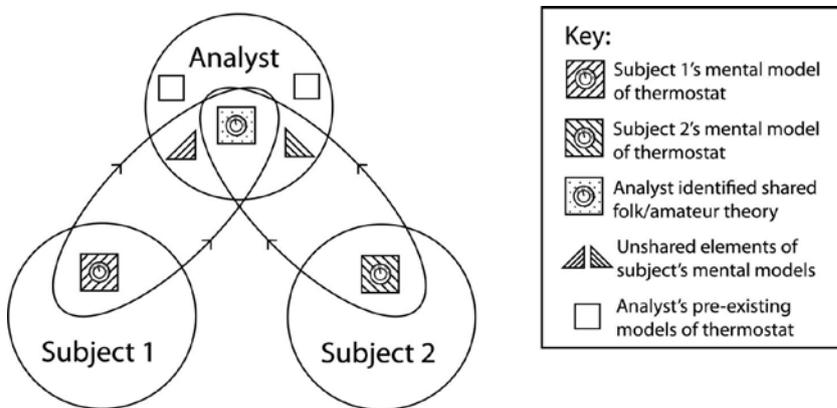


Figure 6 - Depiction of the relationship between agents and models when identifying a shared theory of the operation of a home thermostat (based on Kempton’s (1986) study).

In the depiction in Figure 6, the large circles represent the ‘agents’ involved. The squares within the circles represent the agents’ internal ‘mental model’ and contain an image of the source device (in this case a thermostat dial). The interconnecting ovals represent that a process has taken place for one agent to access the model of another agent. The arrows flow from the source model (which has been accessed) to the resultant model (which is held by another agent and based on the accessed model). The key point to note, is that each agent holds a different model.

For completeness, Figure 6 also shows the unshared elements of each subject’s models, as well as pre-existing models that the analyst may have had (such as from interaction with an expert, or their own experience). In

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Kempton's (1986) study, the significant model is the 'shared theory' held by the analyst and formed by elements that were present in both subject's individual models. How this resultant model is constructed and the processes involved in accessing another agent's model will be discussed next.

#### **2.2.2.1 Bias when accessing another person's mental model.**

Kempton (1986) accessed his subject's mental models through in-depth interviews, where participants were asked to explain their understanding of how the home heating thermostat operated. Particular focus was placed on the relationship between users' comfort and their interaction with the thermostat control. Evident in the subject's transcripts, was the use of analogies to explain their understanding of the thermostat (such as a gas burner or water valve for 'valve theory'). This suggested that subjects were basing their individual models of thermostat control on previous experience. To infer two theories of thermostat control, it is reasonable to assume that Kempton's 'valve' and 'feedback' examples were similarly influenced by his existing knowledge and previous experience when interpreting users' statements. The impact of existing knowledge and experience in the construction and access of mental models has been reiterated in the literature (de Kleer and Brown 1983, Rouse and Morris 1986, Wilson and Rutherford 1989, Payne 1991, Bainbridge 1992, Smith-Jackson and Wogalter 2007, Zhang et al. 2010, Zhang & Peng 2011, Ifenthaler et al. 2011 ) and formed the conclusion of section 2.0 based on the work of Johnson-Laird (1983), Moray (1990) and Bainbridge (1992).

To represent the effect of the agent's background, in terms of experience and knowledge, on the construction of a mental model, a 'Background Bias' ring has been placed around each agent and depicted in Figure 7. The different ring patterns denote that each agent will have a background individual to them. As such, presented with the same device, different agent's interpretations of its workings will vary according to the variations in their background. The 'Background Bias' ring is in essence a filter, which comes into play when processing information from the world. This is similar to the concept of Schema (Bartlett 1932, Stanton and Stammers 2008).

When interviewing subjects, Kempton (1986) noted that many showed insecurity in their descriptions, presumed by Kempton to be due to

embarrassment about their incomplete knowledge. It is also evident from the transcript elements presented, that Kempton's ability to adjust his questioning according to the subject's responses, was key in clarifying and bringing out elements of the individual's model. Kempton also stated that he started the study with a larger number of exploratory interviews, but the lack of specific focus on home heat control, meant they were inadequate for accessing an individual's specific device model. The effect of the social interaction between analyst and subject, and the skill and focus of questioning, cannot, therefore, be ignored and are considered to be examples of 'social bias'. This sentiment is similarly reflected in the literature (Rouse and Morris 1986, Wilson and Rutherford 1989, Payne 1991, Bainbridge 1992, Kennedy and McComb 2010, Frede et al. 2011, Cutica & Bucciarelli 2011) and is inferred by the work on linguistics by Johnson-Laird (1983).

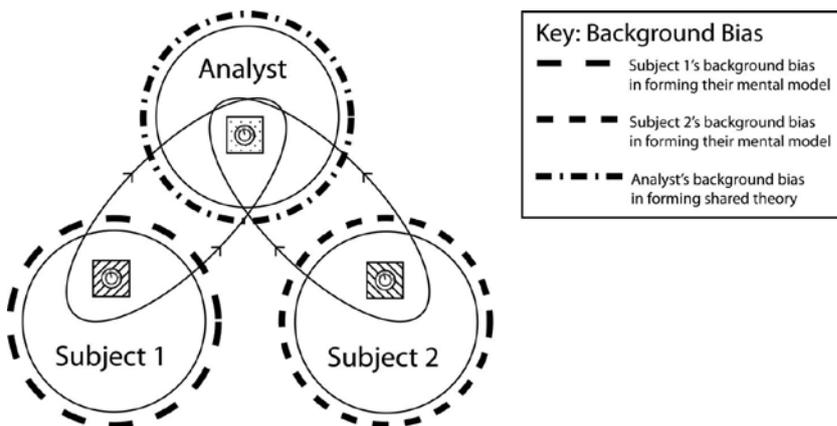


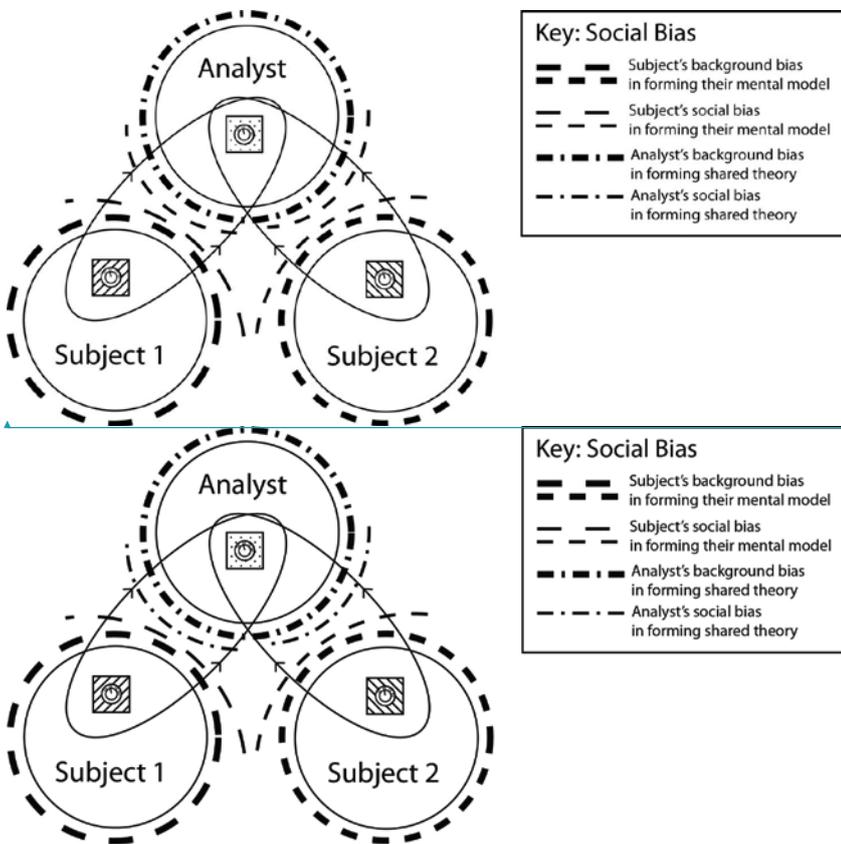
Figure 7 - The influence of 'background bias' in forming an agent's mental model is shown as a patterned ring around each agent.

Figure 8 represents the effect of social bias as an arc around the agent and between communicating agents. An arc, rather than a ring is used to highlight social bias, which only comes into play during an interaction with another agent. The arcs are patterned according to the agent, to show they are individual and specific to that agent, and related to the background bias ring.

Since the way an agent interacts may change according to the social context, and their assessment of what the other agent will understand or relate to, it is suggested that interaction with different agents will produce different 'social

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biases'. As was described in section 3.1, it is proposed that these differences are ultimately influenced by the agents' background and experience. This means the 'background bias' ring not only has primary influence on the construction of mental models, but also affects the 'social bias' ring (as was shown in Figure 5). The 'social bias' ring essentially determines the ease with which one agent can access the mental model of another agent.



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Figure 8 - The influence of social bias on forming an agents' mental model

It has been proposed that the construction of mental models by an agent and their access by another agent, is subject to biases relating to social/communication and background/experience. These influences have been represented schematically in what shall be termed a 'tree-ring profile' in

Figure 9. A tree ring profile is constructed by aggregating the bias rings in order of interaction between agents, starting with the source model. Where more than one ring is shown, an interaction with another agent has taken place.

The mental models belonging to two different subjects vary in their construction according to the different bias of their unique background rings (see Figure 9). Kempton's shared theory is depicted as exposed to considerably more bias. As his theory is built up from more than one subject's mental model, the background bias surrounding the central model is made up of more than one 'pattern'. Similarly, the social bias of more than one subject is shown in the second from centre ring. The final two rings represent the influence of Kempton's own social bias (medium, line-dot pattern) when interacting with the subjects, and finally his own background bias (thick, line-dot pattern) when constructing the shared theory from the common elements of the subject's individual mental models (see Figure 9).

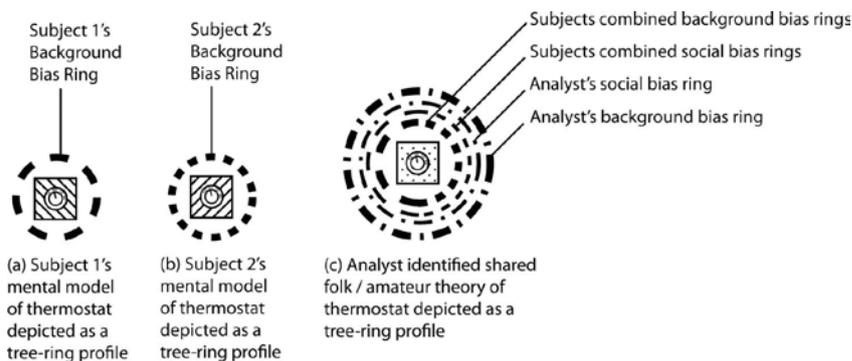


Figure 9 - Tree ring profiles showing the layers of bias that alter the construction and access of an agents' mental model.

We can see from the tree-ring profiles in Figure 9, that variations in models are inherent of variations in individuals. The process of accessing another individual's mental model, that is the methodology of access, is subject to many layers of bias which by implication distort an analyst's description from a 'true' representation of an individual's mental model.

Whilst Kempton (1986) was not claiming to represent any one individual's mental model, but a 'shared theory', he nevertheless depended on accurate

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extraction of subject's individual mental models in order to identify common elements to form his hypotheses. The next section considers the perspectives from which analysts access mental models, positioning Kempton's individual and shared theory within these.

### **2.2.3 Accuracy in definition – The perspective from which data is gathered**

We have shown how the methodology undertaken in mental model research affects the risk of bias and therefore confidence in the accuracy of the knowledge structure. In the introduction, we emphasized how the literature has not reached a consensus on the definition of a mental model. This section argues the importance of characterizing mental models based on the perspective (in terms of model source and type) from which they are considered. To do this, existing definitions of mental models will be represented schematically to highlight the similarities, differences and ambiguities.

Norman (1983) provides a clear set of definitions relating to the concept of mental model when interacting with devices. These will be contrasted with those provided by Wilson and Rutherford (1989) to show the variety and potential ambiguity in definition. These definitions have been chosen on the basis that they appear in articles with high citation ratings, implying widespread influence on subsequent research.

#### **2.2.3.1 Norman (1983)**

To prevent confusion when undertaking research or discussing mental models, Norman (1983) emphasises the importance of distinguishing between the following four conceptualizations: 1) The *target system*, 't', which is the system that the person is learning or using; 2) The *conceptual model* of that target system, 'C(t)', which is invented by instructors, designers or scientists to (ideally) provide an accurate, consistent, and complete representation of the target system; 3) The *user's mental model* of the target system, 'M(t)' which is "the actual mental model a user might have", and can only be gauged by undertaking observations or experimentation with the user; 4) The *scientist's*

*conceptualization*  $C(M(t))$  of the *user's mental model*, which, by implication, is the mental model a user is *thought* to have.

These definitions have been represented schematically by the author in Figure 10. Note that  $M(t)$  is the only term where interaction with another agent is explicitly specified. It is not clear from Norman (1983) how  $C(t)$  or  $C(M(t))$  is constructed. It might be presumed that there was interaction with the device itself, with other agents such as experts on either the user or the device, or with cognitive artefacts such as user guides, market research reports or technical specifications. Because the method for construction is not explicit, the influence of bias rings cannot be represented beyond the background of the analyst and designer (see Figure 11). This means that subsequent researchers using the same (quite well specified) terminology may do so with significant variation in the set of 'bias rings' impacting the access or construction of the mental model sought.

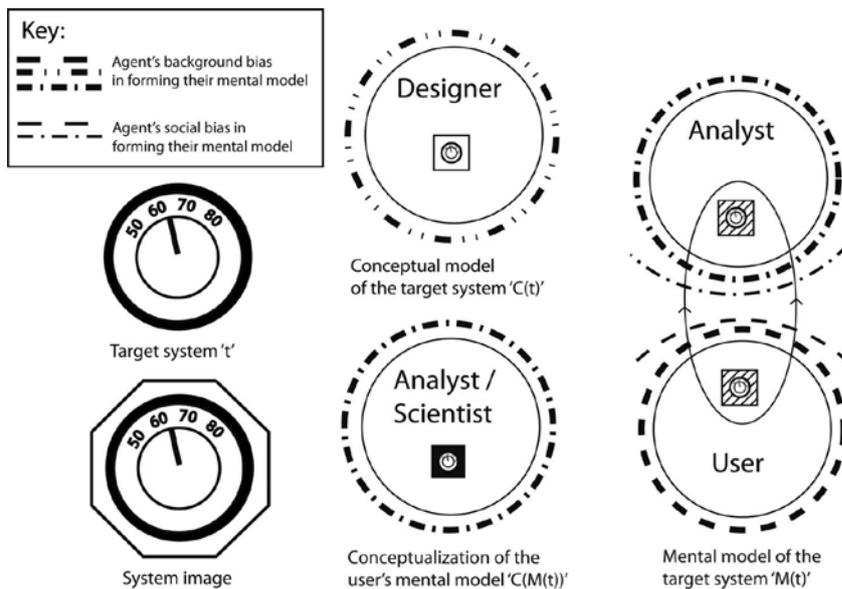


Figure 10 - Norman's (1983) definitions of mental models represented schematically.

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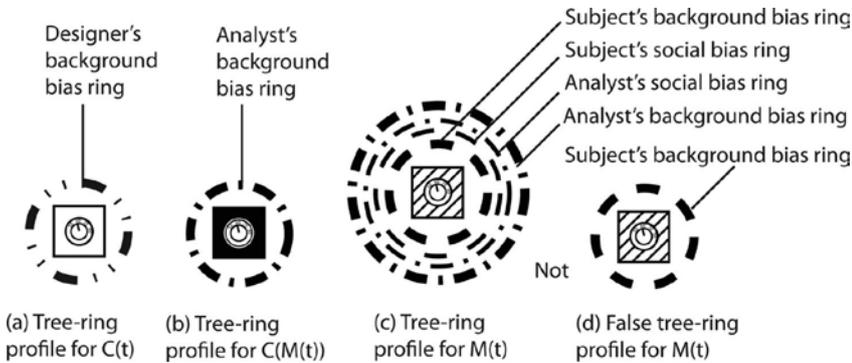


Figure 11 - Tree-Ring Models representing the bias explicit in Norman's (1983) definitions.

Figure 11 depicts the difference between a concept with a stated methodology, and that without, when looking at the two examples of  $M(t)$ . Norman's (1983) definition provided the insight that  $M(t)$  can only be gauged by some methodology, rather than accessed directly. Since all of Norman's definitions apply to mental constructs, the presumed or recommended method of access would benefit others who wish to use the defined construct in a consistent way.

Comparing the Tree-Ring Models in Figure 11 to those in [Figure 9](#)~~Figure-7~~, we can see similarities. Norman's (1983)  $M(t)$  is similar in the pattern of bias rings to Kempton's (1986) 'Analyst identified shared theory', with the exception in Norman, since interaction with only one 'user' is presumed, that a single line style is used to make up the rings of the agent holding the source model. Kempton's (1986) subjects' individual mental models, are equivalent to Norman's refuted example of  $M(t)$ . Since Kempton (1986) made clear his methodology in terms of in-depth interview and analysis of transcripts, Norman's (1983) interpretation of a subjects' individual model could be represented as the tree-ring model in Figure 12.

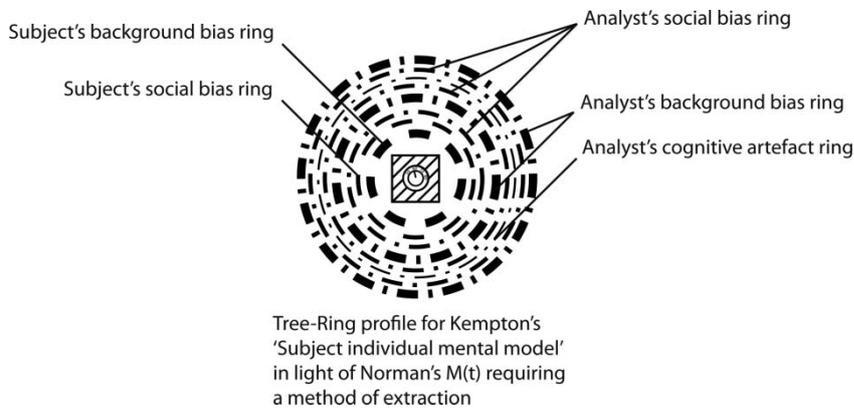


Figure 12 - Re-representation of Kempton's (1986) subject's individual mental model, in light of Norman's (1983) definition.

The addition of a bias ring representing a 'cognitive artefact' is shown as a thin ring in Figure 12, to indicate that a model is likely to be understood, or at least validated, as the result of analysis of the transcripts, rather than instantaneously during interview. The form of the cognitive artefact, is a 'bias' since different interpretations may be possible based on its qualities (i.e. text-based as opposed to graphical) and structure (alluded to by Rasmussen and Rouse 1981, Smith-Jackson and Wogalter 2007).

The two analyst background rings show two separate steps took place to access the model. The first, interviewing the subject whilst creating a cognitive artefact for future analysis. The second, interpreting the cognitive artefact produced (see Figure 12).

### 2.2.3.2 Wilson and Rutherford (1989)

Wilson & Rutherford (1989) argue that Psychologists and Human Factors analysts are talking about different things when discussing and researching mental models and that a unified terminology is needed if the cross disciplinary efforts to research this construct are ever to be successfully applied or built upon. They offered the following definitions to this end:

"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 representations of the system, defined in

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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.” (p.631)

The first two terms will be discussed initially and are represented both schematically and as Tree-Ring Models in Figure 13. Since both the Designer's Conceptual Model (DCM) and User's Conceptual Model (UCM) are defined as 'representations', and no discussion of access is offered, the presumption is that these are internal representations that have not been gauged or shared by another agent. As such, the schematics in Figure 13 contain only one agent for each concept, and the tree-ring models show the effect of a lone background bias ring. It should be made clear, that the DCM is not a model of a device (as with the UCM), but of another agent (in this case the user). To show this distinction, an image of a person, rather than a device is shown in the square representing an internal model. It is assumed that Wilson & Rutherford (1989) consider the DCM akin to a stereotype of the user, based on an assumed user background. The application of this type of model could be in designing a device based on assumptions about what the user will need or understand. This is distinct from the UCM which, if used as a design aid, could suggest how a user would *act* as a result of their internal model of a system. However, since both the UCM and DCM do not include a methodology for either 'access' or 'construction' in their definition, as with Norman's (1983) C(t) and C(M(t)), it would not be possible to determine the biases affecting their impact in any application. Wilson & Rutherford's (1989) UCM is equivalent to Kempton's (1986) subject's individual model and the false tree ring profile of Norman's (1983) M(t) shown in Figure 11.

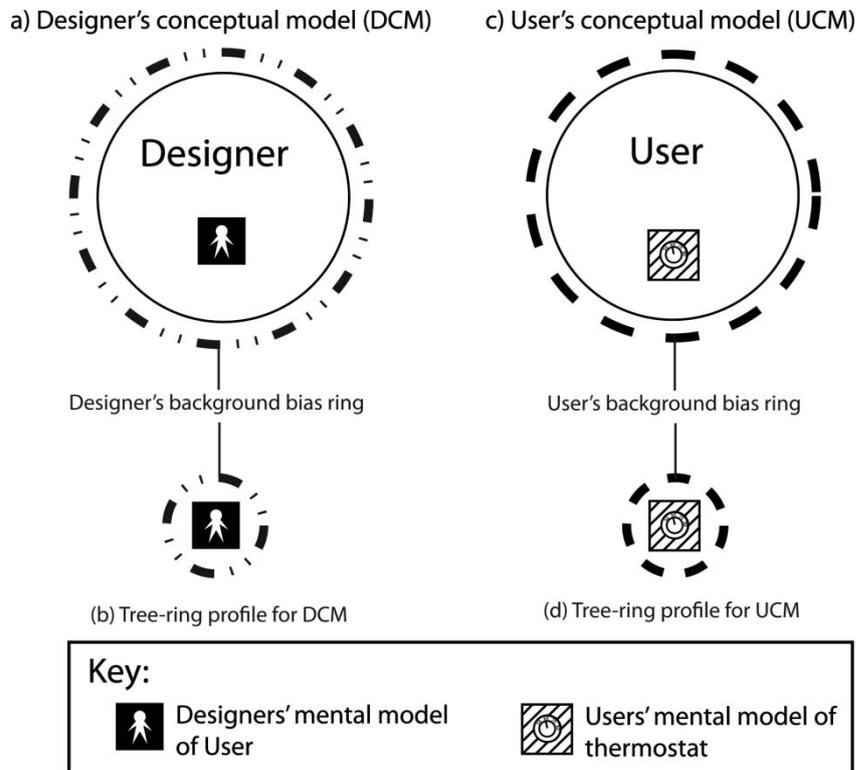


Figure 13 - Wilson and Rutherford's (1989) definitions of mental model concepts, depicted as a schematic and Tree-Ring profile.

As Wilson & Rutherford's (1989) definition of a User's Mental Model (UMM) declared the existence of "descriptions of the user's internal representations" (p.631), it seems reasonable to assume that a cognitive artefact is included in this concept. Since these descriptions are "informed by theories from Psychology" (p.631), the involvement of an analyst with a background in Psychology seems logical. What is not clear, from this definition, is if any other agents, or the target device are involved in the UMM's construction, or if another agent is intended to access the resulting cognitive artefact.

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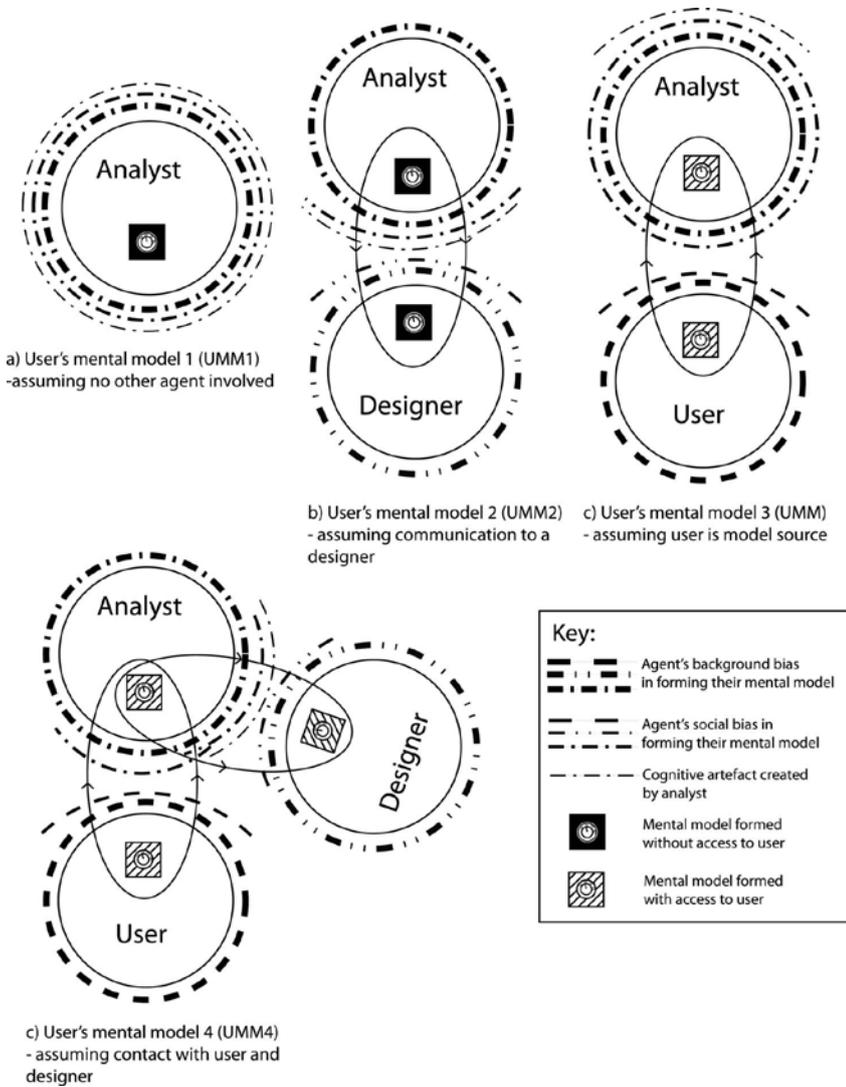


Figure 14 - Four different schematics for Wilson and Rutherford's (1989) definition of a 'User's Mental Model'.

Figure 14 shows four different interpretations of Wilson and Rutherford's (1989) definition of a UMM represented in schematics, with associated Tree-Ring profiles shown in Figure 15. Interaction with a device has not been

represented, the addition of which could produce another four schematics based on those depicted. UMM 1<sub>7</sub> assumes that no other agent is involved, and is equivalent to Norman's C(M(t)), with the addition of a cognitive artefact bias ring. UMM2 builds on UMM1, but with the assumption that the descriptions produced are intended for access by a Designer (see Figure 14 and Figure 15). This would be a relevant example of conveying a mental model for practical application in device design, as recommended by Norman (1983) for the construction of a System Image.

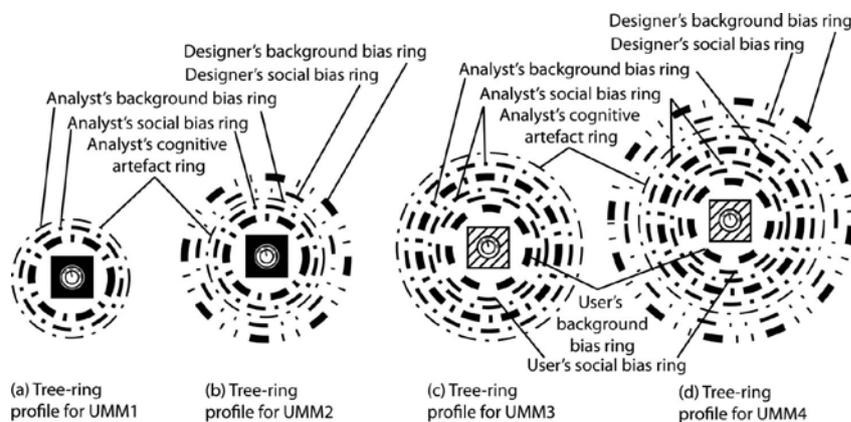


Figure 15 - Tree-Ring Models representing the four different schematics for Wilson and Rutherford's (1989) definition of a 'User's Mental Model', highlighting the variation in biases based on interpretation.

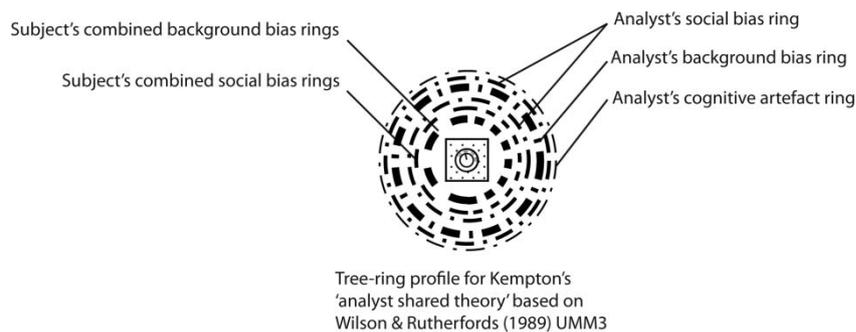


Figure 16 - Re-representation of Kempton's (1986) analyst's shared theory, in light of Wilson and Rutherford's (1989) User Mental Model definition (assuming contact with the User).

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UMM3 assumes the Analyst has derived a mental model after initial contact with a User. This is equivalent to Norman's  $M(t)$ , with the addition of a Social bias and Cognitive Artefact bias rings. Given Kempton's (1986) examples of 'shared theories' have been presented as a description, the addition of these rings would be appropriate to show a similar Tree-Ring pattern to UMM3 (see Figure 16) with the key distinction being the composite line styles in the central two rings, representing the multiple users who held the model source for the shared theory.

UMM4 shows an extension of UMM3, whereby an Analyst's model, which has been derived through contact with the User, is described in a cognitive artefact, which in turn is accessed by a Designer (see Figure 14 and Figure 15). Whilst it is evident that these assumptions cannot be attributed to the wording in Wilson & Rutherford's (1989) definition of the User Mental Model, this is included as a likely application in Human Factors research of this definition. As such, the differences clear in the Tree-Ring profiles shown in Figure 15 highlight graphically how the same definition can be subject to different interpretations by different researchers, preventing commensurability of findings due to the considerable differences in the layers of bias.

### 2.2.3.3 Summary of Comparison of Perspectives of Mental Models

By comparing the definitions of concepts provided by Norman (1983) and Wilson & Rutherford (1989), similarities in the concept of  $M(t)$  and UCM are shown, both signifying the internal representation on the user.

A key distinction is found between Norman's (1983) and Wilson & Rutherford's (1989) consideration of the model held by a Designer. Norman offers the concept  $C(t)$  representing the target system, whereas Wilson & Rutherford describe the DCM, which represents the user as an agent, rather than an interpretation of the model a user may hold.

Despite the worthy intention of clarity in definition, Norman's (1983) concepts of  $C(t)$  and  $C(M(t))$ , and Wilson & Rutherford's (1989) concepts of DCM and UCM are rather vague in terms of their construction and possibilities for access. This prevents a precise understanding of the layers of interpretation to which any model description may have been subject. Whilst this vagueness

may be considered appropriate, given the intention of their formation was to provide tools for theoretical discussion, adopting these same terms when moving from theory to practice, necessitates focus on specifics.

When depicting Wilson & Rutherford's (1989) UMM, the ambiguity the definition offered in terms of the original source for the model, and the resulting recipient was obvious. The Tree-Ring profiles in Figure 15 show how the choice of source and recipient is crucial in understanding the layers of bias present. We have also shown how the tree rings for Kempton's (1986) individual mental models and 'shared theory' can be positioned and extended, in line with these perspectives.

### **2.3 Application of Adaptable Framework - Charactering Mental Models by Perspective and Evaluating 'Risk of Bias'**

A framework has been developed, which has been useful in illustrating the differences between definitions of mental models, the perspectives from which data is gathered, and the risk of bias in the accuracy of the knowledge structure description. This framework can go further than illustration and pragmatically aid commensurability and application.

To demonstrate this, schematics have been created to compare Kempton's (1986) 'shared theory' of thermostat function with Payne's (1991) 'mental model' of bank machine function (see Figure 17). Figure 18 shows a table populated from these schematics and details found in the respective theorist's papers. Figure 18 has been divided into 2 main sections which reflects the focus of this chapter. The first, considers the perspective from which data is gathered, and that this is key for commensurability and application. Echoing the literature to date (e.g. Bainbridge, 1992), it is clear that the context in which data is gathered on mental models is critical to applicability, since they represent a 'specific state of affairs' (Brewer's (1987) c.f. Stanton (2000)).

The richness of the mental model description also constrains the applicability by others to design, behaviour change or instruction. We have seen that mental model definitions in the literature vary widely in meanings, Richardson and Ball (2009) have consolidated examples of mental representation terminology

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emphasising the range and subtle distinction between terms. It is proposed that for mental model research, where the same terms are employed with quite different meanings, it may be more prudent to specify the model source and recipient as an aid to commensurability than address consensus in terminology. The mental model source and recipient form a key point of distinction between definitions, but are often difficult to identify in the literature. The schematics allow model and source to be clearly identified.

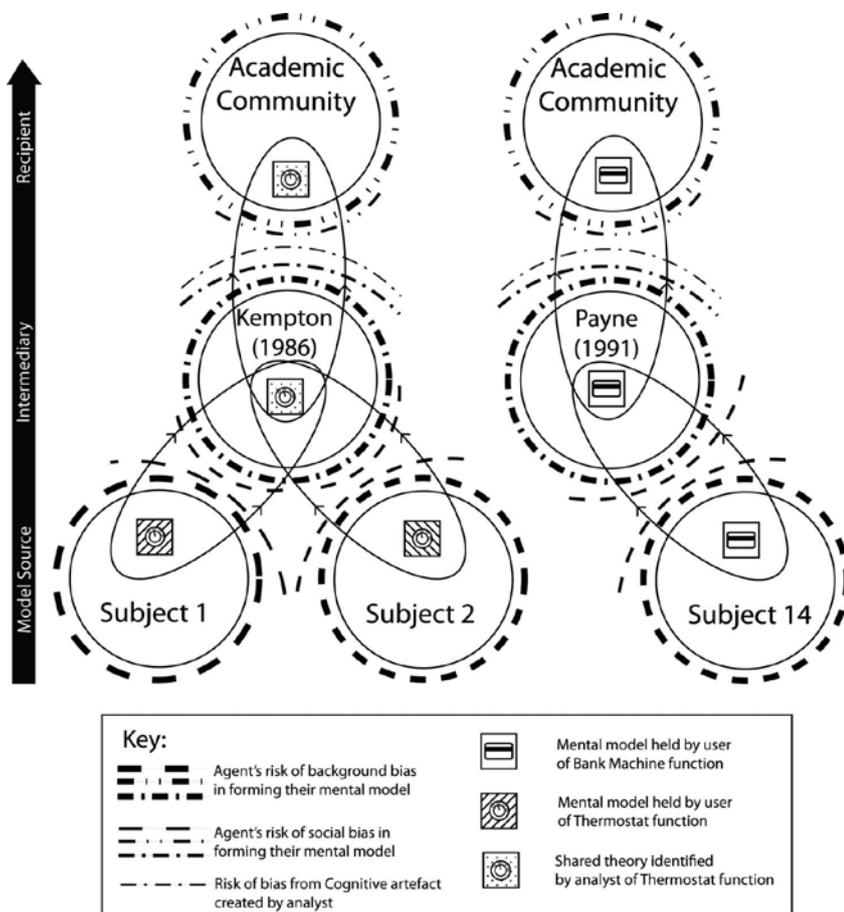


Figure 17 - Kempton's (1986) study showing model source (subjects), intermediary (analyst) and recipient (academic community).

Table 2 - Table to show application of proposed framework to Kempton (1986) and Payne (1001) to better specify mental models for commensurability, considering the risk of bias in interpretation and the perspective from which data is gathered.

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Perspective of gathering data	Kempton (1986)	Payne (1991)
Mental Model Description	Valve	Distributed model
Context (domain, behaviour/task, goal)	-Domestic, patterns of adjusting temperature dial, -Comfortable body temperature in the home at a reasonable cost	-The workings of high street Bank Machines -Operation to withdraw cash -Role of card, what happens during the transaction, how the machine operates
Mental Model Definition used (generic mental model, folk theory/ conceptual model User Mental Model etc.)	Shared theory	Mental model (Individuals' specific knowledge)
Source (e.g Device user(s), Designer, Analyst)	Multiple users of domestic thermostats	Single user of Bank machine
Intermediaries (e.g. Analyst(s), System Image, Instructor)	Analyst	Analyst
Recipient (e.g. Analyst, Designer, Academic Community)	Academic Community	Academic Community
Layers of 'Risk of Bias'		
Source Background Ring (s) (e.g. Number, Defining demographics, relevant experience <i>applicable bias</i> )	-Multiple -Michigan homeowners (American) -Male & female <i>Representativeness</i> <i>Availability of scenarios</i> <i>Adjustment from Anchor</i>	-Single -Lancaster Uni student (English) -No formal computing instruction <i>Representativeness</i> <i>Availability of scenarios</i> <i>Adjustment from Anchor</i>
Source Social Ring (s) (e.g. Number, method of communication, applicable bias, incentive) <i>applicable bias</i>	-Multiple, -Answers to in-depth interview, <i>Confirmation bias</i> <i>Belief bias</i> <i>Consistency bias</i>	-Single -Answers to structured interview, <i>Confirmation bias</i> <i>Belief bias</i> <i>Consistency bias</i>
Analyst Social Ring (s) (e.g. Number, applicable bias, access method) <i>applicable bias</i>	-Multiple -In depth interview <i>Order bias</i> <i>Belief bias</i> <i>Experimenter bias</i>	-Single -Semi-structured interview <i>Order bias</i> <i>Belief bias</i> <i>Experimenter bias</i>
Analyst Background Ring (e.g. Number, Defining demographics, relevant experience, analysis method) <i>applicable bias</i>	-Single Analyst -Anthropology -Energy and Environmental Studies -American -Infer folk theory from indepth interview data using methods from Lakoff & Johnson	-Single Analyst -Psychology , Computing -English -Content analysed answers based on descriptions of devices, evidence of spontaneous construction, underlying analogies
Analyst Social Ring (e.g. Number, <i>applicable bias</i> )	-Organisation of textual information for 'Cognitive Science' Journal Paper reviewers	-Organisation of diagrammatic information for 'Behaviour and Information Technology' Journal Paper reviewers
Analyst Cognitive Artefact Ring (e.g. Type(s), <i>applicable bias</i> )	One-word analogous Textual description	Basic diagram, key components and conduits for data transfer showing relationship between components. Data types held by each component specified
Academic Community Social Ring (e.g. Type(s), <i>applicable bias</i> )	Typical organisation of information for 'Cognitive Science' Journal Paper expected	Typical organisation of information for 'Behaviour and Information Technology' Journal Paper expected
Academic Community Background Ring (e.g. Type(s), <i>applicable bias</i> )	Cognitive Science audience	Behaviour and Information Technology Audience

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Figure 18 – Table to show application of proposed framework to Kempton (1986) and Payne (1001) to better specify mental models for commensurability, considering the risk of bias in interpretation and the perspective from which data is gathered:

The schematics also identify the number and character of intermediaries, and key aspects of their means of interaction with the source and recipient (single, multiple, synchronously or via a cognitive artefact). Figure 18 considers the risk of bias associated with these interactions in the second section of the table. By using the schematics directly, or through the development of tree-ring profiles, the layers of ‘risk of bias’ can be considered in turn. The table’s left hand column prompts for specific information, thought relevant to bias. The prompts are illustrative and are proposed as necessary rather than sufficient. They hold the role of directing consideration of relevant types of cognitive bias which may come into play during construction or access of the specific mental model. Examples of applicable bias are provided in the background ring of the source, and the social rings of both source and analyst.

The benefit of this framework, is to provide a systematic means of identifying the risk of bias that is flexible enough to be applied to all types of mental model research. By doing so, efforts to mitigate or control for bias can be made, providing greater confidence that the accuracy of the mental model description reflects the construct held by the model source. Greater accuracy would be a considerable aid to applicability in design, behaviour change or instruction. Similarly, awareness of the limitations of accuracy allows the practitioner to adjust their expectations of the benefit of mental model descriptions to the prediction of human behaviour.

## 2.4 Conclusions

This chapter stated that the problem of commensurability in mental model research was based on a fundamental lack of consensus in its definition. It further argued that even with a consensus, existing approaches to definition would not be sufficient as the notion could not be applied pragmatically unless there was some confidence in the accuracy of the mental model accessed or constructed. This chapter highlights how the risk of bias to an accurate

representation of a knowledge structure varies considerably depending on the perspective used and the methodology of capture. Using a case study of Kempton (1986), an adaptable framework was developed to emphasise this graphically, and it was shown how the resulting schematic could be deconstructed in tabular form to specify more fully the similarities and difference between different research contributions.

The first part evaluated 3 major research figures in the field and their theories of the role of inferred knowledge structures in cognitive processing to conclude that variations in nature of 'background information' bias the content of inferred knowledge structures.

The second part of the chapter considered the role of cognitive bias in mental models research, with a view similar to Tversky and Khaneman (1974) adopted in this thesis, that cognitive bias interacts with mental simulation rather than can necessarily be explained by existing mental model theory. The terms of 'filtering information' and 'bias in interpretation' were described as a precursor to development of an adaptable framework. Using the case study of Kempton (1986) and the textual definitions provided by Norman (1986) and Wilson & Rutherford (1989), the framework was developed to demonstrate the importance of methodology on the risk of bias, ultimately determining confidence in the construct description. Clarity in the mental model source and recipient for commensurability was also highlighted.

Part three brought together the findings of parts one and two to propose the criteria necessary to better specify mental models research with a view to commensurability and better confidence in levels of accuracy. The framework was used to derive the 'layers' of potential bias, providing a prompt for mitigation or appropriate caution when applying the mental model description.

The limitations to the work are as follows. A more extensive breakdown of the elements considered part of the 'background' ring and specification of the criteria which promote bias in the social and cognitive artefact rings is needed. In addition, a catalogue of types of cognitive bias specifically relevant to the methodologies typically adopted in mental models research, and means for mitigation would provide considerable benefit in improving the accuracy of knowledge structure descriptions.

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Other areas central to mental models research such as memory, external representations and interaction with devices is either lightly touched on or absent. The focus has also been on the mental models held by individuals rather than shared or team mental models. It is reasonable to be confident that the framework can accommodate these areas, but it is beyond the space limitations of this chapter and provide an opportunity for further work.

The first task towards confidence in applying mental model descriptions for the benefit of design, behaviour change or instruction, is an appreciation of the risk of 'bias in interpretation'. This chapter offers a systematic way of approaching this issue and [the authors](#) believe that through their framework, a different approach to specifying mental model research could further the goal to achieve commensurability.

The next step following the development of the tree-ring method, to further the objectives of this thesis, is to collect evidence of mental models of domestic heating systems in a real world environment, with explicit awareness of the biases involved. Mitigation of biases can then take place were possible. Where this is not possible, the limitations of findings subjected to bias can be acknowledged. Conversely, intentional biases in line with the objectives of this thesis can be ensured. Chapter 3 shows application of the tree ring method for householders new to the UK and provides initial insights of how differences in present day mental models of heating systems can influence behaviour with controls.

### 3. Case studies of mental models in home heat control: Searching for feedback, valve, timer and switch theories

#### 3.1 Introduction

[This chapter looks at the relationship between householders' mental models of home heating at both the device and system level. It considers how differences in the mental model held can explain householders' self-reported behaviour with heating controls. This contributes to Hypothesis 1 described in section 1.2, that investigates the influence of users' mental models of devices on their pattern of device use. Greater understanding of the link between mental models and behaviour is critical to furthering this thesis' key aim, to use the notion in Design strategies, in order to elicit changes in behaviour that increase the achievement of home heating goals.](#)

Mental models can be thought of as internal constructs that explain human behaviour (Wickens, 1984; Kempton 1986). The notion has been associated with many domains over the last 20 years, including domestic (Kempton, 1986), transport (Weyman et al., 2005) and military (Rafferty et al., 2010). Mental Models have formed the basis of strategies to improve interface design (Carroll and Olson 1987; Williges, 1987; Norman 2002; Baxter , 2007; Jenkins et al. 2010), to promote usability (Norman, 2002; Mack and Sharples 2009; Jenkins et al. 2011; Branaghan et al., 2011; Larsson, 2012), and to encourage sustainable behaviour (Kempton, 1986; Sauer et al., 2009; Lockton et al., 2010) amongst others. In 1986, Kempton described two distinct 'forms' of mental models of thermostat function that were prevalent in the population of that time. He proposed that the form of model held, could result in significant variations in the amount of energy consumed due to home heating, by promoting different patterns of manual thermostat adjustment. Currently in the UK, 25% of carbon emissions are from domestic customers, 58% of which is due to domestic heating. The UK has legislated to cut 80% of greenhouse gas emissions by 2050 (Climate Change Act, 2008). Since Kempton's study, almost three decades have passed and technology has changed. It seems appropriate, therefore, to explore if Kempton's (1986) shared theories can still be identified,

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and if so, to question if they remain relevant to design strategies targeted at combatting climate change.

As described in Chapter 2, the term ‘mental model’ is used in different domains to mean different things (Wilson & Rutherford, 1989) and even within a domain, can be used to describe internal constructs that differ significantly in terms of content, function or perspective (Richardson & Ball, 2009; Revell & Stanton, 2012). The form of mental model descriptions may have similarities to the way other types of models (e.g. process models or logic models) that do not depict internal constructs, are represented, resulting in confusion when interpreting outputs. Specificity in the type of mental model is considered essential for commensurability when conducting research (Norman, 1983; Wilson & Rutherford, 1989; Bainbridge, 1992; Revell & Stanton, 2012). Please bear the extended clarification of the way the term is used to this chapter. The intention is to allow sufficient understanding to determine the relevance and applicability of the findings presented. This chapter refers to mental models in three different ways: 1) in terms of its function; 2) in terms of its source, and; 3) in terms of its individuality.

In terms of function, the definition most fitting is a “device model”. Kieras & Bovair (1984) adopted this terminology to describe a mental model held by a user of how a device works. It includes a set of conceptual entities and their interrelationships (Payne, 1990). In this chapter, the device of interest is the home heating system, and we seek to describe the conceptual entities and their interrelationships held by users. Device models, as a type of mental models, may be incomplete, inaccurate, and inconsistent (Norman, 1983). It is proposed, in this thesis, that understanding where omissions, inaccuracies and inconsistencies occur in users device models of home heating, could provide insights into how to reduce energy consumption resulting from non-optimal operation.

In terms of its source, this chapter adopts Norman’s (1983) definition of a “User Mental Model” (UMM). He describes this as “the actual mental model [of a target system] a user might have”, that can only be gauged by undertaking observations or experimentation with the user. In this chapter we are seeking the model of the home heating system held internally by a user. As we cannot

access this model directly, we have adopted a method appropriate to our aims to gain data to describe the user mental model.

In terms of the individuality of mental models, we also refer to Kempton's (1986) 'shared theory'. A 'shared theory' is derived by an analyst through the identification of similarities in separate UMMs of individuals. These individuals are within a social group, who may share similar types of individual goals. a 'shared theory' differs from concepts such as 'shared' or 'team' mental models that refer to shared knowledge structures within a team or group who are working towards group goals (Richardson & Ball). The benefit of identifying shared theories of home heating, is broader reach when targeting strategies; to combat climate change; at individuals within the home.

The 2 shared theories identified by Kempton (1986) were described as 'valve' and 'feedback'. Users with a valve shared theory, considered changes in the set point of their thermostat to be controlling the intensity of heat in their furnace, with the onus on the user to ensure a comfortable home temperature. Users with a feedback shared theory, considered it their responsibility merely to select the desired thermostat set point. The thermostat would maintain comfort in the home by controlling the boiler operation period, in response to measurements of house temperature. Kempton (1986) referred to this latter theory as an 'amateur theory' of home heating, as it is a simplistic version of the actual way the heating system works. Kempton (1986) described how different shared theories may predict different behaviour patterns of thermostat set point adjustment. He discovered that holders of valve theory, had a unique behaviour characteristic absent in those holding feedback theory. At night, valve theorists regularly set the thermostat back to below normal comfort levels, which Kempton (1986) described as 'night set back'. Kempton (1986) proposed that despite the valve theory being less accurate than the feedback theory, this behaviour characteristic was likely to result in greater energy savings overall.

Since Kempton (1986), additional shared theories of thermostat function have been proposed in the literature such as 'Timer' (Norman, 2002) and 'Switch' (Peffer et al., 2011). Users holding the timer theory are thought to select greater values of set point, when longer periods of boiler operation are desired. Those holding the switch theory are thought to use the thermostat merely as

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an on/off switch. Both of these theories assume the user, not the system, is responsible for maintaining a comfortable house temperature. Norman (2002) and Peffer et al. (2011), do not refer to studies which informed these types of shared theory, nor do they describe distinct behaviour characteristics which may influence energy consumption. When investigating current user mental models of home heating, it is relevant to determine if these, or new shared theories of home heating, could be identified. Understanding how resulting shared theories associate with energy consuming behaviour could provide insights to inform novel approaches to reduce consumption.

The reader may question if Mental Models need to be accurate or is it sufficient that they are effective. Depending on context and the specific user behaviour being considered, what is considered 'effective' will vary. Kempton 1986 described how a faulty mental model of home heating control could lead to more energy efficient behaviour; than a more accurate model. Norman (1983) contends that designers and instructors should ensure a 'functional' (not necessarily accurate) mental model to enhance user interaction with a system. Norman (1986) emphasises that the appropriateness of the user's underlying model of a system is essential when troubleshooting, as the user is able to derive possible courses of action and possible system responses. Kieras & Bovair (1984) concluded that for very simple devices or procedures, there will be little value in providing a device model to users. Manktelow and [jones-Jones](#) (1987) warn that systematic errors may result from an inappropriately simple mental model. So, taken together, it is concluded that for simple procedures, simple devices or systematic errors that have minor consequences, a 'functional', simplified or even lack of mental model, may be effective. For more complex systems or procedures, where the need for troubleshooting is likely, or if the consequence of systematic errors is significant (as in the case of non-optimal home heating during an energy crisis), a more accurate user mental model may be needed for the effective use of devices.

Hancock and Szalma (2004), emphasised the importance of qualitative methods in revealing user intention in a way that can inform the development of design principles. Flyvbjerg (2011) argues that rich data gathered from detailed, real life situations can provide meaningful insights, that could not be gained from context-independent findings. Virzi (1992), R.A (1992), when

conducting research into usability, found 80% of problems, including the most severe, are detected with the first 4-5 subjects, illustrating how key insights can be gained with very small samples. Hancock et al. (2009) also argue that ideographic case representations are increasingly relevant for the design of human-machine systems, as advances in technology begin to focus on exploiting individual differences. Supporting these sentiments, this chapter describes the results from an intergroup case study of home heating control, focusing in detail on 3 individual case studies taken from a pool of 6. The intention of this chapter is to: 1) Demonstrate the existence of distinct mental model descriptions of the functioning of present day UK home heating systems, that differ significantly from actual functioning. 2) Seek evidence of Kempton's (1986), Norman's (2002) and Peffer et al.'s (2011) shared theories of thermostat function in the case study group, and 3) discuss the present day relevance of Kempton's (1986) valve and feedback models of thermostat function, to design strategies targeted at combatting climate change. Additional implications and the limitations of the study are also discussed.

## **3.2 Method**

### **3.2.1 Participants and setting**

The case study group was non-randomly selected and comprised mainly overseas postgraduate students with families, new to the UK, who resided in semi-detached university owned accommodation in Southampton, UK. Participants arrived in their accommodation at the start of September 2011 and used the central heating system during the autumn and winter months. Southampton has an oceanic climate, with cool winters (temperatures typically below 5°C). The accommodation, home heating devices and levels of insulation were matched, so that variations in mental model descriptions could be attributed to characteristics of the participant, rather than the environment. The layout of the home heating devices and specific models used are shown in a diagram in Figure 19. The Participants were recruited by letter, email and approached door-to-door by the author. Permission was sought from the Faculty Ethics committee prior to contact and Research Governance was arranged. The participants that agreed to take part were all from warm countries where centralised home heating devices are uncommon. This user

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group characteristic, whilst not originally sought, ensured minor experience of other home heating devices. This benefits the mental model descriptions of home heating systems, by making them more closely aligned to the specific home heating devices installed, rather than previous experience by the participants of other home heating devices. Insights from this case study could therefore use the specific design and layout of the setup as a starting point for energy saving strategies.

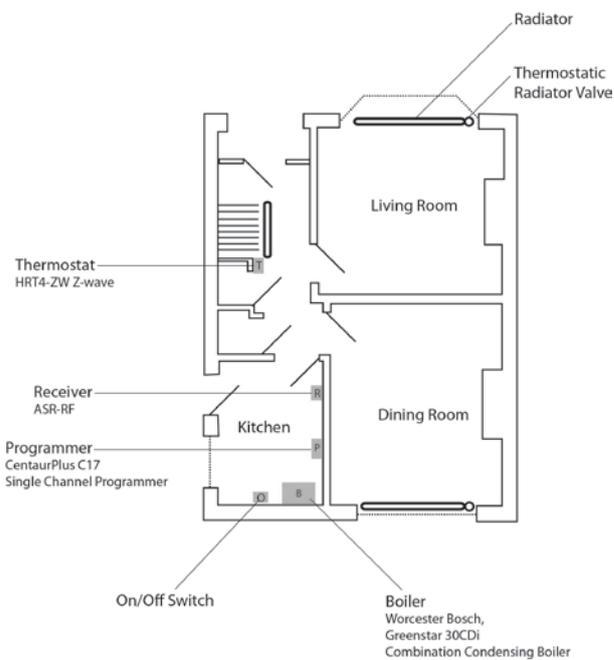


Figure 18 - The layout of the home heating devices and specific models used during the intergroup case study

#### 3.2.2 Data Collection

A pragmatic worldview is adopted in this research. Whilst a postpositivist worldview is suggested by the objective to verify Kempton's (1986) shared theories of home heating, to ensure the data collection method allowed interpretations of the data beyond this scope. It was important that alternate shared theories or unique UMMs could be revealed. This would allow further

understanding of people's mental models of home heating function to be gained, that could inform design based strategies (amongst others) for reducing energy consumption. A method adapted from Kempton (1986) and Payne (1991) was developed to these ends. Payne (1991) described 'shared theory' device models in a concrete diagrammatic form that better communicates misunderstandings of function to design practitioners, than textual or non-deterministic schematic representations. Kempton (1986;1987) used in depth interviews and analysed the transcripts using metaphorical analysis (devised by Lakoff and Johnson, 1981). He provides recommendations on the interview process and example questions and probes specific to home heating systems. From this, an interview approach could be developed to access content that allowed the analyst to identify shared theories. The resulting method devised in this thesis was a semi-structured interview that included a paper-based activity whereby the participant represented [represent](#) their device model in a concrete diagram form.

For pragmatic application of mental models research, Revell & Stanton ([2012](#)), emphasised [in Chapter 2](#) the importance of accuracy in the capture and representation of internal constructs. This accuracy requires the description of the mental model to reflect its source (in this study, the user of home heating systems), rather than assumptions by the recipient (e.g. the analyst). The risk of bias as a means of causing inaccuracy in mental model research, and the need to take pains to minimize bias is well documented in the literature (Rouse & Morris 1986, Wilson & Rutherford, 1989, Bainbridge, 1992, Richardson & Ball, 2009, Revell & Stanton, 2012). [In Chapter 2](#), Revell & Stanton (2012) developed a 'tree-ring' method in order to identify risk of bias when conducting mental models research, resulting in an adaptable framework (presented in table format). This framework required specification of both the risk of bias and the type of knowledge structure, to aid commensurability (see Revell & Stanton, 2012 [and Chapter 2](#), for an example of the tree ring method applied to Kempton (1986) and Payne (1991) plus the resulting table). The tree-ring method (Revell & Stanton, 2012 [and Chapter 2](#)) was applied to the approach devised for this study, and amendments were made to the data collection and analysis process in response to identified bias. The risk of bias identified through the tree ring method (Revell & Stanton, 2012 [and Chapter 2](#)) related to: 1) The background experience of both the analyst and participant,

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2) The social expectations and means of communication of both the analyst and participant, 3) The structure of cognitive artefacts used in the interview, and 4) The method of analysis of cognitive artefacts. These types of bias, and the strategy for mitigation or clarification are shown in Table 2. The leftmost column shows criteria to be specified, with the section labelled ‘perspective of gathering data’ standard in every table. The section labelled ‘layers of risk of bias’ is specific to the approach considered. The type and number of layers of bias, are dictated by the results of the tree-ring method. The middle column specifies the details required. Alphabetised in italics, are types of relevant bias that may need mitigation. The right-most column details how the approach adopted responded to the identified bias (also alphabetised). Table 2 allows readers to gauge the scope of efforts to promote accuracy in the capture of the UMM in the mental model description produced.

Table 3 - Risk of bias and mitigation strategy for method adopted, derived using tree-ring method from Revell & Stanton (2012) as described in chapter 2.

Perspective of gathering data	Mental models in home heating control	
Mental Model Description	Valve, Feedback as defined by Kempton (1986), Switch (Pfeffer et al.)	
Context (domain, behaviour/task, goal)	Domain: Domestic Behaviour: Patterns of adjusting thermostat dial, Goal: Comfortable body temperature in a family home, reducing waste of energy/money	
Mental Model Definition used (e.g. shared model, user mental model, device model etc.)	User mental model (Norman, 1983) Shared theory (Kempton, 1986) Device Model (Kieras & Bovoir, 1984)	
Source (e.g. Device user(s), Designer, Analyst)	Users of domestic central heating systems in the UK	
Intermediaries (e.g. Analyst(s), System Image, Instructor)	Analyst	
Recipient (e.g. Analyst, Designer, Academic Community)	Academic Community interested in climate change, behaviour change, device design, Psychology, Human Factors	
Layers of ‘Risk of Bias’	Intergroup Case Study	Mitigation Strategy in Method to address Bias identified
Source Background Ring (s) (e.g. Number, defining demographics, relevant experience, <i>Applicable bias</i> )	-Multiple (6) -Recent residents in University of Southampton Accommodation. - Families with young children, recently arrived to the UK from countries with hot climates) -Male & female <i>A) Representativeness</i> <i>B) Availability of scenarios</i>	A) Unusual user group allows mental model descriptions to be attributed to interaction with specified devices, rather than habit (Specific mental model descriptions cannot be generalised to native UK population, however). B) Questions regarding background of participant and previous experience with central heating, added to interview.
Source Social Ring (s) (e.g. Number, method of communication, incentive, <i>applicable bias</i> )	-Multiple (6) -Answers to structured interview based on Kempton (1986) and Payne (1991) -Concept map representing users mental model description	A) Topic of study – method seeks user’s beliefs of home heating system function. B) Positioning provided in interview that inconsistencies are ‘ok’ and expected, to reassure participants. C) To prevent embarrassment, careful positioning reiterated

Perspective of gathering data	Mental models in home heating control	
	<ul style="list-style-type: none"> <li>A) <i>Belief bias</i></li> <li>B) <i>Consistency bias</i></li> <li>C) <i>Embarrassment of incorrect answer</i></li> <li>D) <i>Reluctance to offer 'ridiculous' answer</i></li> <li>E) <i>Misunderstandings – not native English speakers</i></li> </ul>	<p>throughout interview that technical accuracy is not sought, only how participant 'imagines' what is happening.</p> <p>D) To encourage free discourse, participants told upfront, of the opportunity to verify which parts of concept map they felt 'sure' about, and which they were uncertain of.</p> <p>E) Misunderstandings reduced by requiring subjects to have good levels of spoken English. Paraphrasing by the analyst, was used throughout, providing opportunities to check understanding.</p>
Analyst Social Ring (s) (e.g. Number, access method, applicable bias)	<ul style="list-style-type: none"> <li>-Single</li> <li>-Semi-structured interview</li> <li>-Concept map activity</li> <li>A) <i>Order bias</i></li> <li>B) <i>Belief bias</i></li> <li>C) <i>Experimenter bias</i></li> <li>D) <i>Confirmation bias</i></li> <li>E) <i>Leading by experimenter</i></li> <li>F) <i>Cueing</i></li> </ul>	<ul style="list-style-type: none"> <li>A) Order bias acknowledged</li> <li>B) Analysis table developed to encourage objective categorisation, to mitigate for belief bias</li> <li>C) Experimenter bias minimised by conducting interviews 3 months after the study initiated, and taking care not to provide subjects with information about their heating devices that may alter their thinking/behaviour.</li> <li>D) confirmation bias minimised by analyst avoiding exposure to how the devices in the study function, ensuring participant is required to fully explain their own thinking</li> <li>E) leading minimised by analyst by providing semi-structured interview template, and piloting interviews prior to data collection.</li> <li>F) Cueing minimised by using participant initiated terminology and using plain paper (rather than a template) to construct the concept map.</li> </ul>
Analyst Background Ring (e.g. Number, Defining demographics, relevant experience, analysis method, applicable bias)	<ul style="list-style-type: none"> <li>-Single Analyst</li> <li>-Psychology</li> <li>-Design</li> <li>-British</li> <li>-compare user mental models descriptions and transcripts to Kempton's (1986) shared theories of home heating.</li> <li>A) <i>Belief bias</i></li> <li>B) <i>Confirmation bias</i></li> <li>C) <i>Bias in interpretation of outputs</i></li> </ul>	<ul style="list-style-type: none"> <li>A) To confront belief bias, analysts own bias accessed by answering the interview questions prior to commencing interviews.</li> <li>B) To aid objective categorisation of individual mental models with, an analysis table based on Kempton (1986; 1987) was constructed &amp; alternate interpretations to Kempton (1986) were actively sought.</li> <li>C) To minimise bias in interpretation, the mental model diagram (that formed the basis for analysis), was constructed with, and verified by, the participant.</li> </ul>
Analyst Social Ring (e.g. Number, applicable bias)	<ul style="list-style-type: none"> <li>Organisation of textual and diagrammatic information for Academic Community interested in climate change, behaviour change, device design, Psychology, Human Factors</li> <li>A) <i>Bias – graphical &amp; descriptive constraints of journal paper</i></li> </ul>	<ul style="list-style-type: none"> <li>A) Bias acknowledged</li> </ul>
Analyst Cognitive Artefact Ring (e.g. Type(s), applicable bias)	<ul style="list-style-type: none"> <li>One-word analogous Textual description.</li> <li>Associated 'concept map' show key components, and their relationship in terms of links, cause and effect.</li> <li>A) <i>Bias- single view of mental model</i></li> </ul>	<ul style="list-style-type: none"> <li>A) Specific view of mental model chosen to inform pragmatic applicable to design / instruction</li> </ul>

### 3.2.3 Dynamics of the interview

The interviews were undertaken in March 2012, in a library cafe at the University of Southampton, to comply with the requirements of the risk assessment. The informal, familiar setting helped place subjects at ease. Interview durations were approximately 1 hour, but varied depending on the level of detail provided by the participant, between 45 minutes and 1 hour 25 minutes. Interviews were recorded and transcribed by an independent transcription service. The interview comprised 3 main parts; 1) Background of

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participant, 2) Self report of user behaviour, and 3) Mental model of device function. For a full explanation of the development and examples of outputs and interview template, please see chapter 4. In brief, part one covers the participants previous experience with home heating devices, determines if they have any formal training that may inform an 'expert' understanding the system, and captures the terminology they use when discussing the heating system in their home. Part two uses standard questions, probes and scenarios to help build up a diagram of 'typical use' of the participants heating system during a week. The final part, uses questions and follow on probes directed by the interview template, to build up a diagram with the participant. The diagram is built up using post-it notes containing the participant initiated terminology, as the analyst probes the participant to describe the relationship they exist between the components. Concepts are linked by drawing lines between the post-it notes with a pen (see Figure 20 for an example of resulting output). To gain insights into cause and effect, and rules of operation, participants were asked follow-on probes such as "How does the boiler know when to come on/off" and "What would happen if you turned the thermostat to its maximum setting?". Participant responses to these probes were represented on the diagram using arrows and text (Figure 20). Following completion of the diagram, the analyst paraphrased each component, link and rule depicted, so the participant could verify if this represented what they imagined (marked with a smiley) or if they were uncertain this reflected what they really imagined (marked with a question mark). Participants were given the opportunity throughout the interview to amend the diagram to better reflect what they thought. These participant verified diagrams from part 3 of the method, represent the device topology and causal model of device function, which deKleer and Brown (1983) consider fundamental to mechanistic mental models. The form of the verified description is similar in form to a 'concept map'. They differ from simple concept maps as they contain written descriptions of rules and variables to enhance understanding of the users 'causal model'. This output is considered to reflect the device model held by the user, of their existing home heating system. Wilson & Rutherford (1989) made the point that the outputs analysts capture when seeking a mental model is distinct from their actual mental model (an internal construct). Throughout this chapter, that

the participant verified diagram is referred to as their mental model *description* of home heating.

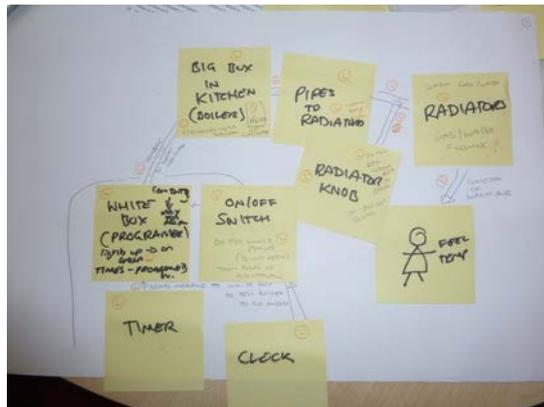


Figure 19 - Participant A's output from the paper-based activity, which formed the basis for analysis.

### 3.2.4 Analysis of outputs

The user verified mental model descriptions, and further evidence from the interview transcripts, formed the basis of discussion to determine aim 1; "if distinct mental model descriptions of thermostat function, that differ significantly from the actual functioning of UK heating systems, can be identified with present day UK heating systems". To determine if the shared theories described by Kempton (1986; 1987) and others, are evident in the case study group, the interview transcripts were also examined. As the approach was designed with reference to the style and content of questions described by Kempton (1986;1987), the interview transcripts from the intergroup case study could be examined to find evidence of responses that met Kempton's (1986) criteria of either a feedback or valve shared theory.

To categorize data from the interview transcripts systematically, according to Kempton's shared theories, a reference table was developed (see table 3). Kempton (1986, 1987), provided extended descriptions of valve and feedback model types. These descriptions were content analysed, identifying 4 distinguishing themes: 1) User Behaviour; 2) Thermodynamics; 3) Cause and Effect; and 4) Sensing/Control. For each of these themes, sub-themes with examples of participant responses considered (according to Kempton, 1986,

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1987) evidence of a particular theory, are shown in table 3. It was then possible to systematically compare the meaning of participant responses in the inter-group case study to those in [Table 3](#), to determine if evidence of Kempton's (1986, 1987) shared theories could be found. The following process was adopted when analysing the transcripts, to aid reliability.

- 1 Examining sections 2, 3 and 4 of the interview transcript, the type of responses by the participant were coded to separate 'meaningful responses by the participant' (the pool for analysis) from 'confirmation of interviewers paraphrase'.
- 2 Each response in the pool for analysis was coded by the main themes in table 3. An 'other' category was used for responses that fell outside of these themes.
- 3 Using table 3, each response was evaluated as evidence of Kempton's (1986) shared theories. Whilst Norman (2002) and Peffer et al. (2011) did not provide sufficient descriptions to produce entries in table 2 for 'Timer' and 'Switch' models, it was also considered if these models could be inferred from participant responses. This thesis also points the reader to chapter 4, where a reference table for quick analysis of diagram outputs from the method adopted, contains inferred responses for 'Timer' & 'Switch' models. Responses were assigned to the following categories: 1) Feedback, 2) Valve, 3) Timer, 4) Switch, 5) Ambiguous and 6) N/A.

Table 4 - Analysis Table for categorizing responses from interview transcripts

Themes		Typical responses from a thermostat user who holds a Feedback Shared Theory (Kempton, 1986)	Typical responses from a thermostat user who holds a Valve Shared Theory (Kempton, 1986)
4) Sensing/ Control	Sensing temperature	<ul style="list-style-type: none"> <li>Thermometer (in thermostat) senses temperature</li> </ul>	<ul style="list-style-type: none"> <li>Human senses comfort</li> </ul>
	Locus of control	<ul style="list-style-type: none"> <li>System regulates</li> </ul>	<ul style="list-style-type: none"> <li>Human regulates – balances heat generated with heat lost</li> </ul>
3) Cause and Effect	Thermostat set point – cause and effect	<ul style="list-style-type: none"> <li>Determines the ‘on-off’ temperature for the furnace – furnace runs at a constant speed.</li> </ul>	<ul style="list-style-type: none"> <li>Linear relationship - Controls the amount or heat / rate of flow – furnace varies in its rate of flow/amount of heat.</li> </ul>
	Consequence of different set points	<ul style="list-style-type: none"> <li>Small increase in set point – furnace on for short time, then turn off</li> <li>Large increase in set point – furnace run for longer to reach the set point temperature</li> <li>Static set point – temperature maintained by furnace switching on/off</li> </ul>	<ul style="list-style-type: none"> <li>Small increase in setting – small increase in rate of flow/amount of heat.</li> <li>Large Increase in setting – large increase in rate of flow / amount of heat,</li> <li>Decrease in setting – decrease in rate of flow / amount of heat</li> </ul> <p><i>Implication: confusion may occur if boiler turns off itself.</i></p>
2) Thermodynamics (device within a broader system ) Thermodynamics	External temperature.	<ul style="list-style-type: none"> <li>No impact, as thermostat will sense inside temp and respond to maintain temperature.</li> </ul> <p><i>Implication: confusion may occur if house seems colder on colder days, or if comfort levels are low despite usual set temperature</i></p>	<ul style="list-style-type: none"> <li>When weather is cold, house gets colder, so user compensates by regulating the thermostat.</li> </ul>
	Indoor temperature /	<ul style="list-style-type: none"> <li>The effect of the house cooling down, means more fuel is consumed when you increase the heat again, than if you had left it at the same setting.</li> </ul> <p><i>Implication: No night set back</i></p>	<ul style="list-style-type: none"> <li>Impact of cold bodies not considered to have an effect on energy used – More fuel is consumed at higher settings than at lower ones, as the rate of flow/temperature is higher.</li> </ul> <p><i>Implication: Night set back</i></p>
1) User Behaviour	Pattern of adjustment	<ul style="list-style-type: none"> <li>Minimal adjustments over short period of time.</li> <li>Will change thermostat set point deliberately at times when different levels of comfort are required. E.g. different levels of occupancy or activity.</li> </ul>	<ul style="list-style-type: none"> <li>Thermostat often changed between each hourly datum .</li> <li>Thermostat is adjusted at least hourly whenever someone is in the house.</li> </ul>

### 3.3 Case studies

Detailed individual case studies are presented of participants A, B & C. These participants were chosen for this chapter, as their mental model descriptions differed significantly from the actual function of the heating system in their home, as well as from the descriptions of each other. The remaining 3 participants from the pool of 6, provided mental model descriptions with conceptual entities and their interrelationships broadly aligned to the actual functioning of the heating system, with a ‘feedback’ shared theory for the functioning of the thermostat. As the way users significantly misunderstand the functioning of the heating system is of interest in this study, the results from these participants will not be discussed in detail in this chapter. Each case

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study will be presented with a description of the participant and their user verified mental model, redrawn for clarity. Discussion within each case study will focus on the consequence of differences in the content (in terms of elements /conceptual entities) and relationship (in terms of conduits between elements and rules of operation) of these mental model descriptions. How these differences influence user behaviour, and consequences in terms of energy consumption, will also be discussed.

### **3.3.1 Participant A: A Feedback mental model of thermostat with elements of Valve behaviour**

Participant A was a female housewife in her 30's. Originally from Malaysia, she lived with her student husband and two school age children. She and her husband both control heating in their home. Participant A's user verified mental model description of home heating is shown in Figure 21. This has been redrawn for clarity and the different elements (in rectangles) have been coded according to the key, to distinguish user controls, the device benefit, and intermediary elements (between user control and device benefit). The arrows between the elements represent 'conduits' of either information or heat distribution. The thick line shows an example causal route between a user control and the device benefit.

Looking at Figure 21, the elements and conduits form a 'loop' shape, which immediately suggests a feedback model. The control devices include the thermostat knob and the main on/off switch for the heating system. When prompted, participant A was not aware of the existence of either the programmer device, or the thermostatic radiators valves. Participant A described her goal when using the heating system, was to control the temperature of the whole house.

Participant A - Diagram of user verified mental model description of home heating function, represented as 'elements and conduits'.

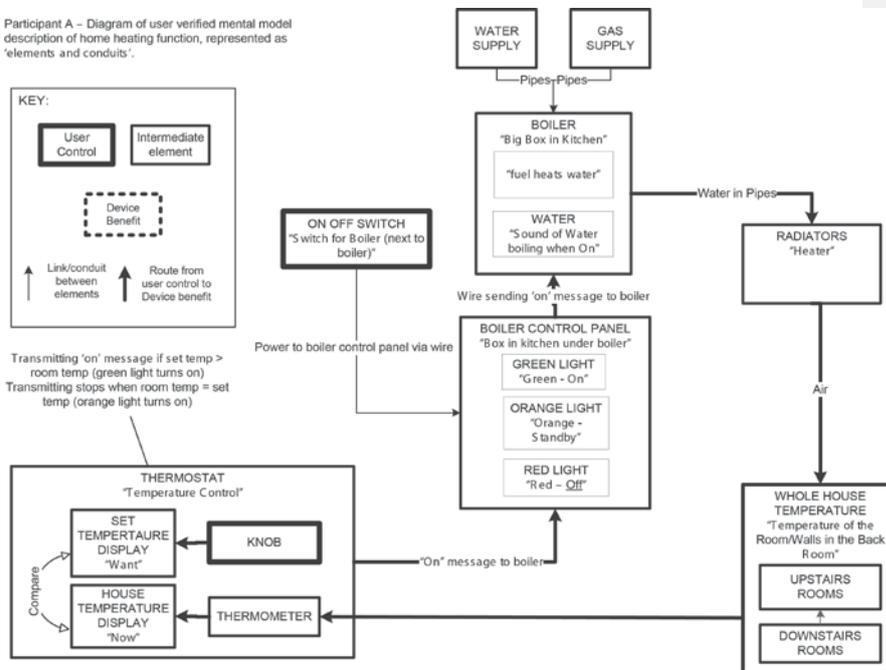


Figure 20 - Verified user mental model description of home heating for participant A

The second aim of this chapter was to see if distinct mental models of home heating thermostats could be categorized according to Kempton's (1986) shared theories. To make analysis easier, the elements and conduits which form the causal path for the thermostat, have been redrawn in isolation, in Figure 22. The left hand element is that which is controlled by the user, depicted with a 'hand'. Automation is represented with a 'robot head', and the rule for automation shown in a thought bubble. Other elements included in the causal path *is-are* shown with a square, and the benefit of using the home heating system is represented with a star shape.

The causal path shown in Figure 22 was further amended using evidence from the transcripts. The type of function to be performed by each element is indicated with an icon representing either a discrete or variable function, to give the reader a 'snapshot' of the relationship between elements. The relationship between these functions in specific scenarios provide insights into cause and effect (deKleer & brown, 1983). An insight into the likely behaviour

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patterns of participant A is gained by understanding how the relationship between these functions allow her to make predictions about the results of her actions.

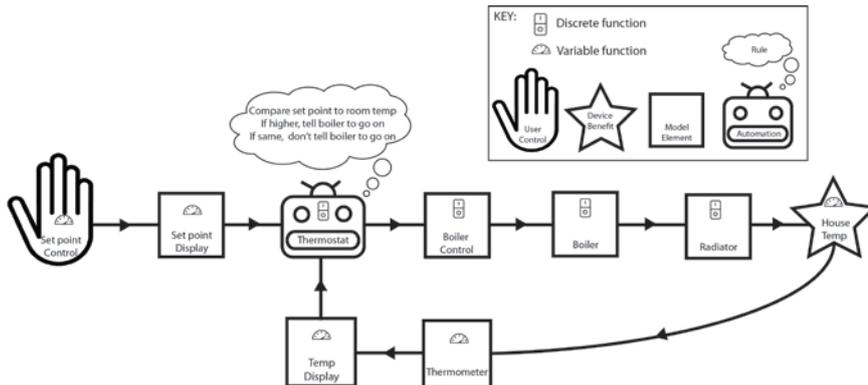


Figure 21 - Isolated causal relationship for thermostat knob taken from participant A’s user verified mental model description of home heating.

Looking at Figure 22, we can see that participant A’s causal relationship includes a thermometer to sense the house temperature and that this feeds back data to the thermostat. The boiler is thought of as functioning like an automatic on/off switch, based on a rule whereby a comparison is made between the temperatures of the set point and house temperature. Referring to Table 3, considering sensing temperature, locus of control and thermostat set point, the data from participant A clearly falls into the typical responses provided by a user holding a feedback model type. When considering the consequence of different set points, Participant A did not explicitly state that the furnace ran at a constant speed, but this is inferred since she only refers to discrete states of the boiler (on/off/standby) rather than variations in temperature or intensity. The boiler control (which is thought to be the programmer device) provides feedback on this status by different coloured lights. The quote below emphasises the boiler control is significant to her model of the boiler regulating the house temperature. When reading the transcript below, please note that that participant A initially favoured the term ‘thermometer’ for the entire thermostat unit. Square brackets in the transcriptions show the intended meaning.

Kirsten M A Revell

*Analyst: .....All right, so we've got this idea when you turn the thermometer [thermostat] up, it [programmer] goes green, normally it's on orange, which is our middle one. How does this going green affect what's happening in there? ....*

*PARTICIPANT A: When the temperature in the house probably down a bit ~~then~~ than the temperature that we set, that's why it come green.*

*ANALYST: So you're saying you've got the temperature that you set, which is from the thermometer [thermostat].*

*PARTICIPANT A: Yes, set and then maybe the temperature in the house getting colder a bit because of the outside maybe and then ..... automatically turn to green to make the house warm again to the set temperature.*

Participant A is also very clear about when the boiler automatically switches off, stating "It's nice and warm to the right temperature, it [the boiler] don't do anything." and "It [thermostat] will tell [the boiler] stop working!".

The first quote also considers thermodynamics relating to external temperature, showing again that the device, rather than the user, compensates for changes in external temperature. According to Table 3, this is a typical response from a user with a feedback shared theory.

In terms of patterns of adjustment (Table 3), participant A initially provides clear evidence of a feedback shared theory. She reports adjusting the thermostat to deliberate set points corresponding to specific times relating to occupancy and activity, as we can see below;

*ANALYST: And can you... do you happen to know what temperature you turn it up and down to?*

*PARTICIPANT A: At the evening, around 6 or 7, I tend to put it up to 23 then we go to sleep we keep it to 21. And, during the day, we normally keep it to 20.*

-----

*ANALYST: So, at sleep it's 21, when you wake up in the morning, do you change it or do you just leave it until your children come home?*

*PARTICIPANT A: Well, usually I keep it to 20 because I want to keep the house warm because my kids go to school and then I keep it 20 because there is sun outside and if I'm in the lounge, it gets too hot.*

There is an indication, however, that in certain conditions, in certain parts of the house, the device is not able to regulate house temperature sufficiently to maintain comfort, which affects participant A's set point choice. This is a

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response expected from a user with a valve shared theory (see Table 3, external temperature). The thermostat used is positioned in the hall (see Figure 19) in participant A's house, and actually takes air temperature readings at its location, influenced primarily by the heat output of the hall radiator. The transcript below reveals that participant A imagines the inside temperature display represents the temperature of the 'whole house', rather than a single area.

*ANALYST: And how does it know what the house temperature is?*

*PARTICIPANT A: Usually, the house temperature is... you're not touching anything by the small box you're talking about. If you just look at that, I think that is temperature of the room... of the house.*

*ANALYST: Of the house. So when you say the house, do you mean the walls, or...?*

*PARTICIPANT A: The whole house ..*

This misinterpretation in her mental model is significant in terms of her self-report of behaviour patterns. Whilst originally describing a regular routine for set point change, when provided with a typical scenario where comfort levels are too high, she revealed ad-hoc adjustments also occurred.

*ANALYST: Next one scenario 3: The heating is on, you can feel the radiators are on but you've been rushing around doing housework or exercise or looking after the children or cooking and now you feel really hot and uncomfortable, what would you do?*

*PARTICIPANT A: I would scream my husband put it off!*

*ANALYST: And when you say put it down, you mean this button [point to thermostat].*

*PARTICIPANT A: Yes, I tell my husband.*

*ANALYST: O.K. your husband.*

*PARTICIPANT A: Because I do exercise at home, I work out at home, I do my exercise at home.*

*ANALYST: How typical is this and how often would that happen?*

*PARTICIPANT A: Er, when I go to sleep, actually, every night. Because sometimes he has a habit to make it to 23. I think because he's sitting all the time. When I go upstairs to go to sleep, I scream you've got it so hot!*

Further exploration revealed that this 'comfort battle' between her husband and herself, occurs regularly, during the day. If her husband is home, he

frequently increases the thermostat set point to 22°C, and she returns it to 20°C. This pattern of behaviour is closer to that expected from a user who holds a valve shared theory (see Table 2). Kempton (1986) stated that conflict battles may result in valve behaviour patterns. However, participant A reports that the battle occurs when she and her husband are located in different parts of their home, where thermodynamics of the house structure also effect comfort levels. As Participant A's believes the 'whole house temperature' is measured by the thermostat, it is logical, when considering the causal path in her mental model description (Figure 22), that comfort would be regained by adjusting the set point, rather than a different strategy. More appropriate strategies, such as adjusting the thermostatic radiator valves to different settings to accommodate both her husband (studying downstairs) and herself (exercising, or sleeping upstairs) cannot be considered, as TRV's are absent from her mental model description of home heating (Figure 19). As a result, heat energy is wasted by overheating rooms where a facility to limit the temperature to comfortable levels exists.

Participant A clearly provided a mental model description of thermostat function that fit the criteria derived from Kempton (1986) of a 'feedback' shared theory. Self-reported planned, regular set point adjustments also fit the behaviour expected from a user holding this theory. Due to comfort conflicts, participant A reported behaviour patterns, which if viewed from set point measurements alone, would indicate a valve theory was held. However, it is argued that this behaviour pattern is driven not just by 'comfort conflict', but by misinterpretations in the thermostat mental model, as well as an incomplete mental model description for the heating system as a whole.

### **3.3.2 Participant B: Feedback behaviour without a feedback mental model**

Participant B is a female student in her late 20's. Originally from Mexico, she lives with her husband and young child. Participant B's mental model description for home heating is shown in Figure 23 below. She is the sole operator of heating in her home.

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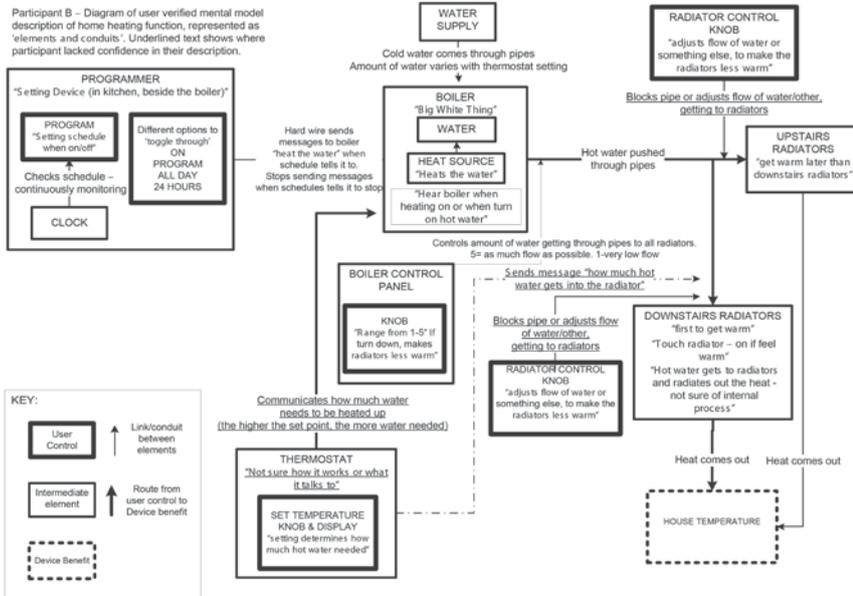


Figure 22 - Verified User mental model of home heating for participant B

We can see from Figure 23 that the mental model description of home heating developed with participant B is more complex and detailed than that for participant A. The shape contains no 'feedback' loop input to the thermostat device, which suggests the user does not hold a feedback shared theory of home heating. Participant B describes multiple control devices, including the program schedule, the override button, the thermostat set point control, boiler control knob and radiator control knobs (TRV's) for each radiator. The only heating control absent from this description is the power switch for the whole heating system. Participant B similarly described the purpose of using the heating system, was to warm the whole house. Figure 24 shows the causal path of the thermostat control, isolated from the other control devices, with icons added to represent the function of each element as inferred from the interview transcript.

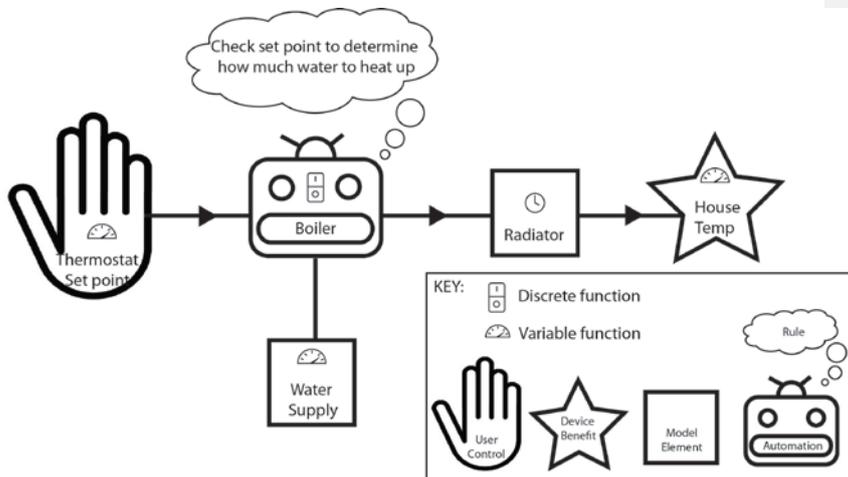


Figure 23 - Isolated causal relationship for thermostat set point taken from participant B's user verified mental model description of home heating.

Looking at Figure 24, we can see that participant B's causal relationship for the thermostat set point is dependent on the water supply. There is no thermometer or feedback loop included in the mental model description by participant B. Variations in set point are matched with variations in the volume of water to be heated up by the boiler. In general usage, the boiler operates according to discrete states, automatically switching off when the corresponding amount of water has been heated. A larger volume of heated water (following, according to participant B's model, from a higher set point value), takes a longer time period to run through the radiators, resulting in a greater amount of radiated heat, and ensuring a higher house temperature.

When comparing Figure 24 to the criteria in Table 3, the lack of thermometer refutes a feedback theory being held. However, when responding to questions regarding the boiler override control, it appears participant B is aware there is an inside temperature display on the thermostat device (see transcript below). She did not consider this of significance, however, when producing her mental model description of home heating (Figure 23).

ANALYST: ..... what situations do you normally go in and press the button to get it to come on?....

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*PARTICIPANT B: Basically if I see the temperature is 16 or 17 degrees I feel it's a bit cold.*

*ANALYST: Okay. So even if you perhaps didn't feel cold but you noticed it was cold then perhaps turn it on, or is it only if you feel cold?*

*PARTICIPANT B: Yeah, I feel cold and then I check the temperature and say, "Okay, I'll turn –*

*ANALYST: So you making sure you really are cold?*

*PARTICIPANT B: Yeah, that it's not just me. (Laughs)*

*ANALYST: If you're cold. So you check... and that's on the thermostat?*

*PARTICIPANT B: Thermostat.*

This transcript clearly shows that participant B uses the device to determine if the house temperature is appropriate, rather than her own sense of comfort, which from Table 3 is characteristic of a holder of a feedback, rather than valve, mental model. Considering cause and effect (Figure 24), there is a clear linear relationship between the thermostat set point and the amount of water heated, suggesting a variation on the criteria for valve theory (Table 3). We could consider participant B has a 'valve' theory, for the relationship between the thermostat with the water supply, but not with the boiler intensity.

*ANALYST: ..... So what would happen then if you had the thermostat, like, up to 30 or something, if you had the thermostat at a really high temperature, the maximum temperature that you can go to, what do you think would happen?*

*PARTICIPANT B: Well then the boiler will have to produce more hot water and keep going and going through the radiators until they reach the temperature, I mean they make the temperature to 30.*

*ANALYST: So if 30 degrees is set on the thermostat lots of hot water is made Okay. Alright. What would you think would happen if you turned it right down to 5 degrees?*

*PARTICIPANT B: The boiler will not operate*

A more appropriate analogy may be that each set point temperature has a fixed volume of water associated with it. When adjusting the set point, a message is sent to the boiler to select and heat up the corresponding volume of water. This also is clearly different from a feedback theory, whereby the boiler operates until the house achieves set point temperature, sensed by a thermometer. However, it may lead to similar behaviour, as it is accepted by participant B that the system ensures, through this selection of water volume

that the desired house temperature will have been reached when the boiler deactivates. Continuous adjustments of thermostat set point would therefore be unnecessary. The consequence of different set points, when considering the relationship with water volume again can be interpreted as belonging to 'valve theory', as larger amounts of heated water result from larger increases in set point.

The transcript above, however, could also be interpreted as 'feedback theory' according to Table 3, despite following from a mental model description that lacks a feedback loop. Heating larger volumes of water, assuming the boiler runs at a constant speed, also predicts the furnace will run for longer periods. When questioned, participant B was clear that the water temperature in the boiler was not raised by the thermostat, so a valve theory for boiler operation, as described by Kempton (1986) is refuted.

When questioned about her behaviour patterns when operating the thermostat, participant B reported keeping the set point at a single value, relying on the programmer to regulate the heat. This behaviour again fits better with a response expected from a holder of a feedback, rather than valve, model (Table 3).

*ANALYST: .....Okay, so you're saying the thermostat's normally set at 20, sometimes you notice it's cold, would you then when you notice it's cold turn the thermostat up or just go to the programmer and press the programme?*

*PARTICIPANT B: Go to the programmer.*

*ANALYST: Okay. .... is there any reason you would go and change through your thermostat?*

*PARTICIPANT B: No.*

*ANALYST: No? Okay. So not during the week or weekends or holidays or anything like that, you would just keep it how it is and make everything controlled through the programmer?*

*PARTICIPANT B: Yeah.*

A goal of this chapter was to see if distinct behaviour patterns of thermostat function could be categorized according to Kempton's (1986) shared theories. This has been difficult to achieve with participant B's mental model description. Many traits which would be expected from a user holding a feedback theory were discovered. However, the concept of feedback, or temperature sensing

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was not present in her verified mental model description (Figure 23). The linear relationship between the thermostat set point and the water supply, was more akin to a valve theory, however it should be noted that this is not with the sense intended by Kempton (1986), which relates to heat flow or intensity in the boiler. Kempton (1986) suggested that users with a feedback shared theory could unnecessarily waste energy by avoiding ‘night set back’ of the thermostat. Participant B uses the programmer to limit consumption at night, so the need for night set-back is negated regardless of the theory held. The reasoning of feedback theory holders, according to Kempton (1986) (and summarised in Table 2) is that it will take more energy to re-heat a cold house, than to maintain a warm house. This thinking is evident with Participant B in the following quote. From participant B’s transcript, neither the thermostat or programmer settings are adjusted when away from the house at the weekend, or on holidays, suggesting energy is wasted by heating an unoccupied house.

*PARTICIPANT B: Well I was actually thinking with that setting that I need... or that the house needs to be heated for not such a short time because maybe it will have to work more the next day. I mean to not leave the house unheated for a long period of time.*

The desire to identify distinct mental models of device function, is to be able to predict user behaviour. Participant B, whilst using a deliberate thermostat set point, does not habitually make adjustments (preferring to use the programmer and override device). Figure 23 shows uncertainty in much of the mental model description relating to the thermostat device, with underlined areas show low confidence in the description. Participant B’s mental model for thermostat function may be poorly developed, because she does not use the thermostat. On the other hand, participant B may not use the thermostat because her mental model of the thermostat is ambiguous or incomplete, undermining confidence in the outcome of her actions. The ability to predict behaviour patterns relating to user mental models of device function is necessary if design strategies to improve usability or influence behaviour are to be successful. This association is clearly more likely to be found when the participant actively uses the device under investigation.

3.3.3 Participant C: Timer model for alternate control devices

Participant C was a female student in her 20's. Originally from Brunei, she lived with her husband, young child and father-in-law, and is the sole operator of the heating system. Figure 25 shows her user verified mental model description of home heating.

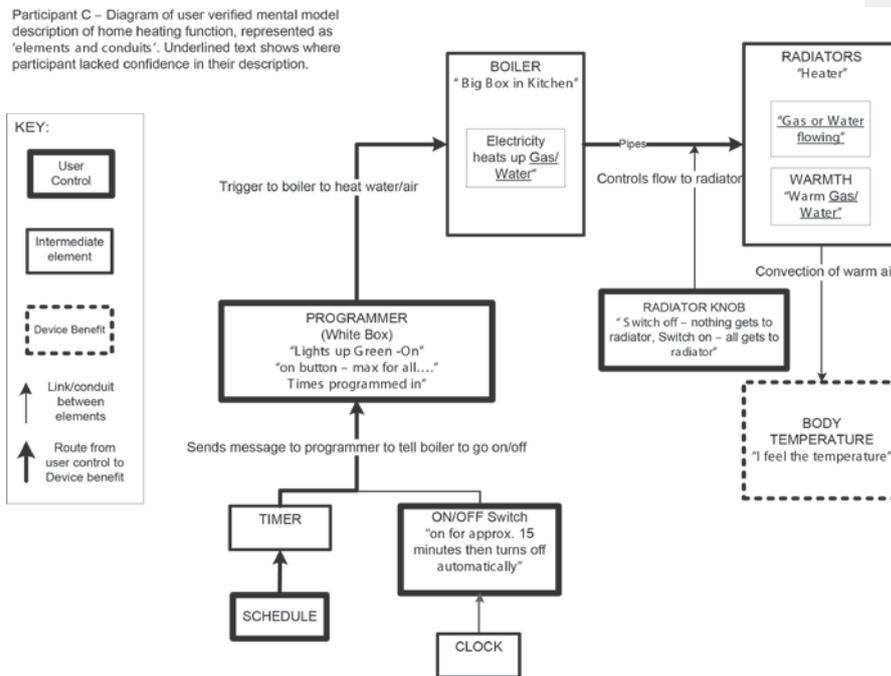


Figure 24 - User verified Mental Model description of home heating function, from participant C

Participant C's mental model description of home heating, is linear and branched in shape, and shows 3 different user controls; the schedule for the timer, the on/off (or override) switch for the programmer and the radiator knob (Thermostatic Radiator Valve (TRV)). The device benefit is not considered the house temperature, as with participants A and B, but rather her own thermal comfort. Conspicuous by its absence is the thermostat device.

The second aim of this chapter was to determine if mental model descriptions of thermostat function can be categorized according to the shared theory types in the literature. It is clear from the lack of thermostat device in Figure 25, that

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this type of analysis couldn't be undertaken. To further the initial aim, that distinct mental model descriptions of home heating exist, two causal paths will be described from participant C of alternate control devices, as they provide further insights into the consequence of incomplete mental models. The causal path of the program schedule, and of the boiler override button are shown in Figure 26 & Figure 27. Unlike the previous causal paths, which focused on the thermostat, these include icons representing a time based variable.

Participant C clearly describes the programmer unit as a time based automatic switch, responsible for turning the radiators on and off;

*"It is a digital device for the system to say at what time you want it to come on, and it will light up to yellow colour if the radiator is on and it will light up to red if the radiator is off, and it is automatically turned to on and off by the program"*

Figure 26 displays a linear route from manual input of the schedule to the resulting increase in body temperature, with the schedule function being time-based. The timer button (program option on the programmer), boiler and radiators are reported in the transcripts as being either be-'on' or 'off' so function according to discrete, rather than variable states. This is an appropriate mental model for the programmer, if used in isolation. It is not clear from the transcript if the benefit, in terms of body temperature, is directly linked to the schedule, so an icon is absent from this element in Figure 26.

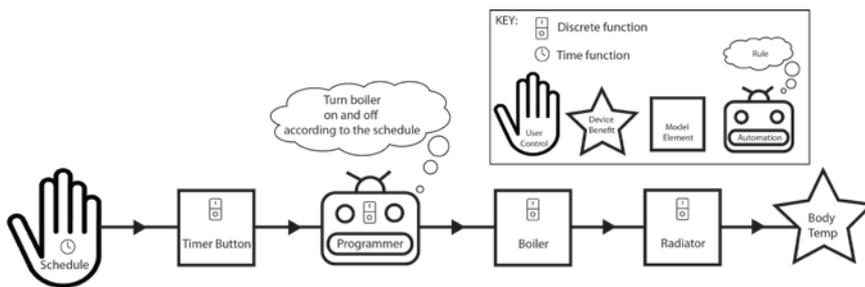


Figure 25 - Cause and effect route of schedule function for participant C

Figure 27 shows the cause and effect route for the override button for the programmer, which participant C referred to as the 'on/off' switch. This button allows the boiler to be activated outside of scheduled times.

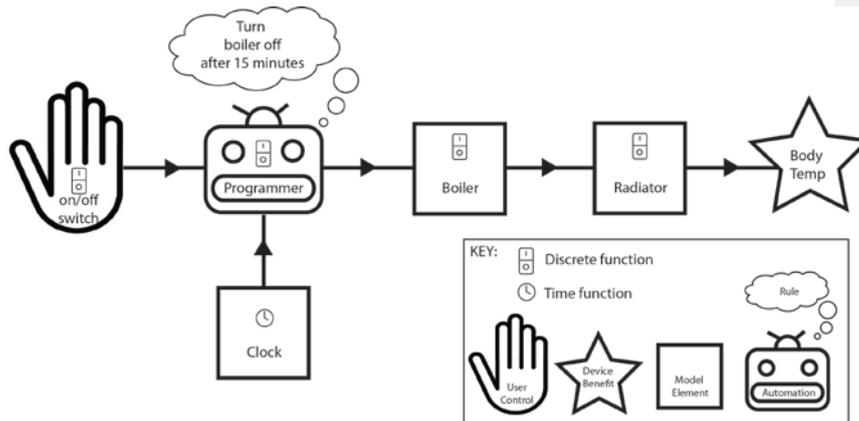


Figure 26 - Cause and effect depiction of override button for participant C

Participant C reported that when using the override switch, the boiler switched itself off after approximately 15 minutes. The following transcript describes her confusion about this outcome. The blank lines represent parts of the conversation that have been omitted as they do not add new insights.

*ANALYST: How do you think it knows when to come off? ..... is it from the timer? Or something else that makes it switch off?*

*PARTICIPANT C: It can't be the timer because the timer is already being programmed so it must be something else. It's by default it will just go off.*

-----

*ANALYST: So maybe after a certain period of time, or?*

*PARTICIPANT C: Yeah.*

*ANALYST: Okay. So you've kind of got this idea about whenever you switch it on, it's almost like it's only on for a short period.*

*PARTICIPANT C: Yes it doesn't obey me.*

From the last comment, it is clear that participant C does not feel in control of the effects of this device. Further discussion led to the idea of a 'clock' telling the program when to switch off. The uncertain language used in the transcript

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above (“it must be”, “it can’t be”) mean it is likely that this link was a construct of the interview, rather than the participants’ existing mental model of the user (Payne , 1991). It is argued that the need to add to a mental model to explain an unexpected phenomenon shows that the existing model of the system is not fully functional for this participant. Moray (1990) emphasised how it was not possible to troubleshooting problems successfully if the mental model held by a user, lacked the elements responsible for the problem source. It is likely that the true cause of the boiler deactivating a short period after the participant presses the override button, is the thermometer registering its surrounding air temperature equal to the thermostat set point (presumably set to a value below participant C’s comfort levels). Since a thermostat device and thermometer are both absent from this participants mental model description (Figure 25), this conclusion could not be arrived at by participant C herself.

Participant C relies on a daily schedule, which she believes ensures the boiler operates to produce heat for a short period in the morning, an hour for lunch, and a longer period in the evening. The schedule is repeated 7 days a week, regardless of changes in activity. When asked when she used the override button, participant C revealed that she regularly overrides the system when the heating is scheduled to be on (between 5pm and 10pm). Participant C does not appear to see a conflict with her mental model of the timer, which is turning the boiler ‘on and off’ according to the schedule, and the need to override the program during scheduled ‘on’ times. She also admits to using an electric portable heater or “blower” to maintain or increase comfort levels between, or during scheduled times. These additional actions suggest that the home heating system with the existing schedule and (unknown) set point, fails to meet the comfort needs of participant C. Depending on how energy hungry the model of portable heater, and the frequency and durations of operation, this strategy may result in higher levels of consumption than if the central heating had been set up to provide adequate comfort levels. However, it is possible, that this proximal ad-hoc heating from an alternate heat source is more energy efficient at meeting comfort needs, than if the whole house was heated for longer periods.

When provided with scenarios where her comfort levels are too low, participant C provided a range of strategies unrelated to her mental model description of

home heating (Figure 25). These included washing hands, showering, putting on the portable heater, moving away from the window, putting on a blanket, and even lighting candles. It is inferred from this response that Participant C considers the central heating system in her home to be one of a range of solutions for achieving comfort, rather than the key solution. As her goal for using the heating is body temperature, rather than house temperature, it may be more appropriate to gain this participants mental model of comfort, rather than device function.

Whilst the lack of thermostat in participant C's mental model description meant it was inappropriate to evaluate if Kempton's (1986) shared theories were present, the transcript was examined for evidence relating to generic 'valve' or 'feedback' concepts. When participant C was asked how she knew the heating was on, she reported that *"I will... first thing I will think house is warm"*, suggesting that she is sensing comfort, rather than referring to a device to get feedback of boiler activation. When describing how she thought thermostatic radiator valves work, she similarly described valve thinking *"The amount of the flow of the heating material flowing through the radiator. So if this is being turned on then there'll be more flowing into the radiator"*. There is no sense of variations in temperature or intensity of heat as a result of the heating system, however. Feedback concepts were completely absent from the transcript. For this participant, further exploration of timer mental models of home heating would be appropriate.

### 3.4 Discussion

A small scale intergroup case study was undertaken to identify : 1) If distinct mental models of the way home heating systems function could be found, that differ significantly from the actual functioning of UK systems, and 2) If these models could be categorized according to 'shared theories' of thermostat function from the literature. Data was collected from 6 participants in matched environments using a semi-structured interview including paper-based activities, developed in this thesis (see Revell & Stanton, 2012, and Revell & Stanton, Under Review, for further details). The impetus for the research was to understand if the mental models held by individuals could explain their energy

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consuming behaviour in a way that could usefully inform strategies aimed at reducing consumption through behaviour change.

It was found that 3 of the 6 participants produced mental model descriptions of their home heating system that differed significantly from the actual functioning of their system. The differences explained their self-reported behaviour with their home heating system, which, by association, may also explain their levels of energy consumption. From the mental model descriptions produced by the 6 participants, 4 represented thermostat function in a way that could be categorized according to Kempton's (1986) 'feedback' shared theory (a simplified version of the actual home heating functioning) . One participant described a variation of Kempton's (1986) 'valve' theory, and another participant omitted the thermostat device from her description, preventing comparable categorization. Timer and Switch shared theories for the thermostat, were found useful for categorizing user mental models of alternate home heating controls, such as the programmer and boiler override button. The valve shared theory could also be applied in a general sense to user mental models of the TRVs.

The key findings of this study, that add to the existing body of knowledge, are 1) that UMMs of thermostat function can be found that fall outside of the Feedback, Valve, Timer & Switch shared theories described by Kempton (1986), Norman (2002) & Peffer et al. (2011), and 2) omissions of entire control devices from UMMs of home heating, were evident despite an environment matched in terms of dwelling, and type and layout of home heating devices. In addition, (though not emphasised in the reporting of the three in depth case studies), thermostat set point adjustment was less prevalent than expected, with 4 out of the 6 participants reporting a reliance on other devices (e.g. programmer, override button and TRVs) when adjusting their home heating output. Finally, the discrepancy of the user's goal when using the heating system (e.g. heating the whole house or increasing the comfort of the occupant) and the actual benefit of the system (i.e. to produce a constant rate and intensity of heat, limited in period of operation by the program schedule, in activation by the thermostat set point, and in output by the TRVs set point) was also helpful when explaining reported confusion by the user, when operating the system.

In itself, the existence of UMMs that cannot be easily categorized according to existing shared theories is only important in terms of energy consumption, if the associated behaviour is significantly more or less 'wasteful'. In this study, the associated (self-reported) behaviour of participant B closely matched that expected of users holding a 'feedback' theory, so participant B's specific UMM is not of special interest. However, consensus in the literature (e.g. Kempton, 1986, Norman, 2002, Peffer et al., 2011, Richardson & Ball, 2009) that UMMs fall into these categories of shared theory is challenged. This suggests that the existence of additional 'shared theories' or unique individual UMMs, that may have a significant impact in terms of energy consuming behaviour, cannot be ruled out.

The omission of control devices, rather than merely settings/options on a device, is an important finding. The omitted devices in our study included key controls, such as the programmer and thermostat, which hold a significant role in allowing the user to optimise energy consumption. The lack of key controls in UMMs affects the strategies that users can adopt in order to meet their goals. For example, it could impede users from achieving their desired level of comfort by being unaware they could adjust the thermostat or TRV setting, or that they could set the programmer to start heating before getting up). Alternatively, it could prevent users from reducing consumption by being unaware they could reduce the thermostat or TRV setting, or that they could set the programmer to automatically switch off at times when the home is typically unoccupied. A failure to meet user goals, as in the case of participant C, who reverted to an electric heater when failing to meeting her comfort goals, could encourage alternate strategies that may be more costly in terms of energy consumption ~~that than~~ optimal operation of the home heating system. In addition, the lack of key controls in UMMs of their own heating system, could hinder the success of advice based strategies to encourage reduced consumption in the home, when based on changes to the way users operate 'omitted' devices. For example, government advice in the UK to 'turn down your thermostat by 1 degree' ([www.energysavingtrust.org.uk](http://www.energysavingtrust.org.uk)) would have little effect on participant C in this study, who omitted the thermostat control when producing her mental model description of home heating.

Whilst the number in this intergroup case study are too small to indicate a trend, the preference of the majority of participants in this study to favour the

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programmer and boiler override devices to the thermostat, when asked about ad-hoc or routine adjustments, was surprising given an emphasis in the literature on thermostat behaviour styles (e.g. Kempton, 1986, Norman, 2002, Richardson & Ball, 2009, Peffer et al., 2011). If large proportions of the general UK population also seek out alternate control devices to the thermostat, when making adjustments, it calls into question the present day relevance of Kempton's (1986) insight. It may no longer be important to consider user's 'shared theories' of thermostat function and associated behaviour patterns, as a means of understanding domestic energy consumption. However, this intergroup case study does suggest that a link between UMMs of home heating and their strategies for controlling heating are associated, so applying Kempton's (1986) insight at the system level, incorporating the integration of a range of control devices, rather than to a single control device, may be more appropriate.

When a user needs to translate their home heating goals (e.g. comfort, reduced consumption) in terms of the options available on the home heating system (e.g. home heating control set points, options & schedule durations), the ease of this translation is likely to affect optimal operation. This link between goals, mental models, strategies and performance is clear in the literature for interaction with devices (Norman, 1986) and within complex systems (Bainbridge, 1992, Moray 1990). In this case study, not only was there evidence of users not being able to meet their goals with Participants A & C, but also a misunderstanding of the benefit, that the home heating system could provide (e.g. Participants A & B, who thought the thermostat setting ensured the whole house was maintained at the chosen temperature). A better understanding of how to encourage optimal behaviour with home heating systems would benefit from considering not only how well the heating system can accommodate user goals, but also how appropriate users expectations were, of the heating system's benefit.

The data collection approach was chosen to achieve key objectives for this inter-group case study: 1) to encourage accuracy in the capture of UMMs by considering bias in interpretation in its development, 2) to capture a description of the user's device model, 3) to represent the user's device model description in a concrete diagram form, to aid design based strategies, 4) to

produce data that allows categorization of UMMs of thermostat function by existing shared theories in the literature, 5) to produce data that allowed alternate theories to be considered.

The method developed was intended to enhance previous methods of data collection from established researchers such as Kempton (1986) and Payne (1991) through mitigation of bias and reduction of ambiguity in the outputs. However, a systematic method of considering bias was used in the development of the method, with mitigating strategies or acknowledgement of bias stated in Table 2. This provides readers with transparency so they can appreciate the steps undertaken to increase the chances that the captured mental model descriptions reflects the user, rather than the analyst. The paper-based element of the method was well suited in structure to capture users' device models of home heating. This concrete representation clearly identified missing elements and misunderstandings, providing emphasis for targeted strategies aimed at enhancing UMMs to encourage energy consuming behaviour.

In terms of capturing and depicting the user's device model, the process to develop and the resulting form of the user verified mental model description [meets the objectives](#); is considered. Considering the methods ability to categorize UMMs according to shared theories in the literature, Table 3 was helpful in categorizing according to Kempton's (1986;1987) feedback & valve shared theories, but switch/timer shared theories needed to be inferred as Norman (2002) & Peffer et al. (2011) gave insufficient information to populate the categories derived through content analysis of Kempton's descriptions. However, the readers are assured that any evidence that the users held timer and switch theories for thermostat function in the intergroup case study, was not overlooked. The concepts of timer/switch theories and Kempton's valve theory are clearly applicable to other home heating control devices in the study, both appropriately and inappropriately applied. A more generic (e.g. control device independent) definition of these theories would aid applicability to a range of energy consuming devices and could therefore have broader reach in understanding non-optimal user behaviour. The semi-structured style of the interview was beneficial in allowing participants to freely express ideas that were outside the scope of the shared theories from the literature. This was

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seen with participant B's variation on Kempton's (1986) Valve theory for the thermostat.

When researching mental models, as with any internal construct, there are limitations as it is not possible to directly assess and characterise the concept (Zhang et al., 2010). The method for extracting information and describing the user mental model will always be subject to bias based on the decisions, perspective and requirements of the analyst (Zhang et al, 2010; Wilson & Rutherford, 1989; Bainbridge, 1992; Revell & Stanton, 2011, 2012). In Chapter 2, Revell & Stanton (2011, 2012) argue that by systematically evaluating and stating the bias in data collection and analysis, the risk to bias for the resulting mental model description is explicit. This particular method necessarily accessed mental model subsequent to device use, due to the nature of the domain. As such there is risk of models being spontaneously created as part of the process (Payne 1991), although the language used and hesitancy of answer does provide an indication of this. The interview process itself gives an opportunity for the user to reflect upon and refine their mental model which is unavoidable. Nevertheless, refinements of a mental model that lacks key elements, or contains a misunderstood relationship between components through this process does not provide additional information that would allow misunderstandings to be corrected. The fundamental misunderstandings or omissions, rather than refinements on these understandings are most illuminating in terms determining strategies to encourage energy saving behaviour. There are clear challenges when trying to validate any internal construct, as direct access is not possible. Nevertheless, where there are clear absences of key components of the home heating system, in the mental model description, or unexpected interpretations of cause and effect, it is unlikely through the choice of probes and construction of diagrams, that the participant constructed an alternate view whilst actually holding a more accurate mental model of the heating system.

Another limitation of this research is the general applicability to a typical UK population due to the characteristics of the user group and the small sample size. This group's limited exposure to home heating was, however a benefit in being able to attribute the UMM descriptions to experiences with the devices present in the matched accommodation, rather than the extensive experience a

typical UK resident would have. As the user group was in matched accommodation, it also means the device layout and model types can be considered a starting point from which to consider design based strategies to encourage behaviour change that take into account the misunderstandings and omissions seen.

Further work needs to be done with a larger sample size and more typical UK population to determine if the specific misunderstandings and omissions (in terms of the elements and relationships of components present in users device models of home heating systems) that were found in this intergroup case study are more generally applicable. A larger sample would also better indicate the current prevalence of existing shared theories from the literature, applied either to the thermostat, or more generically to alternate control devices. It may also reveal new shared theories to add to those already present in the literature. To understand if the device model or shared theory held, translates to significant differences in users' energy consuming behaviour additional work needs to be done. A study that collects actual user behaviour with the typical range of home heating control devices, in addition to users' device models of the home heating system could shed light on this relationship. There is presently much interest in-to how to improve consumption with heating systems through design, focusing on programmable thermostats (e.g. Combe et al., 2011, Peffer et al., 2013), as well as investigation into the benefit of support aids for central heating (e.g. Sauer et al., 2009). The central heating system needs to be considered as just that, a system. Sauer et al., 2009, considers home heating to be the most complex system in the domestic domain. Consideration of individual control devices, in terms of usability is clearly important, but users need to be aware of which control devices to use in which situations, to fulfil their comfort and consumption goals. Support aids for central heating, or the redesign of central heating devices, that promoted a functional mental model to users of the integration between components of the heating system, could provide benefits beyond enhanced feedback or proscriptive guidance. It is proposed providing users with a pragmatic understanding of cause and effect for the multiple control devices presented on their heating system that allows them to: a) relate their actions to their individual goals, and, just as importantly, b) understand when their individual

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goals cannot be met by the system. This could not only reduce consumption, but enhance comfort, providing the ‘optimal consumption’ we all seek.

### **3.5 Conclusions**

Through comparison of user verified mental model descriptions of home heating, distinct mental models that differ significantly from the actual functioning of UK heating systems were shown. Evidence of Kempton’s (1986) feedback shared theory for the functioning of the thermostat was found. Other shared theories from the literature were useful in categorizing alternate control devices. A user mental model of the thermostat that could not be assigned to the existing shared theories in the literature was also found. Differences in the control devices present in mental model descriptions could explain confusion in operation. Differences in the causal path for specific control devices explained differences in reported behaviour. Variables such as the type and number of controllers and assumed device benefit appeared to interact with mental models of device function to explain reported behaviour. To apply the notion of mental models of home heating to encourage optimal energy consumption misunderstandings and omissions in user mental models could target design focus to encourage users to hold more integrated, functional models. Further work is needed to prove association between shared theories categorized by this method, and actual behaviour with devices, as well as methods for applying mental model descriptions in design strategies. What is needed is a structured method for eliciting mental models in an efficient manner. This method is developed in chapter 4.

## 4. The development of the Quick Association Check (QuACk) for exploring the relationship between mental models and behaviour patterns of home heating systems

### 4.1 Introduction

[This Chapter shows the development of a method to further investigate Hypothesis 1 \(see section 1.2\), that users' mental models of devices, influences their pattern of device use. Its development is heavily influenced from the insights identified in Chapter 2, that concludes consideration of bias in access and analysis of Mental Models is essential for confidence in application. A systematic means of exploring association between mental models of home heating and behaviour with heating controls provides a mechanism for generating data to further the key aim of this thesis: to understand how the concept of mental models can be applied in design to elicit behaviour change that results in improved achievement of home heating goals. The method described in this chapter was applied to case study participants discussed in chapters 3, 5 and 6, to a home heating expert in chapter 6, and to participants of a study involving a home heating simulation in chapter 8.](#)

Over the last 30 years, the notion of mental models has been applied as a strategy to predict how users will behave when interacting with a device and understand the reasons for inappropriate interaction. These range from research into consumer devices (Norman, 2002), computer interfaces (Caroll & Olson, 1987 Williges, 1987) and complex systems ( Moray , 1990) and is particularly prevalent in domains such as transport (Stanton and Young, 2005, Weyman et al., 2005, Grote et al, 2010) and command and control (Rafferty et al. 2010). Kempton (1986) proposed that different patterns of behaviour when operating a home heating thermostat resulted from different mental models of thermostat function. This association is yet to be proven, and it is possible the mental models and behaviour patterns found in Kempton's (1986) study may

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have been specific to that period in history (with associated heating technology) and sample group (Michigan, US, middle class householders). However, if Kempton's (1986) findings are still applicable today, they could point to strategies for combatting climate change.

Understanding why a user may behave inappropriately with their home heating devices, allows the possibility of mitigation. Understanding why groups of users display patterns of inappropriate home heating behaviour allow mitigation strategies to be far reaching. Such strategies could include instruction (Weyman et al., 2005, Sauer et al., 2009), automation (Stanton et al., 1997, Sauer et al., 2004, Lenior et al., 2006, Baxter et al., 2007, Larsson, 2012), simplification (Papakostopoulos & Marmaras, 2012), or various approaches of device and interface design (Williges, 1987, Weyman et al., 2005, Baxter et al. 2007, Sauer et al., 2009, Branaghan et al., 2011,).

A quick method that allows a link to be made between a user's mental model of a device and their behaviour with that device would permit a targeted approach for any of these strategies. The considerable cost and logistical issues involved in proving association (Kempton, 1987 and personal communication, 2011) was the impetus for the development of the Quick Association Check (QuACK). A quick, resource light, method for exploring association. A method of this type may provide benefits to researchers exploring the association between mental model and behaviour in other contexts and domains. QuACK focuses on the home heating context, and this method could produce insights of relevance to a broad audience including ergonomists, designers, industrial engineers, design engineers, and human-computer interaction specialists, as well as those involved in instruction, behaviour change and energy conservation.

This chapter uses Norman's (1983) definition of a 'user mental model', that is, the internal representation that is held by an individual user, and can only be understood by an analyst through some method of extraction. In this context, this reflects the analyst's description of a user's mental model, of the way the home heating system functions. The means of categorizing mental models so they can be linked to trends in user behaviour when interacting with a device,

is taken from Kempton's (1986) definition of 'shared theory'. This can be thought of as a descriptive term that groups individual user mental models by common elements.

To have confidence in the pragmatic application of mental models, an accurate description is desired but, like all knowledge structures, [is](#) difficult to validate (Rouse and Morris 1986, Wilson and Rutherford, 1989, Bainbridge 1992, Richardson and Ball, 2009, Revell & Stanton, 2012). A key problem is bias both in the access and interpretation of mental model descriptions (Revell & Stanton, 2012). A method that hopes to access user mental models would therefore improve the validity of the description by considering bias in its development. This in turn increases the likelihood of finding any association with behaviour patterns that may exist.

Hancock and Szalma (2004) emphasised the need to embrace and integrate qualitative methods in ergonomics research. Hancock et al. (2009) argue that ideographic case representations are increasingly relevant for the design of human-machine systems, particularly as advances in technology begin to focus on exploiting individual differences. According to Flyvbjerg (2011), meaningful insights (that would be missed from context-independent findings), can be gained from rich data gathered from detailed, real life situations. In response, QuACK was developed using case studies and participant observation as methods that provide rich feedback. This feedback was used to drive iterative developments to the prototypes.

QuACK comprises interview instructions, a participant information sheet, interview script and self-report template. This chapter sets out to: 1) Describe the methods used for the development of QuACK prototypes 2) Demonstrate how qualitative methods resulted in iterative improvements to QuACK, and 3) Describe the results of initial reliability tests. In addition, the benefits and pitfalls of the method are discussed, its generalizability is touched upon and how insights gained from applying QuACK could inform energy conserving strategies is explored.

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## **4.2 Methods used for the development and evaluation of QuACK**

Figure 28 shows the stages in the development process of Quack, which is broken into 3 parts: 1) Prototype development (derived from theory & literature), 2) Qualitative iterations (by applying the prototype method, reflecting on issues and implementing changes), and 3) Reliability testing (for self-report of behaviour and categorization of outputs). To encourage flow, each of the stages of development will be described in turn, broken down according to the different cells in Figure 28. The relevant section headings have therefore been added to Figure 28 to aid navigation. The starting point was a literature review seeking previous work related to the association and categorisation of users models and behaviour both in general, and specifically with home heating systems. Methods, questions and probes considered appropriate for the home heating context, and shown to be successful in previous studies contributed to the QuACK prototype. An iterative approach was adopted to refine QuACK, through qualitative methods such as participant observation and case studies. Finally, initial reliability tests were undertaken to instigate validation of the method.

The Quick Association Check (QuACK) Development

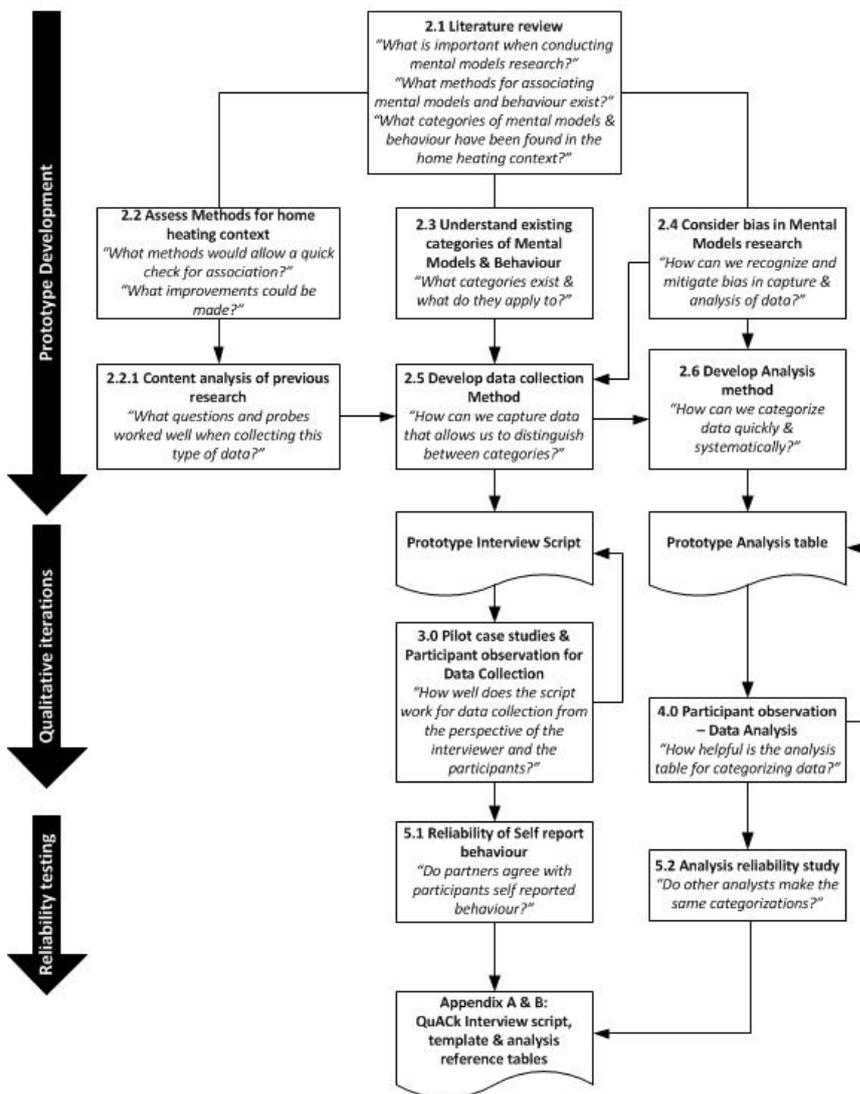


Figure 27 - Process for method development of the Quick Association Check for home heating (QuACK)

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#### **4.2.1 Literature review**

The Human Factors and cognitive science literature was reviewed with 3 objectives: 1) to understand key considerations when conducting mental models research, 2) to identify existing methods for accessing mental models associated with behaviour, and 3) to identify existing categories of mental models and behaviour patterns relating to the home heating context. The conclusion of the first, was identification of the need to consider bias in data collection and analysis methods, culminating in the development of the “tree-ring method” for depicting bias in mental models research (see Revell & Stanton, 2012 for a comprehensive debate and examples of applying the tree-ring method). The outcome of the second was used to determine the form of QuACK as well as to identify relevant questions and probes for content analysis (see section 4.2.2). The results of the third were used to form hypotheses for association and to understand the differences between existing categories of models and behaviour in the literature (see section 4.2.3). These differences were used to inform data collection on appropriate variables and to aid development of an analysis table for distinguishing between categories (see section 4.2.6).

#### **4.2.2 Assessing the suitability of methods for associating mental models with behaviour for the home heating context**

The literature review failed to yield a quick and easy means for exploring mental models and behaviour. However, Rouse and Morris (1986) provided an excellent review of data collection methods for identifying mental models associated with actions, culminating in a succinct generic categorisation of method types. Using this categorisation, and seeking more recent work that fell within these groups, these methods’ appropriateness for understanding user mental models of home heating and associated behaviour of home heating, was assessed. The behaviour considered was a typical week in the [naturalisticrealistic](#) domestic setting, as this allowed direct comparison with Kempton’s (1986) behaviour pattern examples. The ease and time taken to collect data, the ease with which data could be analysed to explore association,

and the costliness of the approach, were considered. The results of this evaluation are shown in Table 4.

Table 5 - Methods for identifying mental models associated with behaviour by Rouse & Morris (1986), evaluated for the domestic home heating context, based on speed, ease and cost of data collection and analysis.

Method types identified by Rouse & Morris (1986)	Ease of data collection for home heating context	Time taken to collect data in home heating context	Ease of data analysis for home heating context	Estimated Cost in home heating context
Inferring characteristics via empirical study	Technical expertise and access to dwellings required to collect 'actual' set point data.	Real-time data collection necessary (1 week to 3 months) but data from multiple households can occur simultaneously.	High data volumes require extensive processing before analysis. Behaviour as sole variable open to bias.	High cost of data collection equipment , installation & support and analysis.
<i>(Inferring model held by measuring related variable, in controlled experiment e.g. Kessel and Wickens, 1982, Mathieu et al., 2000, Langan-Fox et al., 2001, Sarter et al., 2007)</i>				
Empirical modelling	Complexity of home heating context and human behaviour within it, requires representation of multiple variables to prevent actions being attributable to alternate explanations.	To collect <del>naturalistic</del> realistic data to enable accurate modelling real-time data collection necessary (1 week to 3 months) but data from multiple households could occur simultaneously.	High data volumes require extensive processing before analysis. Behaviour as sole variable open to bias.	High cost of data collection equipment , installation & support and analysis.
<i>(Algorithmically identifying the relation between users perceptions &amp; actions - only possible in simple scenarios, where user perceptions can be assumed, and resulting actions have not alternate explanations e.g. Jagacinski and Miller, 1978)</i>				

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Method types identified by Rouse & Morris (1986)	Ease of data collection for home heating context	Time taken to collect data in home heating context	Ease of data analysis for home heating context	Estimated Cost in home heating context
Analytical modelling	Technical expertise and access to dwellings required to collect 'actual' set point data.	Real-time data collection necessary (1 week to 3 months) but data from multiple households can occur simultaneously.	High data volumes require extensive processing before analysis. Behaviour as sole variable open to bias. Kempton 's (1986) examples could be used if better specified for systematic categorization.	High cost of data collection equipment , installation & support and analysis.
<i>(Using theory/data to assume the form of different mental models, then comparing these 'model' forms to user performance e.g. Anderson , J.R, 1983, Yakushijin &amp; Jacobs, 2011)</i>				
Verbal protocol	Imprecise to collect naturalistic/realistically in home heating context, as behaviour is unscheduled and occurs over long time periods. Subject requires training and method for recording needed.	1 week minimum but may not provide typical behaviour depending on external weather conditions	Lengthy transcription and analysis times. Kempton 's (1986) examples could be used if better specified for systematic categorization.	Minimal (pen, paper, audio recording device)
<i>(Transcript of subject "Thinking aloud" as they perform a task e.g. Rasmussen &amp; Jensen, 1974, Norman, 1983, Greene &amp; Azevedo, 2007, Ball &amp; Christensen, 2009)</i>				
Interviews/questionnaires	Can be performed anywhere with minimal equipment, and does not need to occur during task performance	Controlled by length of questionnaire/interview (typically less than 2 hours per subject)	Lengthy transcription and analysis times can be influenced by design of interview/questionnaire. Kempton 's (1986) examples could be used if better specified for systematic categorization.	Minimal (pen, paper, audio recording device)

Method types identified by Rouse & Morris (1986)	Ease of data collection for home heating context	Time taken to collect data in home heating context	Ease of data analysis for home heating context	Estimated Cost in home heating context
<i>(Analyst asks participants about what they think and how they behave, either verbal or written e.g. Hutchin, 1983, Kempton, 1986, Stanton &amp; Young, 2005, Schoell &amp; Binder, 2009)</i>				
Key: (Suitability to method aims)		Well Suited	Moderately suited	Poorly suited

From Table 4, Interviews and questionnaires were identified as the most suitable method type to achieve the goals of this thesis, with recognition of the need to clarify and reduce the time for analysis. The literature was then searched to identify options for the format and structure and content of the questionnaire, providing the data for content analysis described in section 4.2.2.1.

#### 4.2.2.1 Content analysis of questions and probes

The work of Kempton (1986, 1987) and Payne (1991) both have high citation ratings and consider the mental models of everyday devices. As such, they were selected as a credible and representative sample of questions and probes for eliciting the mental models of domestic devices. The transcripts and questions provided in these texts were content analysed by question type, subject and inferred purpose for capturing mental model descriptions. These are summarised in Table 5 below and informed the choice of questions and probes in the QuACK prototype, which used all question types, but was predominantly made up of open questions, direct questions & scenarios.

Additional considerations were made in the choice of probes. Firstly, Oppenheim (1992) emphasised how the data from hypothetical questions should be treated with care. To distinguish between typical, possible, and hypothetical scenarios, the participants were asked how likely each scenario was for their lifestyle. This allowed the data to be assigned the appropriate validity, if more in depth analysis of the transcripts was desired (see chapter 3 for an example of in depth analysis of user mental models of home heating using data collected by QuACK). Secondly, although Kempton (1986) suggested analogies to his participants as an example that they could confirm or dispute, it was felt this added a risk of bias that encouraged the participant to reframe their mental model in a form that was easy for the analyst to categorize. However, as Payne (1991) emphasized how analogies were frequently used by

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participants to describe their thinking, a direct question, rather than a leading question was used to illicit analogies i.e. “Can you think of any other device that works in the same way” rather than “Does the thermostat work the same way as a gas stove”.

#### 4.2.1 Comparing Categories of Mental Models and Behaviour Patterns

Kempton (1986) identified two key ‘shared theories’ of home heating, which he termed ‘feedback’ and ‘valve’. Norman (1988) expanded these to include ‘timer’ and Peffer et al (2011) refer to a ‘on/off switch’ model. Richardson & Ball (2009) provides useful descriptions of valve, timer and feedback theory (with the latter ambiguously labelled a ‘switch theory’). These and Peffer et al’s switch theory, are summarised in Table 6, relating specifically to the thermostat as the key device to control home heating.

Table 6 - Table summarising the subject and purpose of probes used in Kempton (1986) and Payne (1991)

Question Type	Topic of enquiry	Purpose to assist data collection for mental models
<b>Direct question</b> e.g. “How does the thermostat work?”	Device within a system	Variables which influence device function
	Device function	Model of how a device works
	impact of time	Cause and Effect in mental model
	Dependencies	Cause and effect in mental model
	Experience with device class	Source of mental model
<b>Open Question</b> e.g. “Why does the boiler turn off?”	All subjects	Reduce interview bias
<b>Scenarios</b> e.g. “it’s a cold day and you want to warm up, what do you do?”	Typical	Likely behaviour, experience of consequences of behaviour
	Possible (speculation)	Reasonable speculation about behaviour, or consequences of behaviour (from which mental models could be inferred)
	Unusual/Hypothetical (speculation, own behaviour, consequences of behaviour)	Speculation about behaviour or consequences of behaviour (from which mental models could be inferred)
	Varying conditions	Determining if mental model is influenced by specified variables
<b>Leading questions</b> e.g. “ you mean the thermostat	Suggesting Analogies	Checking analysts understanding of subjects mental model
	Suggest reasons for response (to be confirmed or	Check if variables of interest to analyst are significant, or facilitate the participant if

<b>works like a gas stove?</b>	otherwise by participant)	having difficulty articulating response
	Providing options	Categorize response with regard to areas of interest to the analyst.
<b>Other techniques e.g. "Uh- huh"</b>	Reassurance/Encouragement	Reduce social bias
	Checking	Verify understanding
	Gauging importance	Verify significance of response to mental model held
	Paraphrase / summarise	Allow opportunity for participant to accept or correct interviewers understanding

Table 7 - Description of mental model categories of home heating from the literature

<b>Thermostat theory</b>	<b>Description</b>
<b>Feedback</b>	Turn the thermostat up and the heating stays on at full power until the temperature set is reached, then switches off (Richardson & Ball, 2009)
<b>Valve</b>	Turn the thermostat all the way up and heat of a greater temperature is produced such that the room will get warmer faster (Richardson & Ball, 2009)
<b>Timer</b>	Turn the thermostat up and the heating will stay on at the same temperature for a greater proportion of time (Richardson & Ball, 2009)
<b>Switch</b>	Turn the thermostat sufficiently up, the heating will turn on. Turn the thermostat sufficiently down, the heating will turn off (inferred from Peffer et al. 2011)

Kempton (1986) hypothesised the behaviour patterns associated with feedback and valve mental models of home heating. These patterns were based on thermostat set point controls over a week period. Kempton (1986) proposed that users with a valve shared theory, considered changes in the set point of their thermostat to be controlling the intensity of heat in their furnace (rather than maintaining a specific house temperature), so they felt the onus on them to ensure a comfortable home temperature. He anticipated valve behaviour patterns to show frequent, irregular adjustments to the thermostat, and low settings over-night to save energy. Conversely, Kempton (1986) described users with a feedback shared theory, considered their responsibility merely to select the desired thermostat set point to ensure a constant house temperature, and the system would take care of the rest. He expected

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feedback behaviour patterns to show infrequent, regular adjustments to the thermostat, as changes only needed to be made in line with changes to occupants' activities. Kempton (1986) provides example outputs of thermostat set point changes over a week period to illustrate the expected difference between users with valve and feedback mental models of their domestic heating system. The literature did not provide illustrations or descriptions of long-term behaviour patterns associated with switch and timer mental models, however. The four categories of mental model and two categories of associated behaviour patterns were used as a basis to: 1) Infer behaviour patterns for the remaining categories, 2) Identify the criteria that distinguishes between categories. To help explore association between users models of home heating and their associated behaviour – these patterns and criteria would be used to aid development of probes and templates for data collection (see section 4.2.5), as well as populate an analysis reference table for categorizing mental model and behaviour pattern outputs (see section 4.2.6).

#### 4.2.2 Bias reduction

The literature review identified bias as a key issue when conducting mental models research. The tree ring method (described in chapter 2) was developed to consider bias when evaluating methods for capturing and analysing mental models. This method was applied to Kempton (1986) and Payne (1991), as their approaches for mental model access was relevant in terms of the source, intermediaries and recipient, to the proposed form of QuACK. The bias rings identified are described in [Chapter 2 and Revell & Stanton \(2012\)](#) and relate to :1) The background experience of both the analyst and participant, 2) The social expectations and means of communication of both the analyst and participant, 3) The structure of cognitive artefacts used in the interview, and 4) The method of analysis of cognitive artefacts. These types of bias, and the strategy for mitigation or clarification, informed the choices made during the development of the QuACK prototype (see Table 7). In addition, the generic advice provided in Oppenheim (1992) on reducing bias in interview design [were was](#) incorporated.

Table 8 – Bias Rings identified in the collection and analysis of data derived from interviews, their cause and the mitigation strategy employed in the development of QuACK prototype.

Identified bias ring	Cause of bias	Strategy for mitigation or clarification
Background (participant and analyst)	<ul style="list-style-type: none"> <li>• Previous experience with heating devices, formal knowledge of energy, thermodynamics, heating systems, attitude to using heating</li> </ul>	<ul style="list-style-type: none"> <li>• Add questions and probes to gather data on background experience so responses can be viewed in this context.</li> <li>• Analyst answers questionnaire to clarify own background bias.</li> </ul>
Social (means of communication)	<ul style="list-style-type: none"> <li>• Participants' anxiety or embarrassment about incorrect, inappropriate or inconsistent answer.</li> <li>• Analysts' assumptions about meaning of responses, or accidentally leading the participant.</li> </ul>	<ul style="list-style-type: none"> <li>• To reduce anxiety &amp; encourage free dialogue: <ul style="list-style-type: none"> <li>- Careful positioning of the purpose of the interview and the desired responses</li> <li>- Provide opportunity for participant to make changes to response</li> <li>- Provide opportunity for participant to assign confidence level to responses</li> </ul> </li> <li>• Follow recommendations by Oppenheim (1992) to reduce bias caused by interviewer when conducting structured interviews</li> </ul>
Cognitive Artefact	<ul style="list-style-type: none"> <li>• Pre-prepared terms or template for mental model construction biasing the responses given by the participant</li> </ul>	<ul style="list-style-type: none"> <li>• No pre-prepared templates (e.g. blank paper, post-it notes, pen)</li> <li>• Terminology for components initiated by participant</li> </ul>
Social (method of analysis)	<ul style="list-style-type: none"> <li>• Inaccurate data from which to form the basis of analysis due to leading, spontaneous construction of model during interview, or misinterpretation of responses</li> <li>• Data misinterpreted if analysed an extended time after the interview, or data is ambiguous</li> <li>• Data unable to be compared and categorized if they contain different data elements</li> </ul>	<ul style="list-style-type: none"> <li>• To promote accurate interpretation: <ul style="list-style-type: none"> <li>- Record interview to help interpretation after extended time</li> <li>- Clear focus of content sought for outputs</li> <li>- Key outputs presented in a concrete, meaningful, unambiguous form to aid categorization without further transformation</li> <li>- Verification step by user when outputs complete to identify credible/less credible data</li> </ul> </li> <li>• To promote accurate data: <ul style="list-style-type: none"> <li>- Follow recommendations by Oppenheim (1992) to minimize leading.</li> <li>- Paraphrasing to check meaning of responses to promote accurate data</li> <li>- Multiple opportunities for participant to make changes to outputs to reflect their true meaning.</li> <li>- Record interviews to allow posthumous analysis of spontaneous construction following techniques by Payne (1991)</li> </ul> </li> <li>• Add probes during paper-based activities to encourage data elements required for comparison</li> </ul>

#### 4.2.3 Developing data collection method

Figure 28 shows how development of the data collection method was influenced by: 1) considerations of bias, 2) understanding of existing

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categorizations associated with home heating, and 3) informed by content analysis of questions and probes of previous research. The components of the prototype are shown in Figure 29. The format of the prototype comprised a semi-structured interview, and involved 2 paper-based activities that required only pen, paper & post-it notes to undertake. A voice recorder was also used to record the participants' responses to allow more in depth analysis if needed. This fulfilled the aim of QuACK to be a 'resource-light' method. The questionnaire prototype was just over 3 A4 pages, and was intended to take up to 1 hour to complete, including the activities. For this type of data capture, the author considered this quick in comparison to alternatives. In-depth interviews, user behaviour diaries or the set-up of behaviour monitoring equipment, can take considerably longer, and would not provide data in a format ready for analysis. The primary aim of QuACK was to allow exploration of association between user mental models of home heating function and user behaviour with home heating systems. Figure 29 shows that the key outputs of the method are a mental model description of device function and a behaviour pattern representing the self-report of home heating use.

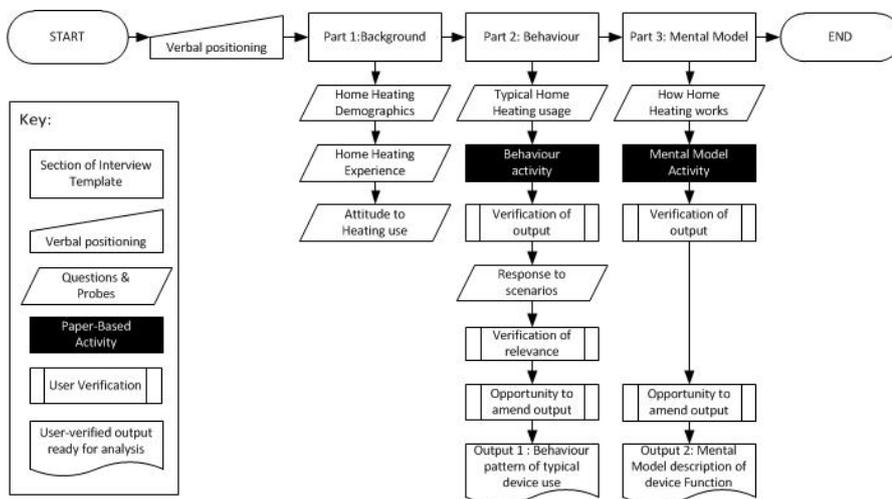


Figure 28 - Components of QuACK Prototype

#### 4.2.3.1 Paper Based Activities

Two paper based activities were included in the QuACk prototype. The first was a self-report of home heating use, the second the development of a mental model description of the way the home heating system functions. For the quick exploration of association, it is beneficial that the outputs are in a form ready for analysis. The activities were designed to produce the desired form of output in conjunction with the participant, allowing them to verify the content before the end of the interaction. This reduced the risk of bias in interpretation by the analyst as additional transformation of the outputs was not required. The structure of output 1 (behaviour pattern of typical device use) was designed to match the format produced by Kempton (1986) by showing changes in thermostat adjustment over a weekly period so anticipated patterns of use could be easily identified. The prototype initially required the week axis to be produced with pen & paper, but eventually evolved into a template axis which could easily be annotated (see Figure 30).

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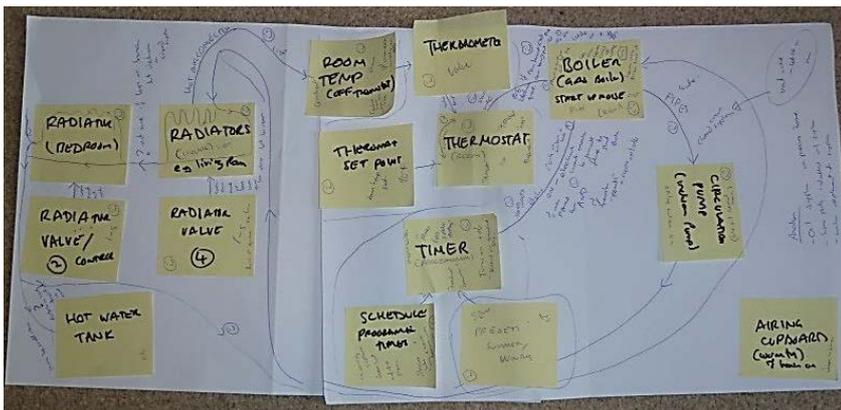
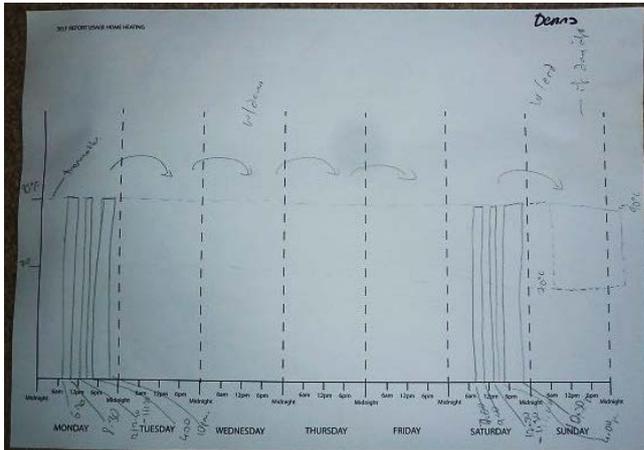


Figure 29 - Example of QuACK outputs: (LeftTop) template with annotated self-report of home heating use. (RightBottom) user mental model description of home heating function

#### 4.2.3.2 Verification of outputs

From Figure 29, the emphasis on user verification is clear. Opportunities for the participant to make adjustments as a type of verification, has been offered as a type of variation, as it results in data that better reflects the participant's intention, than the expectations of the analyst. The emphasis on user verification is considered to be a distinct characteristic of QuACK that is given

minor prominence in existing methods in the literature. In addition to opportunities to amend responses, the QuACK prototype required the participants to deliberately assign a level of confidence to each information component of the outputs. This was added to help the analyst understand the credibility of any association (or lack of association) identified from analysis of the outputs alone. The process of output verification required the interviewer to paraphrase each element of the output in turn. The participant was asked to comment if this reflected what they imagined/thought (in which case a 'smiley' icon was added to that element), if they wished to amend what was represented (the amendment would then be made and a 'smiley' added), or if they felt they were uncertain if this reflected what they really thought (in which case a '?' was added next to the component). Examples of this annotation can be seen in Figure 30. The structure of output 2 (mental model description of device function) is generic and would suit contexts outside of the home heating domain. The format was based on the mental model diagram by Payne (1991), the insight by Gentner and Gentner (1983) with regards to structure mapping and the emphasis by deKleer and Brown (1983) on components and conduits in mental model descriptions. The output ~~and~~ has similarities to a concept map, but includes written rules and causal links. To produce this output, post-it notes, a pen and an A3 blank paper were needed (see Figure 30).

By applying qualitative methods, the method evolved to comprise a participant information sheet, interviewer instructions, interview template (Appendix 1), self-report activity template, and mental model of home heating function activity. The iterations that led to this evolution ~~is~~ are described in section 4.3.0.

#### 4.2.4 Developing analysis method

A key feature of QuACK is a means to quickly explore association between mental models of device function and typical patterns of behaviour. To achieve this, it was necessary for the analyst to easily distinguish between features to categorize the outputs. Table 8 was produced by referring to the criteria that distinguished the mental model descriptions provided by Kempton (1986), Norman (1988) Peffer et al. (2011) and Richardson & Ball (2009). The role of Table 8 is an analysis aid when examining the two verified outputs of QuACK

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following completion of an interview. It is divided into 2 sections corresponding to these outputs: 1) The populated self-report template showing typical home heating use, and 2) Mental Model description of home heating function.

The criteria identified comprised: 1) the thermostat set point, 2) variations in its value and pattern of adjustment, 3) the reason for its adjustment, and 4) the role and function of related devices (e.g. boiler). For each mental model category of thermostat function (valve, feedback, switch & timer), Table 8 describes the form of the output that is expected. This is broken down by a set of criteria for each of the three outputs. Descriptions in italics represent compatible (rather than mandatory) responses that follow when a particular category of model is held. To explore association between users mental models of home heating and their behaviour, the analysis table was constructed to guide the analyst in seeking out particular behaviour patterns and mental model elements and where possible, categorizing them according to the shared theories from the literature (i.e. valve, feedback, switch, timer). The same category of shared theory found in both outputs, would suggest an association may exist that warrants further investigation.

Table 9 – Analysis reference table for quick and systematic analysis of outputs from QuACK. Each output has key criteria corresponding to the form of output expected for each category of mental model held for thermostat function.

Output	Criteria	Form of output for categorization			
		Valve	Feedback	Switch	Timer
1) Self – Report of typical home heating use	Pattern of manual adjustment	Frequent & irregular when home is occupied. <i>Influenced by events / comfort</i>	Routine adjustments to thermostat <i>Event specific</i>	Set point is stable between events <i>Influenced by events / comfort</i>	Higher settings remain unadjusted for longer periods than lower settings <i>Influenced by events / comfort</i>
	Thermostat Set points	Varies above and below internal temperature	specific temperatures	<i>Extreme high/low settings or 'until click' (i.e. 0.5oC above internal temperature)</i>	<i>Manual adjustments typically above internal temperature</i>
	Night set back	Yes	No	n/a	n/a
2) Mental Model description of Home heating function	Thermostat Set point and relationship to boiler	Variations in thermostat set point results in variations in intensity of boiler	Variations in thermostat set point inform the target room temperature to be maintained by the boiler	Increasing and decreasing the thermostat set point , activates or deactivates the boiler respectively	Variations in thermostat control results in variations in the time period of boiler operation
	Boiler function	Boiler heats water to a range of temperatures	Boiler heats water to a single temperature	Boiler heats water to a single temperature	Boiler heats water to a single temperature
	Role of thermometer	n/a	Thermometer feeds back temperature value so comparison with thermostat set point can be made to determine if the boiler needs to come on or off	n/a	n/a

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### 4.3 Pilot case studies & participant observation

To gain an insight of the flexibility of the prototype, variations in age, gender, house type and living circumstances were sought (detailed in Table 9). The initial participant was selected based on availability to provide feedback on clarity, ease of answering questions, undertaking activities and the participant experience (in terms of the social interaction and feelings). The target audience for participants was long term UK residents with equivalent home heating setups (comprising gas central heating, combi-boiler, radiators, separate thermostat and programmer). Casual discussions with the target audience group regarding their behaviour when using their current central heating system formed the selection process to identify participants who reported distinct behaviour patterns. Deliberate efforts were made to identify participants from wide ranging demographics and types of dwelling, to encourage the development of a robust method that could cope with the variations inherent in the UK population. Adjustments were made to the script following feedback from each participant. ~~This meant such that each each subsequent participant subsequent participant exper~~experienced an improved version ~~of the script.~~

The interviewer provided feedback as a 'participant observer' to evaluating the ease with which the QuACK prototype could be applied to the different case studies. The findings from both the case studies and observations were applied iteratively such that an improved version of the prototype was used on each successive case study. The resulting components and process which form QuACK are shown in Figure 31. This diagram illustrates how processes such as positioning, verification, question review and opportunities to amend outputs are core elements of the interview process. It is essential that these are undertaken to increase the quality of the data gathered through questions, probes and activities.

Table 10 - Table to show the iterations to QuACK resulting from case study and participant observations (round bullets reflect amendments to method, dash bullets identify aspects that worked well).

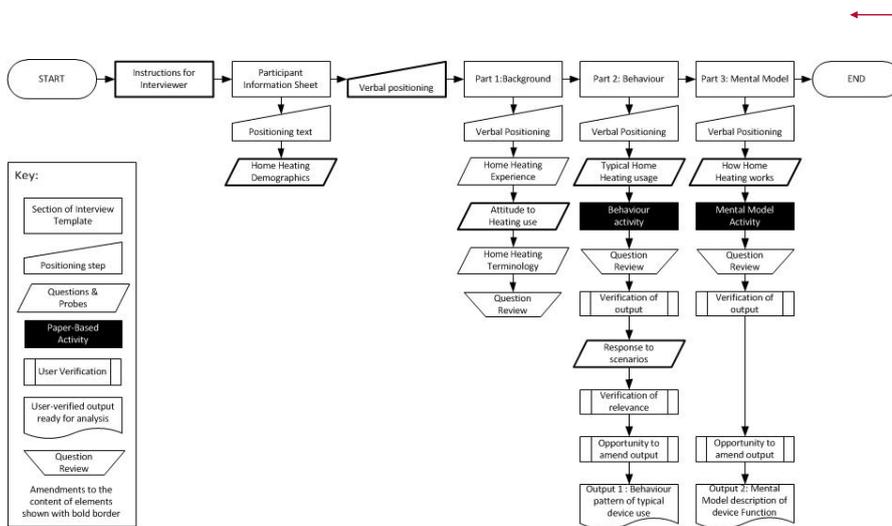
Participant	Key Feedback & Amendments
<p><b>Participant 1</b></p> <p>51 year old working male, living with a young family in a 4 bedroom detached bungalow with 5 different heating systems</p>	<ul style="list-style-type: none"> <li>• Reiterate the purpose of the interview and expectations at the beginning of each section.</li> <li>• Add a 'terminology section' in the background section to define the elements in the function section as well as improve understanding</li> <li>• Limit 'drilling down' to areas that are key for distinguishing between categories, or if the participant appears to be uncomfortable.</li> <li>• Verbalise during <del>that</del> the attitude section that the study is non-judgemental and not aligned to a particular attitude about energy use, and improve the wording.</li> <li>• Change the wording of the analogy questions in the device function and system activities so a response is not mandatory, put at the end of each section.</li> <li>• For cases where multiple heating systems exist, focus interview on the main central heating system.</li> <li>• To avoid embarrassment from answering personal questions – 1) move demographic section out of the interview and provide in paper based format for the participant to fill in prior to the interview, and 2) allow selection of age range instead of asking for an actual value.</li> </ul> <ul style="list-style-type: none"> <li>– <i>Paraphrasing worked well and should be used throughout</i></li> <li>– <i>The requirements of the self-report activities were easy to grasp after a few parts had been drawn out.</i></li> </ul>
<p><b>Participant 2</b></p> <p>25 year old working female, living alone in the week, &amp; with spouse at weekend</p> <p>Session time: 30 mins</p>	<ul style="list-style-type: none"> <li>• Refer to target temperatures as 'a comfortable temperature' rather than providing a specific value, as people vary in their idea of a comfortable temperature.</li> <li>• At the start of the interview, verbalise to the participant <del>the</del> that the interviewers' expertise was on data collection, not the workings of home heating systems, so any verbal or facial cues would not relate to the accuracy of their answer.</li> <li>• Take care not to lead the participant when linking elements during the function activity.</li> <li>• Add a template to the 'self-report' of behaviour section, to speed up data collection.</li> <li>• Add instructions to interviewer to review questions at end of each section.</li> </ul> <ul style="list-style-type: none"> <li>– <i>Reiteration of purpose of interview was welcomed by participant and not considered repetitive or patronising</i></li> <li>– <i>Moving demographics to pre-interview questionnaire filled in by participant worked well</i></li> <li>– <i>Addition of terminology section at start of the interview, enabled a more 'dynamic' tailoring of the interview script which improved understanding &amp; engagement</i></li> <li>– <i>Change to analogy question removed pressure on participant to "come up with something"</i></li> </ul>
<p><b>Participant 3</b></p> <p>64 year old working female living in a four story Victorian terrace with spouse</p>	<ul style="list-style-type: none"> <li>• Verbalise to the participant at the start and throughout, that inconsistencies are normal and may be useful for research purposes. Take care not to demand consistency in participant responses, by referring back to things they have said previously, that contradict new responses.</li> <li>• Produce instructions for the interviewer at the start, and throughout the interview, to help keep on track.</li> </ul> <ul style="list-style-type: none"> <li>– <i>Instructions to interviewer at points within script were helpful for keeping on track</i></li> <li>– <i>Self-report template was a good format for recording behaviour with a variety of devices</i></li> <li>– <i>Self-report template was a good format for recording how many people in the home control the heating, which devices they tend to use, and when they tend to use them.</i></li> </ul>

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Participant	Key Feedback & Amendments
<p><b>Participant 4</b> 87 year old retired male living alone in a semi-detached house. Session time: 92 minutes</p>	<ul style="list-style-type: none"> <li>• Advice in instructions to interviewer, that older participants have specific attributes that may require an adjustment in interview style, e.g. may wander off subject and require steering back to the question, are likely to talk about temperature in °F rather than °C, may respond to questions about home heating function as if they are expected to 'teach' the interviewer rather than 'explain' their understanding.</li> <li>• Advice in instructions to interviewer, that different degrees of knowledge about will affect the interview time</li> <li>• No further changes to the format or approach of QuACK</li> <li>– <i>Instructions to interviewer were useful for orienting and keeping on track</i></li> </ul>



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Figure 30 - A diagram to depict the key elements of QuACK, emphasising the importance of positioning, verification and opportunities for amendment in addition to the data types derived from questions and probes.

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## 4.4 Participant observation – data analysis

With outputs in a form ready for analysis, the next requirement is a quick and clear process of analysis, which can be applied ‘on-the-fly’. This section will 1) illustrate how the analysis reference table (Table 8) could be applied, 2) discusses the benefits of the form of outputs, 3) summarises the utility of the analysis table as a means for categorizing home heating mental models and behaviour patterns, and, 4) identifies changes to the analysis table that could improve its utility.

### 4.4.1 Applying the analysis reference table

Hancock et al. (2009:486) argue that focus on a single case study not only offers insights about that individual, but that it is also possible “*to extract regularities and even generalities*” to the broader population. Participant 3 was highlighted to illustrate the analysis method, as they held a variety of model types and reported a variety of behaviour patterns (encompassing those depicted by participants 2 and 4). This provided an opportunity to illustrate a range of categories with one example.

#### 4.4.1.1 Behaviour pattern

Participant 3 was a 64 year old female living in a four story Victorian terrace with her spouse. Both occupants worked full time. The populated self-report template for typical behaviour when using the home heating system is shown in Figure 32, (redrawn for clarity). The key in Figure 32 identifies three different device used to control the heating (programmer, thermostat and boiler override). It also shows that these were operated by two agents (the participant and her spouse). The participant was not sure of exact set points for the thermostat so the scale displays ‘approximate’ temperature values.

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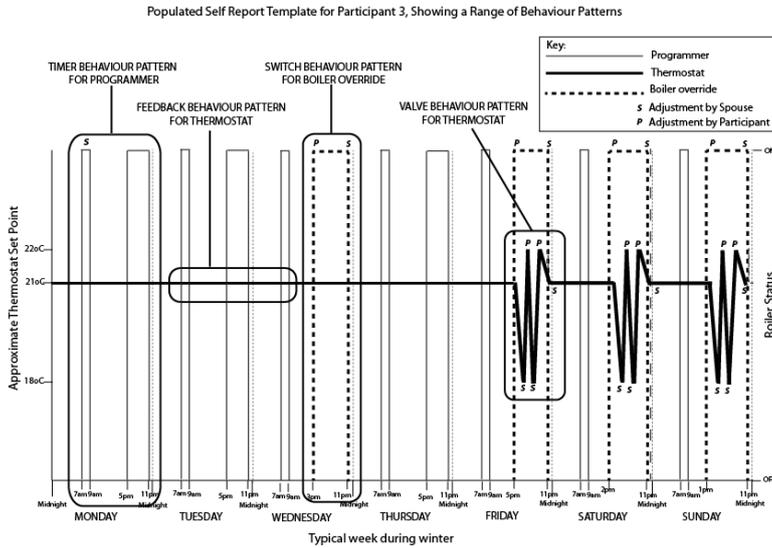


Figure 31 - Output 1 from QuACK, redrawn for clarity, showing “Behaviour when using home heating over a typical week”

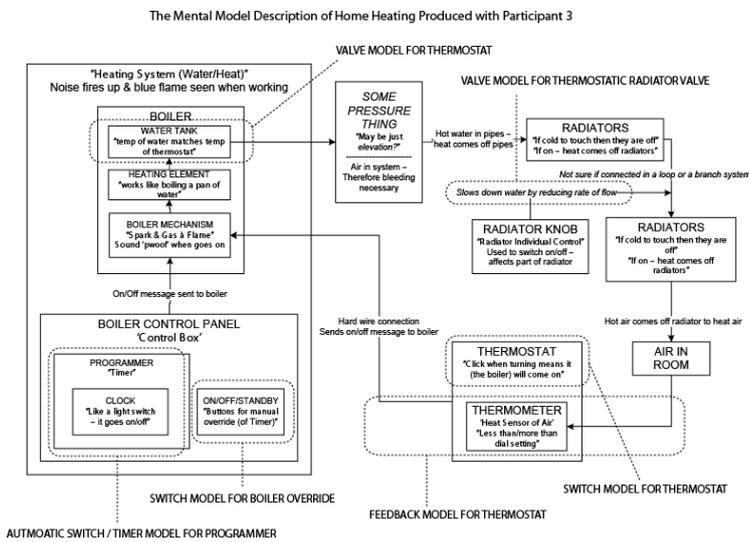


Figure 32 - Mental Model description of device function for Participant 3, redrawn from Output 2 for clarity

Referencing Table 8, and interpreting the contents for multiple control devices, different behaviour pattern categories have been highlighted in Figure 32. The most distinctive pattern is a 'valve' category assigned to the thermostat during the weekend. This pattern complies with the criteria in Table 8 as there are frequent, irregular manual adjustments when the home is occupied, with the set points varying above and below the (presumed) internal temperature. It is not clear, however, if night set-back is adopted as adjustments at the end of the day were undertaken by the spouse, so the participant could not recall the set point chosen. During the working week, the thermostat set point remains at a single setting, and the programmer is responsible for routine periods of boiler activation based around events, such as returning from work. Table 8 does not consider how the behaviour pattern of the thermostat is affected by the use of a programmer. However, the lack of manual adjustment suggested a deliberate single temperature which implies 'feedback' behaviour, if it is assumed the 'routine manual adjustment' described in Table 8 is taken care of by the program schedule. When completing the template, Participant 3 described regularly using the manual override on the boiler, particularly when returning from work early and finding the house cold, or at home over the weekend. The participant switched the boiler setting to 'on', and this remained for a number of hours, until the spouse turned it off at the end of the day (see Figure 32). Interpreting the contents of Table 8 for the boiler override control, we can categorize this as a 'switch' model, as the behaviour pattern depicts a set point that is stable between events, and extreme set points (the only set point options for this control device). Figure 32 shows 'timer' category assigned to the behaviour pattern for the programmer. This cannot easily be inferred from Table 8's description of the 'pattern of manual adjustment' of the timer category for the thermostat. However, looking at the criteria for Timer shared theory in Table 8 relating to the mental model description, the sense that variations in the settings resulted in variations of the timer period of boiler operation, was compatible to how the program settings were chosen.

#### 4.4.1.2 Mental Model description of home heating function

The mental model description of home heating function, for participant 3 has been redrawn for clarity (Figure 33), and depicts a range of control devices including the thermostat, programmer, boiler override, and thermostatic radiator valves (TRV – described in Figure 33 as a "radiator knob"). Each of

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these devices have been categorized using the prototype analysis reference table (Table 8). Participant 3 was distinctive in describing the function of the thermostat differently as the interview progressed, resulting in 3 descriptions and categorizations for the thermostat. This characteristic provides an opportunity to discuss different ways of categorizing the thermostat from one mental model description, as well as drawing attention to the reader that a participant may have multiple, contradictory models for a single device. A switch category from Table 8, was assigned as participant 3 described how the boiler came on if you turn the thermostat until it 'clicks' (Figure 33). This matches the statement in Table 8, relating to the thermostat set points (in the self-report of behaviour section). It also conforms to the criteria for the relationship between the thermostat set point and the boiler for a 'switch' model. A feedback category was assigned to the thermostat due to: 1) the presence in Figure 33 of a thermometer, 2) its described function to sense the air temperature in the room which is compared by the thermostat to see if "less than/more than the dial setting" followed by 3) the link to the boiler with the rule "to send on-off message to the boiler". This describes the thermostat set point and relationship to the boiler described in Table 8. Table 8 requires ~~that for~~ the boiler function in feedback or switch models, ~~that for~~ water ~~to be~~ ~~his~~ heated to a single temperature, ~~which~~. ~~This wasn't met the case~~ in Figure 33, ~~however~~. When discussing the boiler, a valve model of the thermostat was indicated, participant 3 described "the temperature of the water [in the boiler] matches the temperature of the thermostat" (Figure 33). This fits Table 8's requirements for a valve model, in terms of the boiler function, as well as the relationship between the thermostat set point and the boiler (Table 8), although the presence of the thermometer does not comply with 'valve' shared theories.

The mental model of device function is more consistent for the programmer and boiler override - both devices that participant 3 depicted in their self-report of behaviour output. Figure 33 shows the programmer is referred to as a 'timer' and has a 'clock' component to determine when the boiler comes on. From Table 8, we see the relationship between the thermostat at the boiler for a timer model, requires variations in the thermostat control (or in this case,

programmer settings) to result in variations in the time period of the boiler operation. These led to the categorization of the user holding a 'timer' model for the programmer. However, participant 3 also uses the analogy "*like a light switch, it [the boiler] goes on and off*". Whilst this terminology may seem to indicate the 'switch category', that this description is part of the 'clock' element of the model, points to the clock is driving the activation/deactivation of the boiler, rather than the user. This reconfirms the 'timer' categorization. As with analysis of output 1, by making the substitution of the control device in the description provided in Table 8, it is possible to infer relevant shared theory types for different devices. In Figure 33, the boiler override<sub>1</sub> is simply described as an 'on/off/standby' switch, and is linked to, and has the capacity to activate/deactivate, the boiler. Again, by substituting the control device in the description in Table 8, from thermostat to boiler override<sub>1</sub>—this is equivalent to the 'switch' shared theory description for the relationship between thermostat set point and boiler. Table 8 also requires, however, that for users with a switch theory, the boiler should function by heating the water to a single temperature (which was not evident in Figure 33). However, the variations in boiler temperature are clearly shown in the diagram as relating to the thermostat, not other control devices, so a switch categorization is still valid for the boiler override.

Figure 33 also depicts participant 3's description for the function of thermostatic radiator valves. They describe the purpose of the radiator knob to "switch [the radiator] on/off", suggesting a 'switch' category, however, the transcripts indicates this description reflects how participant three uses them, rather than her belief about their 'intended' purpose. The lack of thermometer element depicted by the TRV, and the rule describing how (shown on the link between this control and the radiator in Figure 33) "*slowed down the water [to the radiators] by reducing the rate of flow*" can be inferred from Table 8 to suggest a 'valve category'. By substituting the control device, the affected component, and the variable, the description intended for the thermostat control's relationship to the boiler, could be rephrased as "Variations in the *radiator knob* [control device] set point results in variations in the *water flow* [variable] of the *radiators* [affected component]".

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#### 4.4.2 Benefits of output formats

##### 4.4.2.1 Self-Report diagram

The format of the self-report template had a number of benefits. Firstly, it was flexible enough to incorporate in a single view, a variety of behaviour patterns from a range of control devices. This would be difficult to achieve from existing automated data collection solutions. Secondly, the ability to assign different agents to different aspects of the behaviour patterns was illuminating. From the perspective of exploring mental models, the 'valve' pattern shown in Figure 32 clearly represents a 'conflict of setting choice' rather than considered continuous adjustment to ensure a comfortable house temperature (as described by Kempton (1986)).

##### 4.4.2.2 Mental Model description

The mental model description is useful at identifying misunderstandings about how the home heating system functions in a way that is concrete and explicit. For example, key elements of the heating system may be missing, elements may be inaccurately linked, and the rules of cause and effect between elements may be incomplete or inaccurate. [In Chapter 3, Revell & Stanton \(2013, 2014\)](#) provide examples of in depth analysis of mental model descriptions created by the QuACK method. It also explains how the insights gained can inform strategies intended to encourage behaviour change, or reduce energy consumption through the use of home heating.

The case study of participant 3 described an inconsistent mental model of the thermostat, yet clear and consistent (though not necessarily accurate) representations of other control devices. The ability of this output to identify inconsistent mental models has benefits. Inconsistent descriptions of function may be symptomatic of ambiguity in the communicated function of devices, or the relationships between devices. Where the ambiguity has negative consequences, in terms of performance, usability, or, in this case, wasted energy consumption, identification of this ambiguity could point to design or instruction strategies to clarify function.

#### 4.4.2.3 Association between mental model of device function and behaviour

The results of the analysis of verified outputs for participant three, shows a range of behaviour patterns and a range of mental models held. Purely based on the categorisation, there is evidence of both valve and feedback mental models and behaviour patterns for the thermostat. This may suggest an association between behaviour and mental models for this participant. The case study presented described behaviour patterns that, unlike Kempton (1986), included other control devices (e.g. boiler override, programmer, thermostatic radiator valves (TRVs)). Any exploration between behaviour patterns and mental models of devices requires the same device to feature in both outputs, which was not always the case in the pilot study. However, as output 1 only considered 'typical' behaviour over a week, irregular behaviours, such as adjustment of TRV's may occur less than this, explaining their absence. To consider an association with irregular behaviours, the format of the template to record behaviour, would need to be adjusted.

Caution should be applied to conclusions regarding association from these outputs. For example, as evident from multiple agents being identified on output 1 from the case study, the valve 'pattern' does not necessarily reflect valve behaviour. If viewed through automated data collection, without assignment of agents for different aspects of the behaviour patterns, it could have been mistaken as such. Another example, was seen in the categorization of the TRV in output 2. The transcripts indicated that the participant used the device as a 'switch', even though they thought the device functioned like a 'valve'. User behaviour with this control device, was not primarily caused by their mental models of device function. The source of behaviour may represent a workaround to achieve goals that could not be achieved with other control devices, or to achieve goals that were not an intended function of the home heating system (such as quick response individual room heat control).

The ability of output 1 to indicate multiple agents also helps inform further exploration of association. In Figure 32, the spouse was marked as responsible for the behaviour pattern relating to [the](#) programmer. So, to identify an association, the mental model description of the programmer function would need to be provided by the spouse.

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Evidence in both outputs indicated switch category for the boiler override, and timer category for the programmer for both behaviour and mental models. This provides support for the relevance of existing 'shared theories' in the literature for categorizing models and behaviour associated with home heating. However, this is considering the shared theories from the literature in a 'generic' sense, rather than thermostat specific.

#### 4.4.3 Evaluating the utility of the analysis reference table

By applying the analysis reference table (Table 8) on the outputs of participants 2, 3 & 4, some key insights were found that recommended improvements / adjustments. These have been tabulated in Table 10.

Table 11 - Summary of evaluation of analysis reference table

Insight from trailing analysis	Suggested change to analysis ref. table
All sections of the table were helpful when categorizing each output, suggesting the type of information captured extended beyond those expected for each output when the table was constructed. This may mean Mental models data is being used to categorize behaviour data (or vice versa), or the table doesn't distinguish between the types of data.	Make clear the key data to be analysed on each output, so that categorization can be attributed to <i>either</i> behaviour <i>or</i> mental models. Divide table into 2, so the relevant table is referenced when analysing each output.
Descriptions developed to categorize models relating to the thermostat control only. A range of control devices were evident on the outputs, requiring translation of the descriptions to a different device.	Make analysis table more applicable for outputs resulting from present day heating systems in the UK. e.g. Write descriptions to categorize model types generically, with thermostat as example.
Descriptions developed to categorize behaviour patterns relating to the thermostat only. A range of control devices were evident on the outputs, with different degrees of freedom, range and type (e.g. discrete, continuous, categorical) of input available. The expected behaviour pattern had to be inferred by the analyst, and might not be clear for all devices.	Make analysis table more applicable for outputs resulting from present day heating systems in the UK. e.g. Write descriptions to categorize behaviour types generically, with thermostat as example.
Inference of descriptions to other devices was	Define what is meant by these terms and use

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Insight from trailing analysis	Suggested change to analysis ref. table
aided by substituting either the control device, controlled element, <u>and-or</u> the change variable.	them (and others, if needed) to form the 'generic' descriptions for the table.
Outputs categorized with the same name of shared theory, but applied to different control devices represent a variation on those in the literature. The implications for behaviour patterns and the importance of performance or energy consumption may differ.	Reinterpret the shared theories of home heating use from the literature, within the framework of the generic categorization descriptions.
Sometimes data in the outputs applied to some of the category descriptions but not all. Not clear from the table if particular characteristics had greater weighting over others.	Make the table more 'granular' in its breakdown of characteristics required & provide guidance on 'critical' and 'supporting' characteristics.
Evidence of <u>a-multiple ways of describing the function of a single device within a sole mental model descriptions-with the model for a device described in variety of ways</u> . This led to multiple-, conflicting categorization.	Provide guidance that multiple categorizations of a single control device is a useful finding. It identifies where the user has an inconsistent or incomplete mental model.

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#### 4.4.4 Improvements to the analysis reference table

Appendix 2 shows the resulting analysis tables. Following the recommendations from Table 10, separate tables were created for categorizing behaviour and mental models. A generic example; was provided for each shared theory, and specific examples from the literature relating to the thermostat; were re-phrased to fit within the generic structure. The intention was to make it easier to infer shared theories from alternate devices to the thermostat.

The process for categorization of outputs involves the analysts considering each control device (e.g. thermostat, programmer, TRV etc.) separately and performing the following steps:

- 1 Identify and describe each of the elements from the table heading (control device, Input behaviour, key element, key variable, sensor/sensed variable, rule)
- 2 Compare the descriptions to the generic/shared theory descriptions in the table.
- 3 Select most appropriate category OR identify variations to closest category.

To aid this process, question sheets corresponding to each output were created, with examples of typical answers within the home heating context

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(Appendix 2). This version of the analysis reference tables, as well as the question sheets, were used in the reliability exercise described in section 4.5.2

## 4.5 Validation

The intention ~~is of~~ QuACK is to allow exploration of association between user behaviour with home heating systems and their mental models of those systems. An understanding of how well output 1 captures actual behaviour; is clearly important, as well as the ability of the method of analysis to consistently categorize outputs. This section describes initial attempts to assess measurement validity of output 1, and reliability of output categorization.

### 4.5.1 Measurement Validity of Self-Report Behaviour

The validation approach was focused around the criteria used in analysis table (Appendix 2), since the emphasis was to seek validation of behaviour characteristics relevant to users 'shared theories' or 'generic models' of home heating.

Due to the nature of the home heating domain, direct observations of home heating behaviour over week long periods of time was impractical (as discussed in section 4.2.2). To seek initial validation of output 1, the spouse of the user (where applicable) was contacted to see if they agreed with the representation provided in output 1 for their dwelling, by the user. The spouse was asked to check the set point values of control devices represented on the output (for example, programmer schedule times & thermostat set points). The author then showed and explained the pattern on output 1 and asked the spouse to express their level of agreement that this reflected their household. The author annotated the output to capture their responses, and tabulated the results (Table 11)

Table 12 - Summary of spouses agreement with behaviour shown in output 1  
(Agreement = ✓, Disagreement = ✗)

Agreement by spouse <sup>a</sup> for features of output 1	Participant A	Participant B	Participant C*
<b>Devices used</b>	✓ only boiler over ride used	✓ typically used programmer, boiler override and thermostat	✓ programmer and thermostat typically used
<b>Set points chosen</b> <b>Variations in set points</b>	✓ boiler override set to either on/off ✓ durations and times for boiler 'on' periods	✓ accurate number & duration of sessions for programmer ✓ timings for programmer reasonably accurate (±30 mins) ✓ set points for thermostat broadly correct (± 1oC) ✓ variations in thermostat set point	✓ programmer set points times & durations accurate ✓ static thermostat set point during week, and significant reduction when out for the day ✗Thermostat set point value inaccurate (actual=21oC, output 1 shows 90oF= to 32oC)
<b>Regularity, frequency &amp; synchronicity of pattern</b>	✓ weekend pattern typical (Could not verify weekdays as absent from dwelling)	✓ weekday pattern ✗extended time for override at weekend occurs typically on one, rather than both days	✓ weekday and weekend pattern
<b>Distribution of agents across pattern</b>	✓ user responsible for deactivating boiler override at weekend ✗ spouse OR user activates boiler at weekend (not spouse alone)	✓ spouse responsible for setting programmer ✓ user raised thermostat set point & activated boiler override & Spouse reduced thermostat set point and deactivated boiler override	✓ sole user of devices, responsible for all adjustments

\*Participant C was a lone occupant. He was asked to check device settings and give views on output 1 that he had constructed himself, 1 year after the original interview

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Table 11 shows that overall, spouses were in broad agreement that output 1 represented their typical weekly behaviour with the home heating system. There was full agreement for the control devices used, and general agreement with the distribution between agents, frequency, regularity and synchronicity of the pattern, as well as set point values and variations. There were some exceptions, however: Participant C, revealed a large inaccuracy with the thermostat set point value, though, this is likely to be a conversion error between units of temperature. There was also minor disagreement in terms of regularity of pattern (participant B), and distribution of agents (participant A), though these were not sufficient to alter a categorization of the pattern.

The results of this initial validation was positive in terms of the value of output 1 as an appropriate measure to categorize behaviour according to that predicted by shared theories or generic theories. If part 1 of QuACK was used to generate output 1 for other research goals, such as estimating energy consumption, or understanding the assignment of agents to behaviour, further checks may be needed if a high level of accuracy is required

#### **4.5.1.1 Reliability of Analysis method**

To test the inter-analyst reliability of the updated analysis method, two human factor analysts were asked to analyse 3 sets of output, resulting from interviews performed using the QuACK method. Their results were compared with the author's own categorization of this data to evaluate their level of agreement. The analysts were provided with: 1) 'walk through question sheets' (with examples) that guided observations of the data (see Appendix 2); 2) 'Answer sheets' for recording responses from the question sheet in a form that could easily be compared to the reference, 3) The analysis reference tables for each output (see Appendix 2) 4) Outputs 1 & 2 from each participant, and 4) Transcribed 'paraphrases' describing each output, taken from the interview transcripts. The paraphrase was provided to help orientate the analysts to the outputs. This was in recognition that an analyst using QuACK would typically have interviewed the participant and constructed the outputs, so would be fully orientated to their meaning at the point of analysis.

#### 4.5.1.2 Dynamics of exercise

Prior to analysis, the author trained the analysts in the analysis method. The outputs of participant 3, categorized with generic categories from the updated analysis tables (See Appendix 3) were used as an example and the analysts were walked through how to use the walk through question sheets, answer sheets and analysis reference tables. It was typical of output 2 to have more control devices evident than output 1. As the goal of QuACk is to explore association between behaviour and mental models, the analysts were asked only to categorize control devices on output 2 that were present, and operated by the participant, according to output 1. This resulted in 6 devices needing categorization for each output type. The validation exercise ran for 2 hours, with the training session taking up approx. 30 minutes and the categorization approximately 1.5 hours. The mean time for categorization of a single device from a single output was around 10 minutes. The analysts were only allowed to ask questions to clarify analysis method, during the exercise, but were not given guidance on the appropriate category to select.

#### 4.5.1.3 Results of inter-analyst reliability exercise

Table 12 summarises the results of the inter-analyst reliability exercise. This table shows the level of agreement with the author's analysis of the same outputs using the updated analysis tables and walk through questions.

Table 13 - Results of inter-analyst reliability exercise

Participant	Devices	Output	Author categorization	Analyst 1 Agreement	Analyst 2 Agreement
Participant A	Programmer	Output 1	Generic FB1	✗Timer (Norman)	✓
		Output 2	Generic FB1	✓	✓
	Override	Output 1	Generic Switch	✓	✓
		Output 2	Generic FB2	✓	✓
Participant B	Thermostat	Output 1	Generic FB1	✗Valve (Kempton)	✗Generic Valve
		Output 2	Generic FB1	✓	✓

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<b>Participant C</b>	Programmer	Output 1	Generic FB1	✓	✓	
		Output 2	Generic FB1	✓	✓	
	Override	Output 1	Generic Switch	✓	✓	
		Output 2	Generic Switch	✓	✓	
	Thermostat	Output 1	Generic FB1	✓	✗Generic Valve	
		Output 2	Generic Valve	✗Generic FB1	✓	
	<b>% Agreement</b>	Categorization	Output 1	67%		
			Output 2	92%		
		<b>Overall</b>		<b>79%</b>		

Table 12 shows that overall agreement with the categorization stood at 79% which was reasonable for analysts who had limited orientation to the outputs. Agreement levels in the categorization of output 2 were very good, with 92% agreement, validating the utility of analysis reference table for output 2. Analysis reference table for output 1, however, elicited lower levels of agreement with the author's categorization, at 67%. After examining the completed answer sheets provided by the analysts for the thermostat patterns for participants B&C, the following causes of disagreement were found. Analysts tended to categorize 'valve' for thermostat if reference was made in the transcribed paraphrase that set points were based on 'comfort'. The analysis table 1 explicitly describes the generic feedback category for the thermostat as based on lifestyle activities rather than comfort (taken from Kempton, 1986). However, this does not imply that comfort is not the desired goal from the set point choice, only that constant adjustments to the thermostat are not made to compensate changing comfort levels from other causes (e.g. activity levels). This distinction was not sufficiently clear in the table. The label of the category may also have encouraged a different categorization. Analyst 1 assigned a 'Timer' category (intended only for

thermostat devices) to the programmer. As the programmer is often known as a 'timer', and the description refers to variations in time, this association may have seemed more similar than the generic feedback 1 category. In addition, the descriptions in the two feedback categories may not have emphasised their distinguishing features. Only 1 mis-categorization of output 2 was found with the thermostat device for participant C. The analyst's response to 'Q1c - description of automatic adjustments' showed they misunderstood the meaning of the question. They provided the example 'it sends messages to the boiler' as evidence of an automatic adjustment. However, this depicts a step in a process, not an adjustment. Further training or a clearer distinction in the question could avoid this in the future.

#### 4.5.1.4 Improvements

Providing more examples and further explanations of the walk through questions and examples are likely to improve categorization. Using analysts who have conducted interviews and produced the outputs for the validation exercise, may also result in faster categorizations. In terms of the analysis tables, a greater emphasis of the distinction between categories, either textually, or with diagrams would also help.

## 4.6 Discussion

This chapter set out the following key aims: 1) Describe the methods used for the development of QuACk prototypes 2) Demonstrate how qualitative methods resulted in iterative improvements to QuACk , and 3) Describe the results of initial reliability tests. The first aim was achieved by providing a diagrammatic overview (Figure 28), that stated the methods, questions and features to be resolved. Figure 28 depicted these as a set of interrelated steps, and section 4.2.0 contains descriptions of how these steps were tackled, with examples, (where appropriate) of the synthesis of knowledge at each point that informed subsequent steps. The second aim was realised in section 4.4.0 in two stages, considering first, the prototype interview script & data collection method, and secondly the utility of the analysis reference table. The results and recommendations from pilot studies and participant observation that related to the interview script and data collection method were tabulated, and the change in components was depicted visually in figures 2 & 4 (where the

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components of the interview script before and after amendments, were shown). To demonstrate the benefit of participant observation on the development of the analysis reference table, the outputs from one of the pilot participants was analysed using the prototype reference table (see section 4.4.3). The challenges and insights gained from this process were tabulated and led to the production of 2 separate 'generic' analysis tables, corresponding to either the behaviour, or the mental model outputs (see Appendix 2). Initial reliability tests were undertaken with the method. First, the behaviour patterns depicted on output 1 were verified by spouses of the pilot participants, to see how well they reflect actual behaviour. The method of categorizing the outputs was then tested for inter-analyst validity, by asking 2 Human Factors analysts to categorize 3 sets of outputs using the updated analysis tables, and comparing this to the author's categorizations.

Through this process, it was discovered that whilst the development of QuACK prototypes stemmed from the analysis and application of existing knowledge about mental models data collection techniques from the literature, that exposure to the 'real world' revealed issues fundamental to exploring association between models and behaviour of home heating. These include the consideration of multiple control agents, and the use of (or failure to use) multiple control devices. The qualitative approach for method development inspired by Hancock and Szalma (2004) was invaluable in the iterative development of QuACK. It was found that the improvements to the interview script and template, resulting from the qualitative iterations, largely related to positioning, guidance and structure. It is these sort of improvements; that can only be gained from qualitative methods, as 'hard and fast rules' for specialised contexts may be lacking. Through the participant observation evaluation of the analysis reference table, consideration of the way the characteristics of shared models from the literature were 'inferred', to alternate devices, was insightful. This led to a 'generic' way of looking at shared models of home heating that accommodated shared theories from the literature as specific examples. This supports Hancock et al. (2009) sentiments that generalities can be extracted from single case studies. The initial reliability tests showed good agreement between self-reported behaviour and actual

behaviour, in terms of the impact on categorization of the data. The inter-analyst- reliability test showed good overall level of agreement with the author's own categorization, very good agreement with categorization of output2, and moderate agreement with output 1.

#### 4.6.1 Method evaluation

QuACK was developed to fulfil the need of a quick, resource light, method for exploring association between mental models of, and user behaviour with, domestic heating systems. Further, the method was to consider bias in its development, and allow identification of shared theories of home heating that exist in the literature.

[This method is 'quick' for small to medium samples, compared to other methods of collecting behaviour data compared to methods such as user diaries, verbal protocols and instrumenting homes \(see table 4\). These collect 'real-time' behaviour which would necessitate at least a week for collection for the type of analysis sought \(compared to approximately 1 hour with QuACK\), and is at risk of reflecting non-typical behaviour depending on climate and the householders' routine. Instrumenting a home also brings with it a number of inherent problems, such as ethical issues in terms of accessing the property for installation and maintenance, and use and protection of digital data transmitted remotely. In addition a wealth of technical problems related to ensuring equipment installed is functioning correctly and transmission to external servers is robust means that data capture is not necessarily reliable \(as found in Chapter 5\). Technical problems require expertise and time on-site to resolve. QuACK, taking the form of a structured questionnaire is clearly resource light compared to instrumenting a home as no technical equipment is required. It does require a one-to-one relationship between the analyst and participant however, so for very large samples would be less appropriate.](#)

[In terms of data analysis, QuACK is quicker than other methods detailed in Table 4, such as empirical modelling \(Jagacinski and Miller, 1978\) or analytical modelling \(Yakushijn & Jacobs, 2011\), which require data transformation for categorizations to be made, as well as a computer and software for the analysis. The ready to analyse outputs from QuACK and the systematic analysis tables and walk through questions can be carried out 'on the fly' by a non-](#)

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[technical analyst in 10-20 minutes without data transformation nor technical equipment.](#)

Section 4.4.2 describes the benefits of the behaviour and mental model outputs from QuACK that are not emphasised in the literature. For example, 1) they provide concrete representations of home heating models and behaviour, that can be analysed by practitioners without further transformation, 2) they are a flexible format to record key information relating to behaviour, that present challenges to automated data collection (such as the number of agents responsible for behaviour, range of control devices used), 3) they highlight behaviour patterns that arose from combinations of devices (e.g. if the thermostat is used in combination with a programmer, 'expected' behaviour patterns, for users who hold a feedback mental model, would differ to the 'expected' patterns if the thermostat was used alone), and 4) they are able to reveal not only misunderstandings or misuse of heating systems, but inconsistencies and ambiguities in the participants' home heating models and behaviour. With these characteristics, the outputs from QuACK offer the opportunity, not easily found with other methods, not only to focus further research, but to identify novel models and behaviour characteristics that could enhance the understanding of home heating use in the UK. Collins & Gentner (1987) and Norman (1983) recognized variations in the completeness of mental models between individuals which could account for findings relating to misunderstandings, misuse and inconsistencies in models held (such as with participant 3's multiple models of the thermostat device). This characteristic could be interpreted in line with Johnson-Laird (1987) to suggest that the device itself is ambiguous in the way its presents its function. Multiple or conflicting models, could then be considered 'symptom's' of issues such as ambiguous design, insufficient instruction, or misleading feedback at a 'system' level. This could target further research efforts both into mental models, as well as home heating behaviour in general.

The format of QuACK, is made up of distinct sections relating to specific types of output. This means the interview script can easily be cut down if

practitioners are concerned with data collection of either home heating behaviour or models alone, rather than the association between these two variables. By making audio recordings of the interview, the option of more 'in depth analysis' is also possible. An example of in-depth analysis that considers the mental model output of home heating, combined with supporting evidence found from the interview transcripts resulting from QuACK, can be seen in [Chapter 5 and Revell & Stanton \(In Press\)](#).

The development of QuACK considered bias at its outset, which has been emphasised in the literature as a risk in mental models research (Rouse & Morris, 1986, Wilson & Rutherford, 1989, Bainbridge, 1992, Richardson & Ball, 2009, and Revell & Stanton, 2012 [described in Chapter 2](#)). Section 4.2.4 emphasises the many strategies that were put in place to mitigate for unwanted bias through the tree ring method (Revell & Stanton, 2012 [and Chapter 2](#)), such as verification of outputs by the user, format of outputs ready for analysis, paraphrasing and opportunities for amendment throughout the interview, provision of interview script and instructions to minimising leading etc. The inclusion of deliberate biases, however, were engineered to fulfil the aims of this thesis. For example, the format of the outputs was deliberately restricted in the case of output 1, to show set points over time, and with output 2, to display the relationship between components of a heating system. This bias was necessary to provide insights on the research question, but also to allow a meaningful comparison between participants. Whilst the literature emphasises the face validity that user mental models of device function, influences behaviour with devices (Gentner & Stevens, 1983, Wilson & Rutherford, 1989), [Wilson & Rutherford, \(1989\) makes the pertinent point that](#) an analysts' description of a user mental model is not equivalent to the knowledge construct itself ([Wilson & Rutherford, 1989](#)) [due to the layers of bias inherent in any methodology for capture \(Revell & Stanton, 2012 and Chapter 2\)](#). Moray (1990) also emphasises that mental model descriptions can differ considerably, depending on the perspective taken. So, this deliberate bias, introduces a risk that significant or useful information may be lost, where it falls outside the desired format. This limitation is minor, given the flexibility of the paper based format to allow additional notes or annotations. This flexibility was seen in the pilot studies, by the representation of multiple control devices and agents on output 1, which had originally been intended to

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record behaviour patterns of thermostat set points by sole users. Related to this, a limitation of the mental model description in output 2, can easily be mistaken to represent the 'actual' and 'complete' user mental model of their home heating system. It should be made clear that output 2 represents a single 'view' of the users mental model and the results and analysis need to be viewed in this light. It is though that the risks identified, are outweighed by the benefits of this method, in terms of its efficiency and minimal resources needed.

#### **4.6.2 General applicability**

Whilst QuACK has been developed specifically for the home heating context, its structure and components may have more generic applicability for exploring association between user mental models and their behaviour with devices or systems. The mental model activity, like a concept map, is not domain specific, and the self-report of behaviour template is applicable for devices where behaviour patterns are based on set point choices over time. Only minor variations to the wording and content of questions, and scale of behaviour output, would be needed for closely related domains, such as non-domestic heating systems, air conditioning / cooling systems, or domestic hot water systems. There may be applicability to domains other than space heating, such as domestic energy consuming devices that present simple input controls, but do not have a clear relationship to the task being performed or energy consumed (e.g. microwaves, washing machines, tumble dryers, electronic devices). For these devices, adjustments to the content of the questions and the scenarios presented would be needed. The format of the template for recording self-reported user behaviour would need to be based on either existing behaviour patterns identified in the literature, or follow from exploratory data collection methods such as observations, participant observations, or in depth case studies. With application to a context outside of domestic home heating, iterative development of the questionnaire and analysis table (see section 4.4.0) is recommended.

#### 4.6.3 Avenues of future work

To develop this method, further validity testing is needed. Chapter 6 compares self-reported behaviour with the thermostat device (output 1), with automated data collection measurements (both collected over winter period 2011), indicating consistency with the 3 case study households, but larger numbers would better indicate validity. The interview script has been trailed with an analyst at Herriot Watt University supporting the sufficiency of the instructions and format, but trials with more analysts are needed.

Within the home heating context, chapter 8 shows application of this method to collect data to explore the association of models and user behaviour with a home heating simulation. With a simulation, not only can behaviour data on all devices be collected automatically, meaning the self - report section is not required, but there are additional benefits. For example, the analysts are able to control user goals, the number of agents, the range and usability of control devices available, the house structure (and associated thermodynamics) as well as the outside climate.

The impetus for the development of QuACK arose from the intention to combat climate change by understanding domestic energy consuming behaviour. To apply a successful behaviour change, or behaviour mitigation strategy with an awareness of broader consequences on the system, it is believed it is not sufficient to know how people behave with devices, but to understand how, why, and when their behaviour differs from 'optimal' behaviour with devices. To make a first step towards this comparison, chapter 6 shows the results from applying QuACK to an expert in home heating systems. This was used to gain an 'example' of the model and behaviour thought appropriate by designers and manufacturers of heating systems. Identified energy consuming differences between how a system is expected to be used, and is actually used, could inform energy conserving strategies such as improved design, instruction or automation, or even help desk advice on device use or energy conservation. In addition, findings of impaired performance, through missed use or inappropriate use of devices which don't have a direct consequence on consumption, could also highlight usability issues that cause frustrations to users. Some of these usability issues, may be having 'knock on' effects on the way the heating system is used, indirectly resulting in wasted consumption, by

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the adoption of energy wasting strategies that avoids difficult, frustrating, or inconvenient interactions (Lockton et al. 2010, Combe et al., 2011, Revell & Stanton, In Press [and Chapter 5](#)).

Wilson & Rutherford (1989) emphasise that applying the notion of mental models (particularly in design); increases the total effort to the practitioner. To ensure the benefits of using this notion, in terms of performance or comprehension, they demand that rigor in determining the mental model description is necessary. It is offered that the systematic process in developing QuACK and analysing the output is a step in the right direction. Whilst initial outlay is required in the development of this method, the reduced time in data collection and analysis resulting from a structured interview resulting in verified outputs which are not only 'ready for analysis', but in a simple, concrete form which would be meaningful for the practitioner, furthers this goal.

## 4.7 Conclusion

The QuACK (Quick Association Check) method was developed using qualitative approaches. It is a structured interview method which includes activities and templates to produce verified outputs ready for analysis. QuACK also provides analysis reference tables for each output and 'walk-through' questions to guide the analyst. The benefits of the method include flexibility, speed of data collection, ease with which data can be analysed to explore association. The benefits of rich data from the interview transcripts provide insights which can explain phenomena, target future research or determine appropriate strategies for mitigating inappropriate behaviour when operating devices. It is anticipated that the method could easily be adopted to other devices and domains such as electronic consumer goods, dashboard and cockpit devices in transportation or control room design in military or nuclear domains.

QuACK is applied in this thesis in chapters 5 to a case study of 3 householders to illustrate how its outputs can provide insights about the link between mental models of home heating, self reported behaviour, recorded behaviour and energy consumption. In chapter 6, QuACK is applied to a home heating expert

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and the outputs compared with those produced by home heating novices to highlight differences to inform a design specification of a mental model promoting home heating interface. In chapter 8, QuACK is applied to participants in an experiment using a home heating simulation to investigate how interface design can influence mental models of home heating.



## 5. When energy saving advice leads to more, rather than less, consumption

### 5.1 Introduction

[This Chapter uses a combination of data sources to investigate Hypothesis 1 and 2 described in the introduction in section 1.2. Data relating to mental models of home heating and self reported behaviour with controls from applying the QuACK method described in Chapter 4, as well as automated data collected from case study households relating to thermostat set point changes, internal temperatures and boiler on periods were compared. These are used to investigate how home heating goals \(e.g. comfort and consumption\) are influenced by patterns of device use \(Hypothesis 2\), as well as how mental models of home heating explain the patterns of device use displayed \(Hypothesis 1\). By considering both of these hypotheses within the same case study, this chapter links 3 out of 4 concepts depicted in Figure 1 on page 3. This linking of concepts lends considerable support to the validity of the key aim of this thesis, that design strategies can increase home heating goal achievement by using the notion of mental models to alter behaviour with heating controls.](#)

Domestic energy consumption accounts for approximately 30% of UK consumption, and 60% of this is as a result of space heating (Department of Energy and Climate Change (DECC), 2013). Home heating devices therefore indirectly control approximately 18% of the UK's entire energy production. In the US, Peffer et al. (2011) estimate 9% of domestic consumption is controlled by the thermostat device. Their review of thermostat usage, however, revealed almost half of homeowners only sometimes, rarely, or never programmed programmable thermostats, and around 40% of people with manual thermostats did not set back the temperature at night to save energy.

Shipworth et al. (2009) found that average maximum room temperatures, or the duration of operation, was not reduced with the introduction of standard heating controls recommended by DECC to save energy. Increasingly, we find that technology touted to save energy does not deliver on the promises made. The benefits of Smart Meters has been put into disrepute. High installation

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costs fail to justify the predicted 2% saving on an average bill. Further, this meagre reduction is conditional on consumers changing their behaviour to actively cut energy use. ([www.bbc.co.uk](http://www.bbc.co.uk), 2014 ). Programmable thermostats have been stripped of their energy star certification since 2006 in California (DECC, 2013), and from 2009 in Washington DC ([www.EnergyStar.gov](http://www.EnergyStar.gov), 2009) as significant savings were wholly dependent on consumers knowing how best to use them. The role users play in operating technology therefore cannot be overlooked, and a body of research has found significant variations in energy use are due to behavioural differences of householders (Lutzenhiser & Bender, 2008; Dalla Rosa & Christensen, 2011; Aerts et al. 2014; Fabi et al., 2012).

Key causes of variations in domestic heating usage patterns include technologies, habits, knowledge, and meanings (Gram-Hanssen, 2010). Householder's knowledge of home heating technology and resulting habits of behaviour are considered in this chapter through the examination of thought processes that guide users understanding and actions with technology. An important thought process used in this way is termed a 'mental model'. Mental models can be thought of as a 'picture of the world' held in the mind (Veldhuyzen and Stassen 1976, Johnson-Laird 1983, Rasmussen 1983). Whilst householders may not be consciously aware of it, they are using this internal representation to help operate systems, such as their home heating system (Kempton, 1986). This same representation is also used to predict the effects of their actions on, for example, their comfort and consumption levels, and to help understand and explain the changes that occur (Craik 1943, Gentner and Stevens 1983, Kieras and Bovair 1984, Rouse and Morris 1986, Hanisch et al. 1991). The explanations formed may then lead to further actions (Norman, 1986). Depending on their experiences, the content of peoples' mental models vary (Norman, 1983; Moray, 1990, Bainbridge, 1992). Consideration of householders' mental models of the home heating system, would therefore be helpful when looking for insights into the cause of variations in people's behaviour with home heating systems (Kempton, 1986, Revell & Stanton, 2014). This in turn could focus strategies to realise the potential of 'energy saving' technology.

Kempton (1986) hypothesised a causal association between users' mental models of the way thermostats work, and their behaviour patterns over time

when manually changing the set point of the home heating thermostat. Kempton (1986) identified two typical types of mental models of how the thermostat functioned that were analogous to 'Valve' and 'Feedback' mechanisms. Those who held a 'Valve' model predicted that if the thermostat was turned right up, the house would heat up more quickly (like turning a tap on full to fill up a basin more quickly). Those who held a 'Feedback' model predicted that the speed to heat a house was not affected by choosing a higher than desired set point on the thermostat. He found most of his participants had common elements in their individual mental models that fit either one or the other of these types. Kempton (1986) termed these types 'shared theories' rather than mental models. This highlights that they are shared by a particular social group, and represent the common elements of individual's mental models (Kempton, 1986; Revell & Stanton, 2012).

There are many definitions of mental models and different perspectives from which to consider them (Revell & Stanton, 2012, Wilson & Rutherford 1989, Richardson & Ball 2009), so specificity in definition is key (Bainbridge 1992, Revell & Stanton, 2012). The mental model from which Kempton (1986) derived his shared theories, are best understood in terms of a user mental model (Norman, 1983) and device model (Keiras & Bovair, 1984). That is to say, a mental model held by a user of a specific technology, that contains information about the operation and function of that device, and has been accessed and described by an analyst. Kempton (1986, 1987) suggested that distinct behaviour patterns are associated with 'Valve' and 'Feedback' shared theories of thermostat function. He proposed that characteristics of the Feedback shared theory could result in energy being systematically wasted. Since Kempton (1986), no further work has explored in detail the consequences of how referring to a Feedback shared theory when operating home heating controls affects energy consumption.

Revell & Stanton (2014) built on the work of Kempton (1986) and extended this sentiment to the range of home heating control devices commonly available in present day homes. However, whilst agreeing that consideration of individual control devices in terms of usability and the mental model held is clearly important, Revell & Stanton (2014) ([Chapter 3](#)) argue that users need to be aware of which control devices to use in which situations. This means that the householder needs to be able to adopt an appropriate home heating

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‘strategy’, to fulfil their comfort and consumption goals. This requires householders to have an appropriate understanding of home heating at a system level, as well as at the device level.

Sauer et al., (2009), consider home heating to be the most complex system in the domestic domain. For complex systems, both Bainbridge (1992) and Moray (1990) describe how the user’s mental model of the system constrains the performance with the system. They also emphasise that other variables, such as user goals, influence the resulting strategy adopted with the system. Norman (1986) also highlighted the link between goals, mental models, strategies, and behaviour when users interact with individual devices or interfaces. As the strategy adopted by the user ultimately drives the observed behaviour, efforts to change householder’s energy consuming behaviour would benefit from further understanding of the cause and consequence of home heating strategies.

Following on from [Chapter 3 Revell & Stanton \(2014\)](#), this chapter examines how mental models at the system level affect the strategies adopted at the device level, even when the same Feedback ‘shared theory’ of a home heating thermostat is held by householders. Further, the impact of differences in the chosen strategy on domestic energy consumption, is explored. The “Feedback” shared theory of the thermostat was described by Kempton (1986; p80) in the quote below;

*‘According to the feedback theory, the thermostat turns the furnace on or off according to room temperature. When the room is too cold, the thermostat turns the furnace on. Then, when the room is warm enough, it turns the furnace [Boiler] off. The setting, controlled by a movable dial or lever, determines the on-off temperature. Because the theory posits that the furnace [Boiler] runs at a single constant speed, the thermostat can control the amount of heating only by the length of time the furnace [Boiler] is on. Thus, if the dial is adjusted upward only a little bit, the furnace will run a short time and turn off; if it is adjusted upward a large amount, the furnace must run longer to bring the house to that temperature. Left at one setting, the thermostat will switch the furnace on and off as necessary to maintain approximately that temperature.’*

This theory is a simplified, but essentially correct understanding of how the thermostat works. However, as Kempton (1986) points out, it does not consider the impact on comfort of different levels of infiltration through the home, nor include the importance of internal temperature levels on the rate of heat loss. The former point relates to how different parts of the house will heat up at different rates depending on house structures and heat flow between rooms. This latter point is especially important when considering energy consumption. According to Fourier's Law, the rate of heat loss in a home is proportional to the difference between the internal and external temperatures (Lienhard, 2011). To achieve a specific temperature (e.g. 20°C) in the daytime, when external temperatures are higher, lower rates of heat loss will occur than at night-time. As the thermostat triggers the boiler to come on based on internal temperature levels, greater heat loss at night will ensure internal temperatures drop at a faster rate, requiring the boiler to come on more often. Kempton (1986) was describing behaviour for householders who used the thermostat as their key control device. He found householders with a Feedback model of the thermostat tended to have a usage pattern where they made infrequent, regular adjustments in line with routines of the household. Feedback model holders also tended to keep the thermostat set to a comfortable level at night, as they believed it would take more energy to heat up the cold bodies within the house if the temperature was allowed to drop too much. Due to the lower external temperatures, keeping a comfortable internal thermostat setting at night requires the boiler to work harder, that is, to be on for longer periods, in order to compensate for greater level of heat loss. Kempton surmised that this limitation in the feedback model would result in systematically wasted energy. That is to say, sleeping householders who would be comfortable at a lower room temperature, maintain a higher set point when consumption rates are at their greatest.

The chapter is structured to investigate 3 households known to hold a 'Feedback Shared Theory' of the home heating thermostat at the 'device' level. First, the households will be compared in terms of their energy consumption over a single week. The thermostat adjustment patterns for that week will then be examined to further understand the consumption. Next, the householders' self-reported typical adjustment 'strategy' with the home heating controls will be used to help explain the patterns. Finally, the users' mental model

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description of home heating at a ‘system’ level will be examined to explain the strategy chosen. The implications of these findings for strategies to encourage reduced consumption will be discussed throughout.

## 5.2 Method

This chapter uses data collected at the same time as that reported by a former study investigating variations in user mental models of the thermostat (Revell & Stanton, 2014). The user group comprised overseas doctoral students at the University of Southampton, with young families, new to the UK. The Participants were recruited by letter, email, and approached door-to-door by the first author. Permission was sought from the Faculty Research Ethic’s committee prior to contact and Research Governance was arranged (RGO Ref.8328). The participants were all from warm countries where centralised home heating devices are uncommon. These user group characteristics ensured minimal prior experience of other home heating devices, allowing behaviour patterns to be attributed to the mental model of the thermostat control installed, rather than habitual use from other devices (Revell & Stanton, 2014). With mental models research, bias in data collection and analysis is a key consideration (Revell & Stanton, 2012). The study took a number of steps to mitigate bias, including use of a carefully constructed questionnaire to gain data from the user with minimal leading to capture their mental models and typical behaviour. In addition, an analysis table was created for systematic categorization of householders’ mental models of the thermostat as either ‘valve’ or ‘feedback’ shared theories (Kempton, 1986). More details about ways bias was mitigated and the procedures for data collection can be found in [Chapter 3 and](#) Revell & Stanton (2014). This section will describe the participants, settings, and the methods employed for collecting the different data sources, and the choice of data representation.

### 5.2.1 Participants

The three participants in this case study were non-randomly selected from the Revell & Stanton (2014) study ([Chapter 3](#)). The basis for selection for this particular investigation, was for all participants to hold a ‘Feedback’ shared theory of the thermostat (Kempton, 1986). By controlling this variable, other

causes for differences in behaviour with the thermostat could be explored. Participant X was a student in his late 30s and originated from South Africa. He lived with his wife and two school age children, and shared heating control with his wife. Participant Y was a postgraduate in his late 30s and originated from Taiwan. He lived with his student wife and young son and was in sole control of the central heating. Participant Z was a student in his early 30s and originated from Singapore. He lived with his wife and 2 young children, and took full control of heating for the family.

### 5.2.2 Setting

The dwelling type, level of insulation, double glazing, location, and central heating system were matched by using University of Southampton owned accommodation that had undergone identical refurbishment prior to the study, located on the same street in Southampton. This removed variations in thermodynamics of the dwelling or device design, that otherwise may have influenced the behaviour and consumption levels observed. University accommodation was chosen for a number of reasons; 1) Its convenient location when troubleshooting technical issues, 2) The opportunity to ensure the desired thermostat model was installed, and 3) The ability to pre-install data collection equipment prior to residents arriving. The interviews were undertaken in a cafe in the university library where the participants could feel at ease.

### 5.2.3 Data collection

Four key types of data were examined in this chapter. Data collected from the heating system including outputs of the system and inputs from the user. Outputs from the heating system related to energy consumption (boiler 'on' periods) and comfort (internal temperature). Inputs from the user focused on thermostat set point adjustments over time, as this was proposed by Kempton (1986) to be a significant behaviour variable that could result in systematically wasted energy. To help better understand and explain differences in consumption and behaviour, data was also collected directly from the user. This comprised users' strategies of home heat control and their mental model description of the functioning of the heating system.

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### 5.2.3.1 From Central Heating System

The data collected from the heating system for this study was part of a larger study undertaken by the Intelligent Agents for Home Energy Management group (IAHEM). The method for data collection was developed in conjunction with Hortsmann Ltd. Set point changes to the thermostat and room temperature, were captured at 5 minute intervals. Data was transmitted from the thermostat via Z-wave radio waves to an internet hub housed under the stairs in each household. The hub was connected to a 3G router which sent the data over a 3G mobile network to a Secure Server in Denmark (Seluxit). Data was extracted by colleagues in the IAHEM group from the secure Seluxit website (<http://home.seluxit.com/>). The set point and internal temperature data was calibrated by the IAHEM team with boiler on times, resulting in data points per second. A single common week commencing 7<sup>th</sup> November 2011 for 7 days, is examined in detail in this chapter. This allows illustration of how the different data sources selected can help explain energy consuming behaviour. Differences in consumption between participants were represented with a single column graph showing the time the boiler was 'on' for each participant during that week (the mean thermostat set point was also shown for reference). Line graphs for each participant representing thermostat adjustments and internal temperature values (captured hourly) were constructed to compare actual behaviour. One graph per participant was produced combining this data with the corresponding period of time that the boiler was active.

### 5.2.4 From the User

In March 2012, following the period of automated data collection, the householder was interviewed to gain self-reported data of their behaviour with their home heating controls. To capture each participant's strategy of home heating control over a typical week, a simple template marking out the days of a single week (with an undefined y-axis) was annotated with the householder during a semi-structured questionnaire. For easy comparison, the structure of this output was designed to show changes in heating control adjustments over a week period, to match the format produced by Kempton (1986) and the

automated data collection outputs. In this chapter, these self-reported home heating strategies have been redrawn for clarity.

To capture each participant's mental model description at the device and system level of the heating system, questions and follow on probes directed by a semi-structured interview template, were used to build up a diagram with the participant. The diagram was created using post-it notes containing participant initiated terminology relating to the heating system. Concepts were linked by drawing lines between the post-it notes. To gain insights into cause and effect, and rules of operation, participants were asked follow-on probes such as "How does the boiler know when to come on/off" and "What would happen if you turned the thermostat to its maximum setting?". Participant responses to these probes were represented on the diagram using arrows and text. These mental model descriptions were then redrawn for clarity.

### **5.3 Results & Discussion**

Figure 34 shows the boiler on periods for the 3 households with similar family setup, matched by location, house structure, insulation levels, and home heating technology, for a single week in November 2011. The mean thermostat set point for each home is also indicated, as this variable directly affects boiler on periods.

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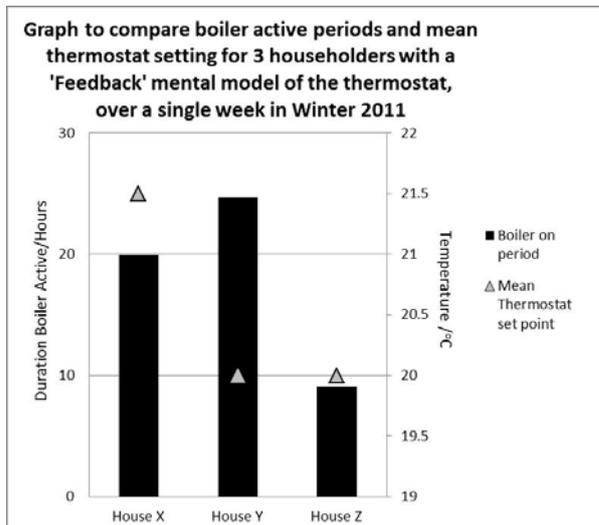


Figure 33 – Graph to compare boiler on periods for 3 matched households over a single week during winter in the UK

The first thing to notice about Figure 34, is the lack of correlation between boiler on periods and the thermostat set point value. House X has the highest mean set point at 21.5°C, but not the highest boiler on period. Houses Y & Z have the same mean set point of 20°C, but considerable differences in boiler on periods; the boiler is on in House Y for more than twice that of House Z. Guerra-Santin & Itard (2010) found the period of time the thermostat was set at its maximum value better correlated with energy consumption. Thermostat set point values over time would therefore better explain the differences seen in Figure 34. Kempton (1986) proposed that significant differences in consumption could be explained by differences in behaviour patterns of thermostat set points over time, where these differences were caused by users holding different mental models of the thermostat. Given the households above all hold the 'Feedback' shared theory of the thermostat, it was thought it possible that variations in behaviour patterns, arising from the same mental model, may account for these differences. To investigate this theory, the thermostat adjustment patterns were compared.

Figure 35, Figure 36 & Figure 37 show the set point adjustment patterns, internal temperature, and boiler on periods.

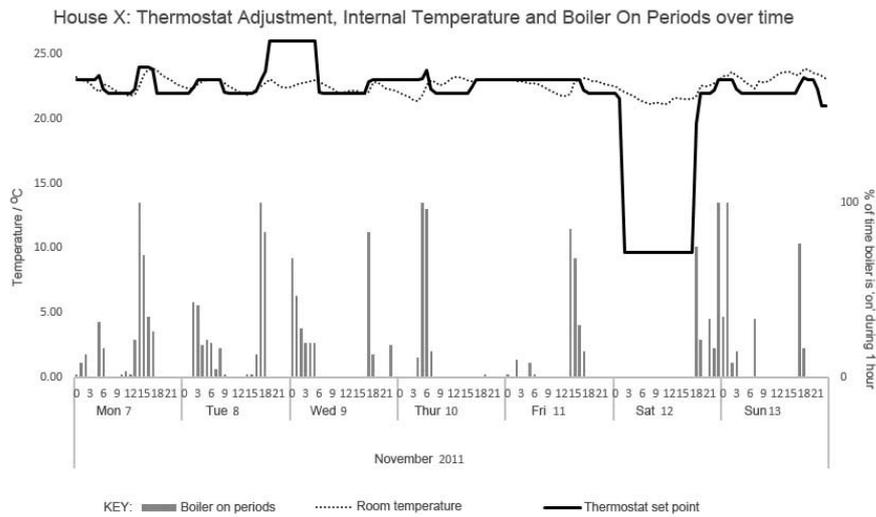


Figure 34 - Remotely recorded thermostat set points, internal temperatures, and boiler on periods during a single week for House X

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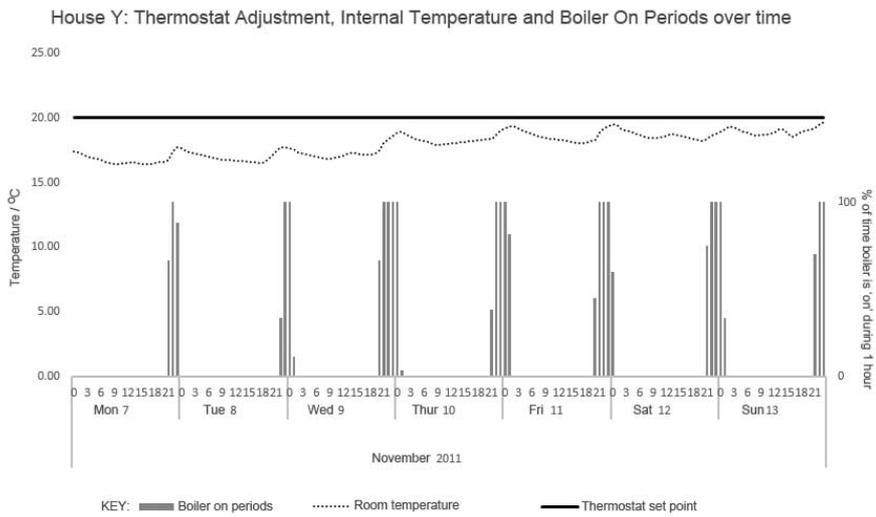


Figure 35 - Remotely recorded thermostat set points, internal temperatures, and boiler on periods during a single week for House Y

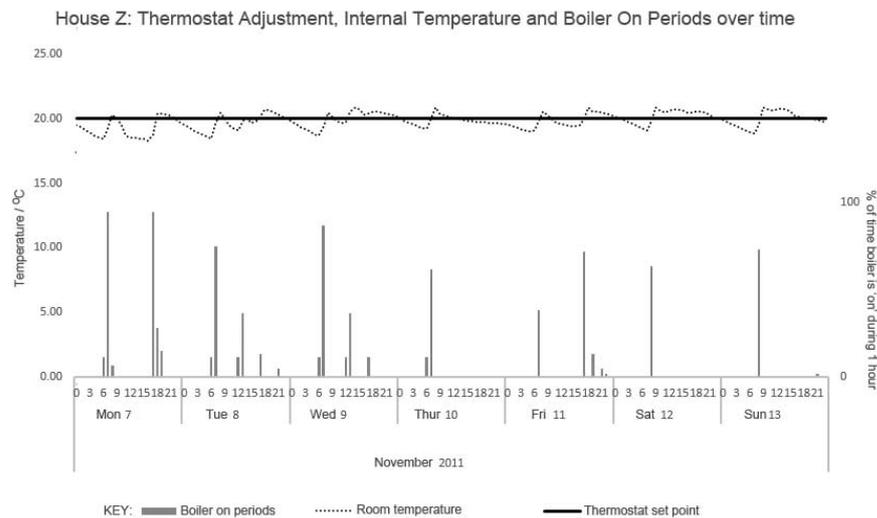


Figure 36 - Remotely recorded thermostat set points, internal temperatures, and boiler on periods during a single week for House Z

Figure 35, Figure 36 and Figure 37 reveal clearly that despite the participants for each house holding a feedback shared theory of the thermostat, only House X displays the infrequent, regular adjustments described by Kempton (1986). The readings from House X clearly show boiler on periods matching increases in adjustment and boiler off periods following decreases in adjustment, indicating the thermostat is a key part of their strategy for heating control. This is contra to the outputs from the Houses Y & Z, which indicate no adjustment of the thermostat set point and very different patterns on boiler on periods. House Y shows boiler on periods only at night (approximately 9pm-1am), often continuously. The internal temperature reading shows that at no point was the desired 20°C set on the thermostat achieved, and the internal temperature sometimes dropped below 17°C during the day. House Z shows boiler on periods 1-3 times a day between 6am and 7pm, and occasionally for a short time at 9pm. However, the internal temperature was far warmer, ranging between 18.5°C and 21°C. House X is clearly from a different population than Houses Y & Z with their approach to thermostat control, but manages to achieve comfort levels following the thermostat set point (Figure

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35). Houses Y & Z, whilst sharing the same adjustment strategy and set point value for the thermostat, have realised very different outcomes. The former has achieved low levels of comfort with high levels of consumption (boiler on periods), whilst the latter has achieved good levels of comfort, with far lower levels of consumption. [In Chapter 3](#), Revell & Stanton (2014) described how householders combine controls in various ways to manage their home heating. To understand where the control settings for other devices are responsible for these differences in boiler on periods, diagrams of the participants' self-reported 'strategies' for home heating control and the associated interview transcripts, were referred to.

The typical strategies adopted by Participant X are depicted in Figure 38. From their transcript, this participant stated their approach to heating the home as: *"to keep warm is one thing, and saving money was another concern.....It's very optimised, our whole heating experience"*. As no other devices are depicted, Figure 38 confirms the assumption following that derived from Figure 35, that thermostat adjustment makes up the sole strategy for controlling home heating. As such, we expect to find a 'Feedback' behaviour pattern as described by Kempton (1986). The infrequent regular adjustment during the day to match the lifestyle is supported in Figure 38 and the transcript below:

*"we would up the heat when we wake up. And then in the afternoon the kids go to school – they normally leave about eight o'clock – we will normally either turn it down... and then later on when they come home again we will up the temperature, because the kids normally get more cold."*

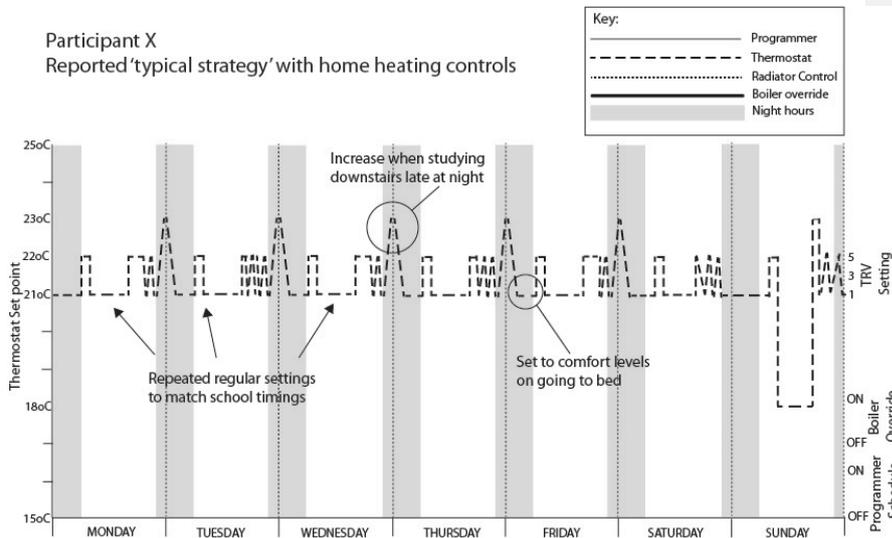


Figure 37 - Devices used and typical adjustments made over a typical week reported by Participant X

Kempton (1986) expected a user with a feedback 'shared theory' not to turn down the temperature on the thermostat below comfort levels. Figure 38 shows that when the thermostat is adjusted last thing at night, it is returned to a comfortable 21oC. Further evidence that Participant X is not aware of the impact on rate of heat loss of increased temperatures at night, is shown in Figure 38 with a 'spike' where the thermostat is turned up to 23oC for a short time. However, when referring to the transcripts, we can see that Participant X does exhibit an awareness of infiltration of heat within the house, which encourages a strategy for heat control that wastes energy.

Analyst: Okay. So there might be situations, say, in the evening where you kind of put it up to 23 a little bit?

Participant X: Yes, for a short while because normally I sleep very late. I do about once or twice a week maybe I am at work until three AM maybe. So I would normally during this time put it up maybe for half an hour up to 23.

Analyst: And then back down to 21?

Participant X: Yeah. And then back to 21.

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*Analyst: To 21. So say you had it on for the evening around 22, you suddenly think “Oh” – because you’re in the cold room – you maybe put it up to 23, but then you turn it right down again?*

*Participant X: Yeah, because typically my habit would be to move from my desk ..... and go to the front room and close the door, put it up on 23.*

*Analyst: So sort of heat up.*

*Participant X: It heats up and then I’ll put it back on to 21*

Participant X clearly has a good sense of how different parts of the house heat differently, elsewhere in his transcript he describes the front room as “*it’s very warm, so you can’t put it [thermostat] more than that [21°C] or you’re feeling too hot*” By opting to work late at night in the coldest room (rather than the warmest) and raising the thermostat to maintain comfort levels in that room during the night, increasing the rate of heat loss, he is getting ‘poor value’ for the amount of energy consumed on these occasions. Looking at the actual thermostat set points on Figure 35, we can also see that temperatures adjusted at night often remain on for longer than the 30 minutes stated, further extending boiler on times. When finally going to bed, as predicted by Kempton’s (1986) Feedback shared theory, this household does not ‘set back’ the thermostat but puts it at a comfortable level, where heat loss will be higher than during the day due to the greater temperature differential. Energy could be saved in this household with minimal impact on comfort purely by setting the thermostat to a lower than comfort level when sleeping.

Figure 39 shows that in addition to the constant thermostat set point, the Thermostatic Radiator Valves (TRVs) and Boiler Override are both typically adjusted. From the interview transcript, Participant Y describes his goal and strategy when managing the heating system:

*“money is a very important driver for how to use the energy...we turn it [boiler override] on at about 9pm..and then we turn it off before we go to bed....But also we change the radiator control so typically right now we have eight radiators, but typically we only turn one bedroom, one living room, and one bathroom ”*

Participant Y  
Reported 'typical strategy' with home heating controls

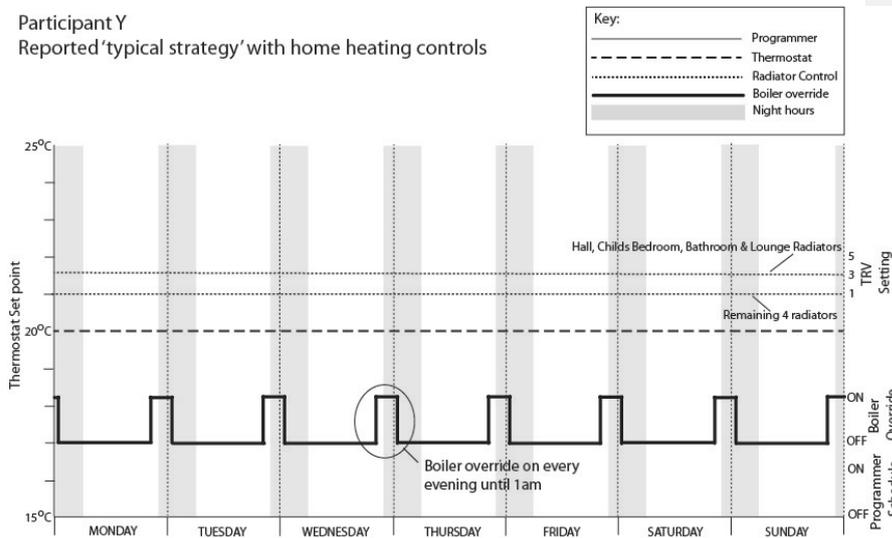


Figure 38 - Devices used and typical adjustments made over a typical week reported by Participant Y

User behaviour relating to night-time thermostat set points (Leung & Ge, 2013) and TRV adjustment (Xu et al., 2009) contribute to increased consumption. The combination of heating only in the evening and night, when external temperatures are at their lowest, as well as using a limited number of radiators for heat transmission could explain the high consumption levels for participant Y. The lack of understanding of thermodynamics within a broader system supports Kempton's (1986) description of a user with a feedback shared theory of the thermostat. Lack of 'night set back' of the thermostat, has instead been extended to the decision to put the heating on at night using the boiler override (which allows the thermostat to operate during this period). During the week discussed the average internal temperature for household Y was approximately 18°C. The mean maximum and minimum external temperatures were 13°C and 9°C (www.wunderground.com), and using these as rough estimates for daytime and night-time temperatures, the temperature difference during the day would work out around 5°C, compared to 9°C at night. Choosing to override the heating at night instead of during the day could almost double the rate of heat loss, increasing the boiler on times to compensate for the greater loss. In addition to this, by reducing the outputs

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for heat transmission by half, unless all doors surrounding the hallway (which houses the transmitting temperature sensor) were closed, the boiler would again need to be on for proportionally longer periods to achieve the desired temperature. Had the heating been left on long enough to achieve the 20°C at night during this specific week, it may have needed a period of up to 4 times the duration necessary than that during the day, with all radiators transmitting. Money was also the driver for the thermostat set point choice as shown in the quote below;

*“...in the beginning we set it [thermostat] to 22, for maybe a couple of weeks..... and then some people [Newspaper advert] say that when you use set the temperature down one degree, some people say that you save 25 or 30 % of your costs.”*

However, given Figure 36 shows the heating was switched off before the boiler had achieved the thermostat set point, it is likely that little, if any, money was saved by making this adjustment. It is hoped that how advice to save energy would benefit from being context specific, has been illustrated. By actively trying to ‘save money’ through heat control, this household resulted in the highest boiler on times of the case studies.

Figure 40 depicts the programmer as the main heating control used in conjunction with a static thermostat set point. Participant Z reported his attitude to home heating control was “I want to keep warm”. They describe their usage of the thermostat as follows:

*I think it's about 6.50am or 7.00am it will switch on, and off at about 8.30am. Then it will be on again about 12.30pm, 1.30pm, until 3.00pm or something like that, and then it will come on again at around 5pm to about half 10.....I will just change it according to what we are doing that day....[if going out for the day] I'd get rid of the middle one and depending on what time we expected to be home I would also adjust the second block.*

Participant Z  
Reported 'typical strategy' with home heating controls

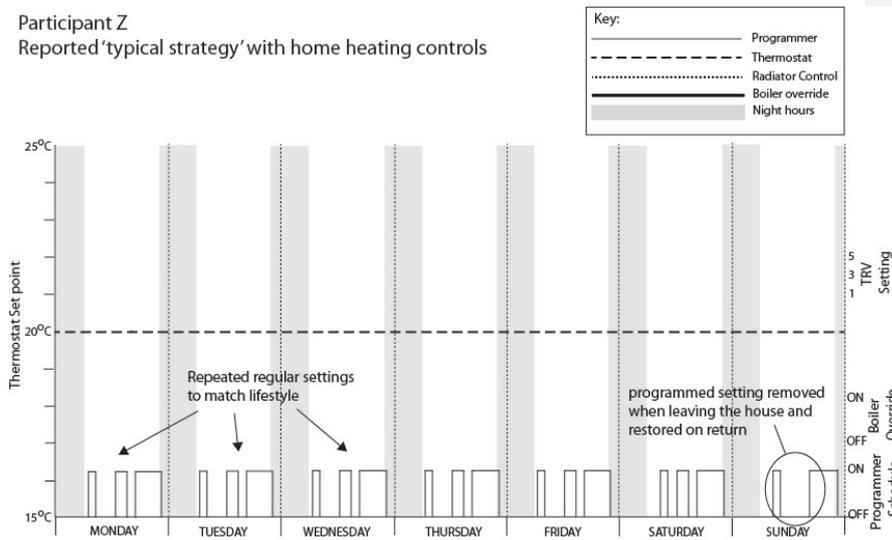


Figure 39 - Devices used and typical adjustments made over a typical week reported by Participant Z

This description is reminiscent of Participant X's feedback strategy, with infrequent, regular changes based on the routines of lifestyle, but choosing to make the adjustment with a programmer, rather than thermostat device. Participant Z does not describe a lifestyle that has frequent late nights, so the need to have the heating on when temperatures are lowest, does not arise. In addition, as the programmer is used in place of the thermostat, the adjustment at 10:30pm to turn 'off' the heating before bed, circumvents this risk. By changing control devices and following lifestyle comfort needs, the largest risk to feedback model holders of the thermostat, excess heat loss at night is averted, without a need for Participant Z to understand the effect of broader system thermodynamics on heating operation.

Participant Z, did, however, demonstrate a sound understanding of the functioning of the thermostat, its dependency on its immediate environment, as shown in the transcript excerpt below:

*Analyst:* ..... You mentioned here that the thermometer measures the hall temperature particularly. How does the radiator and other parts of the house affect the thermostat?

*Participant Z:* Not at all.....Which is something that I didn't like, because of this I have to shut the corridors to control my thermostat....

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*Analyst:* ..... you can't necessarily control how much energy you use in the way that you want because you have to rely on the way it measures it ?

*Participant Z:* Yes. It's the reason I switch on the radiator in the hall because I want to make sure that the boiler turns off when it reaches a certain temperature, not because I will stay in the corridor all the time.

*Analyst:* No (laughs). So the radiator in the hall is purely for operating the device not for your comfort at all, in your mind.

*Participant Z* Yes.

Participant Z mentions shutting doors to the corridor, so is clearly aware of the effects on infiltration on the speed with which a radiator can heat up an air space. This understanding, whilst different from that suggested by Kempton (1986), who was considering user comfort, is nevertheless significant in terms of energy consumption. By providing the appropriate conditions for the thermostat, the boiler can legitimately be told to turn 'off' more often, reducing consumption. The combination of: 1) Choosing the programmer as the key control (so the user does not forget to turn it off), 2) Scheduling heat use during the day (rather than at night), and 3) Creating the appropriate environment to allow a central thermostat to operate effectively (closing corridor doors, keeping the hall radiator on), go some considerable way, to explaining why Participant Z has far lower levels of consumption than Participants X and Y.

All three participants had been categorized as having a feedback shared theory of the thermostat, according to Kempton (1986). Two of the participants, X and Z, had clearly gone some way to 'adding on' a model of infiltration, which benefited them in terms of comfort (e.g. Participant X), or reduced consumption (e.g. Participant Z). None of the participants described an understanding of the effect of differences in external temperature on boiler periods, which explains less appropriate use of the thermostat at night for participants X and Y, wasting energy. It is worth noting that these participants both mentioned saving money as a driver for heating control, yet both consumed considerably more than participant Y, whose aim was to keep the family warm. A willing attitude, therefore, is insufficient for reducing consumption, if how to effectively operate the heating system is misunderstood. The implications for promoting energy saving behaviour is to

provide energy saving guidance for control devices *in the context of their environment*. Where the technology fails to communicate changes in consumption based on temperature differentials or infiltration, advice is needed to highlight these aspects for consumption to be reduced. Each participant, also chose a different strategy, in terms of controls used to operate their home heating. It was of interest, how user mental models at a system level could explain the differences in the chosen strategy, so looked to these participants' mental model descriptions of their home heating system.

Figures 4a, b, & c show the user mental model description of the home heating system for Participants X, Y, & Z. There are clear variations in the complexity and elements present in the descriptions. In this section, we will briefly describe the function of the heating system relating to each model. This chapter will then focus on characteristics of each model that explain differences in the strategies adopted by each participant to control the heating system, and relate this to mental model theory to explain differences in the strategies adopted. In doing so, how the user mental model at a system level warrants consideration even when users hold the same device models of a key heating control, will be illustrated.

Figure 41 shows the model description for Participant X. How the heating system functioned according to this description is paraphrased below:

*The thermostat has a sensor that measures the room temperature in the hallway. It compares this room temperature and the temperature you have set on the thermostat. If there is a discrepancy, it will communicate to the box in the kitchen that the boiler has to go on. The light on the box in the kitchen will go green when the heating is on, and red when the heating is off. When green, water heats up in the boiler then travels to the radiators. You will then be able to feel the heat in the radiators. The thermostat will try to match the room temperature to the set temperature. When it has reached the set temperature it will send a signal telling the boiler to turn off.*

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Participant X – User Mental Model Description of Home Heating System

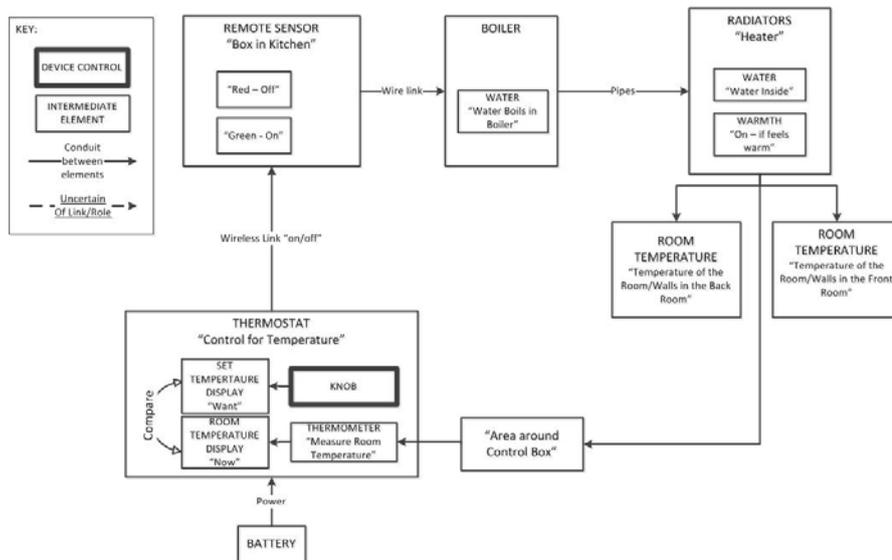


Figure 40 - User Mental Model Description of the home heating system for Participant X

The paraphrased description indicates a clear 'feedback' shared theory for the thermostat based on the description by Kempton (1986). Figure 41 describes the simplest model of the 3 participants, and shows the thermostat as the only control device present. It is unsurprising, then, that this is the sole device to feature in Participant X's strategy for heating control. This matches the findings in [Chapter 3 and](#) Revell & Stanton (2014). However, unlike the participant referred to in that study, Participant X makes reference to a programmer device early in his interview transcript, but described it as *'too complicated'* and *'too much trouble'* to use. He did not refer to it when constructing his mental model description of the heating system. The importance of background knowledge in mental model theory, as a repository from which user mental models of devices can be inferred has been widely adopted in the literature (Johnson-Laird, 1983, Bainbridge, 1992, Moray, 1990, Revell & Stanton, 2012). The programmer clearly was present in Participant's 'knowledge base' (Bainbridge, 1992), but did not make it to what Bainbridge describes as the 'working storage' (user mental model) referred to when

operating the heating system. Different theories of mental models include different concepts (Revell & Stanton, 2012). Bainbridge (1992) emphasised how meta-knowledge, which is, knowledge and outcomes of the users own behaviour, affects the strategies chosen when performing in complex systems. Participant X's difficulty at operating the programmer, could have assigned 'meta-knowledge' to the internal concept of that device, preventing inclusion in the user mental model. This absence would then rule out selection of the programmer as part of a home heating strategy, despite awareness of the existence of the device within the home. The problem of poor usability of home heating programmers is clear from the literature (Peffer et al., 2011, Peffer et al., 2013, Combe et al., 2011, Meier et al., 2013). Absence of programmers from user mental models of heating, when present in background knowledge, may be a widespread problem that gives an alternate explanation to the reluctance by users to revisit operating the programmer after initial frustrations. The strategy to make devices more intuitive is certainly positive. The provision of clear, immediate, and user specific information for operating programmers is also essential for energy savings to be realised (Darby (2001). However, householders who have a programmer absent from their mental model of home heating are unlikely to seek out changing their device to a different model to save energy. Overcoming negative meta-knowledge about the usability of the programmer is also necessary.

Figure 42, produced by Participant Y, shows the most complex model description of the three participants. The functioning of the system agrees with that described by Participant X, but is appended by a range of additional heating controls to the thermostat (Figure 42).

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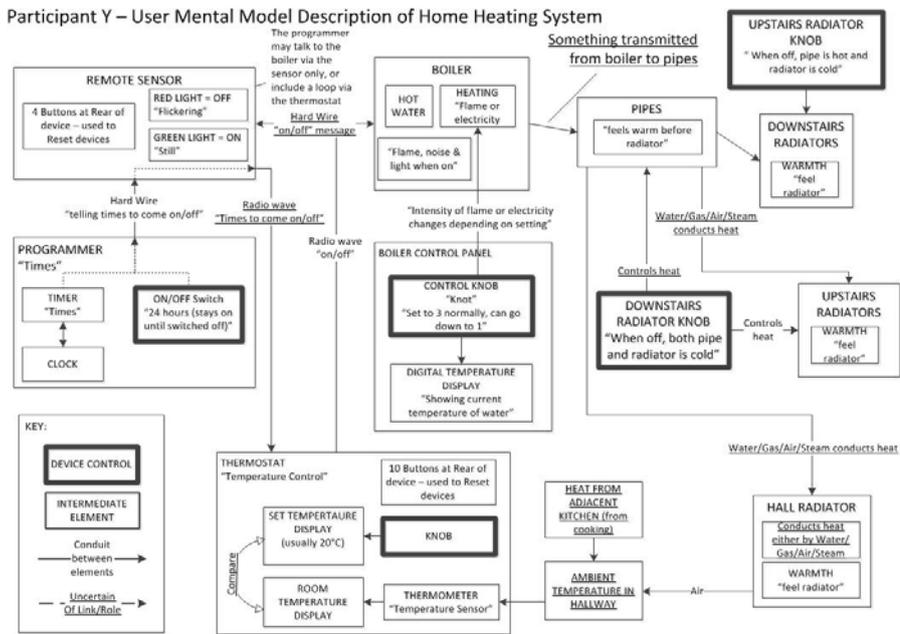


Figure 41 - User Mental Model Description of the home heating system for Participant Y

The boiler override is described as an 'on/off' switch and in Figure 39, it can be seen linking to the Remote Sensor. This then connects to the thermostat so that it knows during which times it can manage the boiler on/off times (in response to the hall temperature). The programmer is described as an automatic version of this boiler override, with the times for thermostat operation programmed into it. Figure 39 also shows a control knob in the boiler control panel that connects to the boiler and controls the intensity of the flame. This in turn affects the temperature of the water going through the pipes into the radiators. This understanding of the functioning of controls is essentially correct. Participant Y misunderstands the functioning of the final control in Figure 42, however, the TRVs. According to participant Y, these controls allow hot water into the pipes or radiators when turned on, but block the water from entering the pipes or radiators, when turned off. Participant Y appears to think of the TRVs as a type of manual on/off switch. The actual functioning of this device is akin to the hall thermostat. The TRV measures the

temperature in the area surrounding the radiator. Each setting on the control is associated with a temperature range. When this temperature range is reached, the TRV slowly blocks the flow of hot water entering the radiator, so no more heat is emitted. When the temperature surrounding the radiator drops below the set temperature range, it slowly unblocks the flow of hot water entering the radiator, so heat can again be emitted. The literature describes how slow responding systems are problematic. Operators of such systems usually achieve far below optimum performance (Crossman & Cook, 1974) and it is more difficult for users to form an appropriate mental model of function (Norman, 1983). The strategy adopted by Participant Y agrees with Brown & Cole (2009) that poor comprehension of heating controls leads to suboptimal levels of comfort.

With such a range of controls in their mental model, what is the reason for Participant Y choosing the strategy in 3b? The data in figures 1 and 3b refer to a specific week in November 2011. The strategy depicted refers to that time period, which was the start of the cold period, and the heating had not been used a great deal before this. It makes sense to use the boiler override, which requires no setup at this early stage of operation. As it got colder from late December, Participant Y reports in his transcript that his strategy changed. The programmer was then set to control the heating to cover a 12 hour overnight period between 8pm and 8am. Whilst we do not have boiler or thermostat data for Participant Y beyond November, it is highly likely that the energy consumed will have significantly increased when the programmer was adopted as the main control, due to extended night-time operation, and the thermostat sensor positioned downstairs with a single radiator emitting heat. Participant Y described a strategy in Figure 39 of keeping only 3 radiators plus the hall radiator turned on, and the others turned off. The impetus for this strategy was to save energy in rooms that are not occupied for long periods. However, this strategy is only effective if the rooms where the radiators are turned off, have their doors permanently closed. Otherwise filtration of warm air from the heated rooms to the colder rooms will lower temperatures in the heated rooms, so the radiators will need to emit more heat. Whilst Figure 42 does indicate that the hot kitchen heats the ambient temperature of the hall, he does not refer in his transcript to infiltration to other rooms lowering the temperature in the hall, nor emphasise shutting doors as part of his strategy

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(as described by Participant Z). Participant Y described his strategy for adjusting radiator controls when using the programmer as follows: During the day, all radiators (apart from the hall) were turned off. During the evening, the downstairs radiators were kept on, and on going to bed, the downstairs radiators were turned off and the upstairs radiators were turned on. This level of control assumes a faster responding control than the TRVs installed in this home. As such, and as was seen in Figure 36, the majority of the time, the internal temperature would be below comfort levels, regardless of the thermostat set point.

Moray (1990) proposed an alternate view to Bainbridge (1992) regarding the mechanisms behind mental models of complex systems, which may explain differences in home heating strategies. He related the organisation of information in mental models in terms of lattice theory, and proposed that operators selected strategies associated with Aristotle's four causal hypotheses. A lattice containing a hierarchy of cause specific information, would be derived from the background knowledge of the system. Depending on the strategy chosen (formal, material, efficient, or final), the operator would limit reference to information in the associated lattice (until a change of strategy was adopted). It is proposed that different attitudes to home heating use could be interpreted in terms of different causal strategies, resulting in focus on the control devices present in the associated lattice. For example, Participant Y's determination to save money by saving energy would trigger reference to an *efficient* cause (by considering ways the heating system can confine and limit heat from being emitted), whereas Participant Z's focus on 'keeping warm' would be classed under a *final* cause (as he is only considering how the heating system can provide comfort). Participant Y's determination to control heat flow may have motivated an interest in home heating that resulted in a greater number of devices being present in his background knowledge, from which to infer the mental model description in Figure 42.

Participant Y also describes adjusting the boiler water control as atypical, such as when going on holiday during winter, as part of a strategy to prevent the pipes from freezing. By having a more complete mental model of the heating system, the options for different strategies to suit different circumstances are increased. However, it also presents a risk of inappropriate strategies being

adopted, particularly if the device model for a single control is inaccurate and the understanding of how the heating system operates within broader systems are not understood

Figure 43 shows the mental model description for Participant Z. The mental model description broadly agrees with that provided by Participant Y, with the addition of a programmer device and on/off switch to the whole system. The remote sensor is represented in this description as a ‘mystery device’ as Participant Z was unsure of its function. However, as the remote sensor was not a control device, merely an intermediary for communicating to the boiler, the omission of this element does not impact the strategies chosen.

Participant Z – User Mental Model Description of Home Heating System

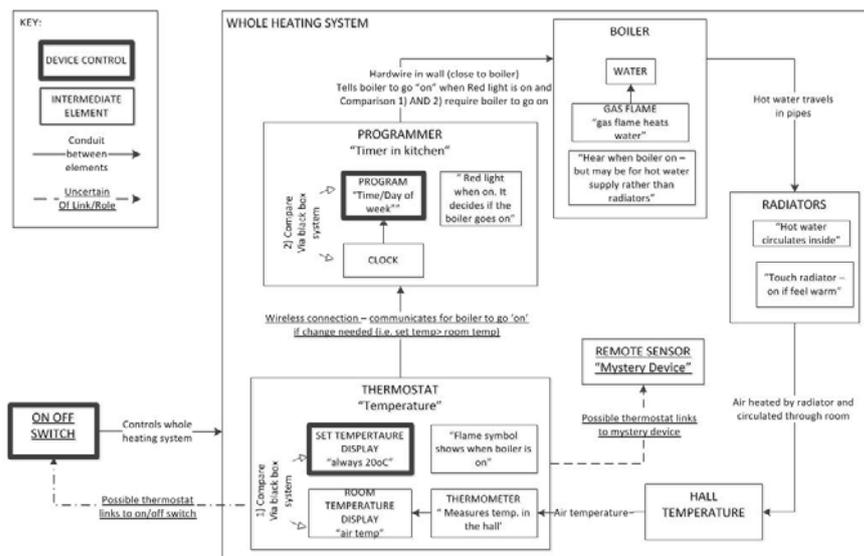


Figure 42 - User Mental Model Description of the home heating system for Participant Z

Unlike the description provided by participant Y (see Figure 42), control devices such as the Boiler temperature control, Boiler override & TRVs are absent from the description in 4c. The lack of awareness of these devices explains why they are absent from the typical strategies shown in Figure 40. From the transcript, Participant Z is a bit unsure of the actual role of the power switch but imagines, correctly, that this is an electrical isolation switch,

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required for the heating system to operate. He does not consider it as a heating control in the same way as the thermostat and programmer, so this does not form part of his typical strategy for controlling heating. Using Moray's (1990) lattice theory, the power switch would form part of a *formal* cause strategy (the system can operate when it is in the 'on' position), rather than a *final* cause relating to providing comfort in the home.

Moray's (1990) perspective on how strategies are chosen provides some interesting implications for the design of technology or provision of energy conserving advice. If, as in this case study, householders with an 'efficient' cause strategy are more likely to have complex mental models for home heating (featuring a large number of controls), then technology that helps promote the way different control devices work together could help realise energy conservation goals. Simplified 'single' device energy saving advice is clearly inappropriate for this audience. A simplified message may be most appropriate for an audience with a 'final' cause strategy, who may be more predictable in the way they follow advice.

## 5.4 Summary and Conclusions

In summary, we have seen how mental model theory, and differences in the topology of the mental model description of the heating system, can play a useful role in explaining differences in strategies chosen, despite users holding the same 'Feedback' shared theory of the thermostat. In this case study, the larger number of control devices evident in the description led to strategies involving more control devices. Inappropriate mental models at the device level for alternate heating controls (such as the TRVs with Participant Y), were shown to enable inappropriate inclusion in a home heating strategy: In this case, contributing to wasted energy and inadequate comfort levels. Kempton (1986) described limitations to users with a 'Feedback' shared theory to include an understanding of the effect of infiltration on comfort and external thermodynamics on rate of heat loss. The interview transcripts brought to light that the effect of infiltration on appropriate functioning of a central thermostat, (rather than comfort alone), is highly pertinent. Where this understanding is missing, and other devices that affect heat output make up part of the householders' strategy (e.g. TRVs) there is a further risk of wasted

energy. Whilst two of the participants mentioned infiltration in this sense in the interview transcripts, there was no evidence in any of the transcripts of an understanding of external temperature on rate of heat loss. That two of the participants had opted to use heating late at night when external temperatures are lowest, corroborates Kempton's (1986) that energy can be systematically wasted with a broadly accurate device model of the thermostat. Where strategies combine thermostat use with the programmer, energy use may be reduced (as with participant Z, where the heating is set to turn off before bedtime), or increased (as with participant Y, who described extending night-time heating after incorporating the programmer into his strategy). Similar variations have been found by Peffer et al. (2011) and Shipworth et al., (2010). It is clear that householders' mental models of home heating needs to include the impact of external temperatures for significant 'systematic' energy savings to be made. Both technology, and energy saving advice could play a big role in this endeavour, by communicating appropriate behaviour with controls in the context of the environmental setting.

Understanding device models are useful, especially where the limitations affect energy consumption. However, patterns of behaviour may not be limited to the device under consideration. Understanding of user mental models at system level allows appreciation of why some combination of devices are used, and where these can lead to a positive/negative effect on energy consumption. Mental Model theory can help to understand why specific devices within mental models at a system level are chosen to form strategies of home heating control. Efforts to understand or mitigate for inappropriate use by looking at outputs from single devices (e.g. thermostat, boiler, programmer etc.) carry a risk, particularly for householders who have complex mental models. The implication for technology and energy saving advice is to promote in the householders a 'systems view' of home heating control (Revell & Stanton, 2014).

Efforts to advise householders on ways to reduce consumption has been shown to be ineffective at ensuring changes in behaviour (Darby, 2001), even when delivered via home visits (Revell, 2014), or even when advice has been actively sought by householders (Mahapatra et al., 2011). Darby (2001) identified a considerable amount of wastage in standardised advice packages, with only some aspects relevant for individual households and confusing information

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resulting in none of the advice being acted on. A growing body of research points to the need for clear, tailored advice that enables householders to act on intentions to reduce consumption (e.g. Darby , 2001; Fischer , 2008; Kuo - Ming et al.,2012;) and approaches have been developed to use technology as a means for providing different forms of custom advice (e.g. Shigeyoshi et al.,2011; Shah et al.,2010). This chapter has illustrated how householders with a Kempton (1986) Feedback shared theory of the thermostat (that overlooks the influence of thermodynamics and heat flow in a broader system) can unintentionally waste more energy whilst endeavouring to conserve it. The findings suggest that tailored advice is required, whether through government campaigns or technological innovations. This advice should consider variability, not just in demographics and attitudes, but in the thought processes that translate intentions into actions. In doing so, promised energy savings may finally become a reality.

Chapter 6 takes this sentiment one step further and looks at how variability in user mental models of home heating could be used to form a design specification for home heating interaction that promotes greater consistency in mental models with a view to encourage appropriate behaviour with home heating controls.

## 6. Mind the Gap: A case study of the gulf of evaluation and execution of home heating systems

### 6.1 Introduction

[This chapter provides a methodology to facilitate investigation of hypotheses 3 and 4 described in the introduction in section 1.2. Using data collected by the QuACk method described in chapter 4 it uses Norman's Gulf of evaluation and execution to determine design elements that should be emphasised to promote a mental model of home heating that would allow appropriate behaviour with controls. This provides a starting point for investigating how device design influences users mental models \(Hypothesis 3\), as well as the overall aim, how design can be used to influence mental models of home heating, to encourage patterns of device use that influence the amount of energy consumed over time \(Hypothesis 4\). The findings from this chapter feed into design decisions made in chapter 7 to create a simulation to test if user models are altered as intended in chapter 8.](#)

Reducing domestic energy consumption is one way the UK aims to fulfil legislation requiring greenhouse gas emissions to be cut by 80% by 2050 (Climate Change Act 2008 ). Home heating contributes 58% of domestic energy use in the UK (Department of Energy and Climate Change, 2011). Considerable differences in amount of energy used in homes results from occupant's behavioural differences (Lutzenhiser and Bender 2008). Understanding the cause of behavioural differences in the way home heating systems are used, provides an opportunity to develop approaches to reduce domestic energy consumption. The purpose of this chapter is to provide insights that could inform the design of a home heating digital control interface to encourage appropriate heating control. 'Appropriate heating control' is considered, in this thesis, to be pragmatic operation of heating devices so householders fulfil their heating goals with minimal wasted energy. The approach taken in this chapter is to apply Norman 's (1986) theory of the Gulf of Evaluation and Execution to data collected on mental models and typical behaviour relating to a domestic gas central heating system.

## Chapter 6 – A case study of the gulf of evaluation and execution of home heating systems

Home heating is considered by Sauer et al. (2009) to be the most complex system in the domestic setting. The domestic setting, varies considerably in its occupants, their energy and heating needs (Lutzenhiser, 93; Stern & Aronson, 84), and therefore heating goals. This diversity encompasses households, that vary in structure, level of insulation and external temperatures, all of which affect the thermodynamics of the dwelling (Kempton, 1987). There are also considerable variations in the heating system equipment within peoples' homes, particularly due to their modular nature. This allows wide-ranging combinations of thermostats, programmers, thermostatic radiator valves (TRVs), boilers, radiators and heat sensors. Different configurations can result in differences in the type and range of heating solutions available. Due to the high cost of equipment and installation, householders typically inherit a heating system configuration when they buy or rent a house. This means there is no guarantee that householders' particular goals can be satisfied by the existing system. These multiple variations complicate approaches to reduce consumption that intend to put consumers 'in control' of the heating system. With so many ways of controlling the heating system, it is difficult for householders to understand how to achieve their heating goals without wasting energy. With variations between households in the system set up, it is difficult for government agencies to offer clear and effective 'one-size-fits-all' advice to householders to realise this end. Government campaigns in the UK (e.g. [www.energysavingtrust.org.uk](http://www.energysavingtrust.org.uk)) tend to focus on energy reduction. Guidance and assistance to reduce consumption, that recognize variations in householders' heating goals, their capabilities and the capabilities of their heating system, will be more eagerly adopted and maintained long-term.

Key issues that prevent householders operating heating systems appropriately include the cognitive and physical usability of the system. Kempton (1986;1987) proposed that variations in the way people operate their home heating thermostat, resulted from their differing 'mental models' of the way the device functioned. Kempton (1986) found evidence that behaviour patterns associated with some mental models were more energy efficient than others, as they encouraged 'night set back'. [In Chapter 3](#), Revell & Stanton (2013) found faulty or incomplete mental models explained non-optimal operation of home heating devices; where energy was either being wasted, or

heating goals failed to be achieved. Considerable energy savings could be made if heating systems were effectively programmed (Combe et al. 2011, cited Gupta et al. 2009), yet in a study by Combe et al. (2011), 66% of participants were unable to complete the set programming task. Peffer et al. (2011) discuss how more energy can be wasted by incorrectly programmed heating controls than if their manual alternatives had been used. Users are not 'in control' of their heating system in the way manufacturers intend, if they misunderstand how home heating systems contribute to their goals, and find it difficult to operate the heating controls.

One way technology has been adopted to assist householders with the management of their domestic energy use is the development of third party interfaces. These engage users by providing feedback on their consumption (sometimes in context to other users), and allow varying degrees of digital control over their physical systems. Originally focussing on electricity consuming devices (e.g. Alertme), more recent offering now target remote home heating control (e.g. British Gas Hive Active Heating, Tado, Honeywell Evohome), or use intelligent automation of home heating (e.g. Tado, NEST). Each of these applications take different approaches to the way information is presented and the type of control possible, and were designed to achieve different objectives. Whether these approaches support or hinder appropriate consumption, would depend on the variations in the heating system, house structure and householder's goals.

To gain insights that could help specify the needs of an interface to support appropriate consumption from the perspective of overcoming cognitive and physical usability issues, this chapter looks to Norman's (1986) theory of the Gulf of Evaluation and Execution. Norman (1986) introduced the idea of the 'gulf of evaluation and execution' to explain why computer users did not operate systems in the way system designers intended. Norman emphasised that this problem specification applied equally to physical systems, directing consideration of home heating as a suitable domain for application. Norman approximates 7 stages of user activity to describe how the user bridges the gulf. These stages take into account user goals, their perceptions, intentions and actions. Norman (1986) emphasised the need for user mental models to be compatible with the design model of the system to effectively bridge the gulf of evaluation and execution. Norman (1986) supports the view of Buxton

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(1986) who highlights how the usability of the input controls can play a significant part in influencing the choice of control device operated. This has particular relevance for home heating control devices, given the number of different control devices that can make up the heating system, and the range and variations in design of each device.

### 6.1.1 Norman's (1986) Gulf of Evaluation and Execution

Norman's gulf of evaluation and execution represents the distance between a user's psychological goals (e.g. I want to be warm whilst watching TV with my spouse in the living room) and physical actions necessary, *with a specific system*, to achieve those goals (e.g. press the boiler override button on my programmer). According to Norman (1986), the user bridges these gulfs by going through a number of stages. (Figure 44) A user bridges the gulf of execution, by a) Forming their intention to use the system to achieve their goal, b) specifying the action sequence that will achieve their goal, and c) Executing the necessary actions with the input devices. They also need to bridge the gulf of evaluation by a) Perceiving the state of the system, b) Interpreting the state of the system so it can be compared to their goal, and c) Comparing the system state to their goal. Combined, with goal specification, these stages make up Norman's (1986) 7 stage model for user activity, illustrated in Figure 44 with home heating as the context. This model shares similarities with Rasmussen's (1983) 'decision ladder' concept . If people are using home heating in a non-optimal way, it suggests that it is difficult to use the heating system in an optimal way. The 7 stage model for action, may bring insights into why people fail to appropriately manage their home heating systems. These insights could point to design requirements that may help reduce wasted energy.

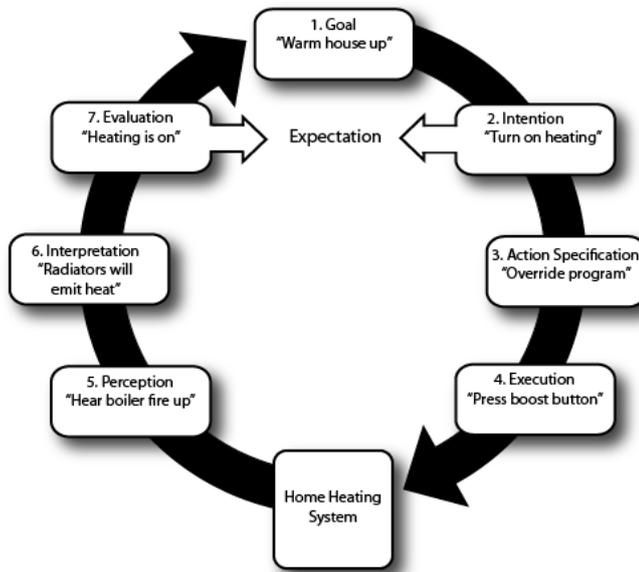


Figure 43 – Norman’s (1986) Seven stages of user activity applied to home heating context. Stages 2-4 bridge the ‘gulf of execution’ and stages 5-7, bridge the ‘gulf of evaluation’.

Norman (1986) suggests that users will be more successful at achieving their goals when interacting with systems, if efforts are made to facilitate users at each of the 7 stages of activity. This can be achieved, either by bringing the user closer to the system (through experience, or training), or by bringing the system closer to the user (Norman, 1986). In the home heating context, the designer does not control the level of experience of the user, nor can they demand they undergo home heating training. Design based approaches to ‘bring the system closer to the user’ to effectively bridge these gulfs, may result in more appropriate use of home heating systems by householders. Evidence of this approach has been offered by Staffon et al. (1989) in the design of power plant processes, where provision of an interface containing a thermodynamic model of plant performance ensured operators had a compatible ‘mental model’ of the system states, before executing the controls. Similarly, Connell (2010) concluded that the gulf of execution and evaluation had advantages over analysis methods that considered taxonomies of error (e.g. Meister, 1977) or skills and rules (e.g. Reason, 1990). When performing

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error analysis on ticket vending machines, Connell (2010) found viewing erroneous button presses within the framework of the gulf of evaluation and execution, more simply explained causes of error and pointed to practical design solutions. The Gulf of Evaluation and Execution has also been used to inform improvements to direct manipulation interaction (Hutchins et al., 1985; Keiras et al., 2001; Mohageg, 1991), understand difficulties in using programming languages (Ko et al., 2004; Edwards, 2005) and to facilitate human-robot interaction (Scholtz, 2002). Norman (1986) believes many systems can be characterised by how well they support the 7 stages of action. Cuomo et al. (1994) applied 3 different evaluative methods to determine how well they addressed issues at each of the 7 stages of user activity. Cuomo et al (1994) found methods better addressed the stages that made up the gulf of execution (intention, action specification, execution), than those associated with the gulf of evaluation (perception, interpretation and evaluation).

Whilst systems have been evaluated from the perspective of the gulf of evaluation and execution to identify or explain execution issues, this has generally been done at the system interface or behaviour level. This chapter takes a different approach, by focussing on the users' mental models.

### 6.1.1.1 Conceptual and Mental Models of home heating systems

Mental models are internal constructs that are considered important in predicting, understanding and explaining human behaviour (Wickens, 1984; Kempton, 1986; Craik, 1943; Johnson-Laird, 1983) The notion has proved attractive when considering interface design (Carroll and Olson, 1987; Wiliges, 1987; Norman, 2002; Jenkins et al, 2010), to promote usability (Norman, 2002; Mack and Sharples, 2009; Jenkins et al. 2011), or enhance performance (Stanton and Young, 2005; Stanton & Baber, 2008; Grote et al. 2010; Bourbousson et al. 2011). The definition of mental models has been the topic of much debate over the last 20 years (Wilson and Rutherford, 1989, Bainbridge, 1992, Richardson and Ball, 2009 & Revell & Stanton, 2012).

In this chapter Norman's (1983) definition of mental models will be used. He distinguishes between user mental models, (UMMs) and Conceptual (or 'Design') models. The UMM is defined as 'the actual mental model a user might have' gauged by observations or experimentation with the user (Norman,

1983). The Conceptual (or 'Design') Model is defined as the model which is invented by designers to provide an accurate, consistent and complete representation of the system. For a fuller discussion of the distinction between these and other definitions of mental models, see Revell & Stanton, 2012.

For effective bridging of the gulfs, Norman (1986) demands the user mental model is compatible with the design model of the underlying system. Norman (1986) proposes that the designer can promote compatible user mental models through the choices they make when constructing the system image, which in turn influences user mental models (see Figure 45).

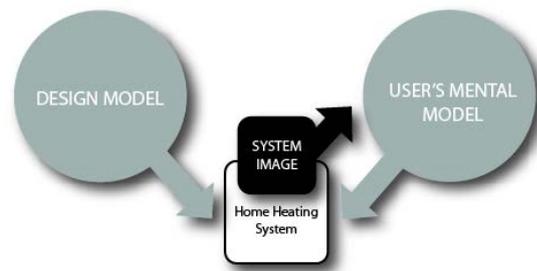


Figure 44 – According to Norman (1986), the system image contributes to the user's mental model, influencing their interaction with the heating system. Appropriate operation is supported, if the user's mental model is compatible with the design model of the heating system.

Norman (1986) considered the conceptual model (or design model) as the 'scaffolding' for the bridges that enable users to cross the Gulfs of Evaluation and Execution. If this underlying structure is unsound, or misplaced, there could be an impact on the 7 stages of activity, ultimately affecting the way users respond to the system design at higher levels (see Figure 46). As a result, well intentioned design efforts may fail to support users, or worse, confuse or mislead them. It is therefore of interest to identify where problems with the mental model 'scaffolding' of the home heating system could cause difficulties that prevent appropriate operation.

Chapter 6 – A case study of the gulf of evaluation and execution of home heating systems

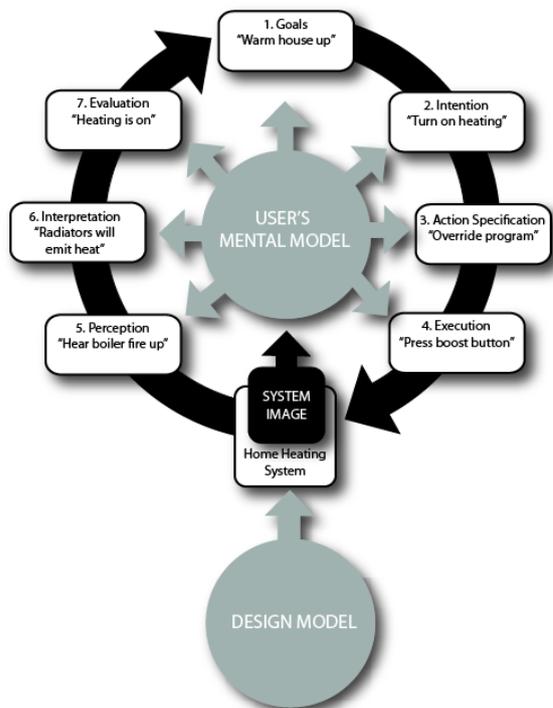


Figure 45 –The compatibility of the user's mental model to the design model at each of the 7 stages of activity characterise the 'structural integrity' of the bridges that span the gulf of evaluation and execution.

This chapter refers to data collected from 6 householders from dwellings with identical structure and central heating systems, using the Quick Association Check (QuACK). This method is described in detail in chapters 3 and 4 and was designed to explore association between mental models and behaviour. The method provides outputs in the form of mental model descriptions (similar to concept maps), graph based outputs of typical usage and interview transcripts. QuACK was also used to collect data from an expert in home heating systems from the heating control manufacturing company who designed the devices installed in the households. This data was used to represent a 'design model' and 'recommended execution' of the home heating system, providing comparable data with which to compare the householders' data.

This chapter is structured to first illustrate the design model and compatible user mental model that would facilitate the recommended execution. How the 7 stages of activity are bridged using the design model is then described. Next, the home heating 'system image' will be considered to understand the ways it supports or undermines householders development of a compatible mental model that enables appropriate execution of home heating controls. Following this, the results of user mental models of householders in our case study, and their behaviour patterns, will be compared to that proposed by the expert. The 7 stages of activity will be used as a basis for discussion to help understand why differences arise. The insights gained that help detail how key features of the user interface impacts users' mental models so that home heating and energy saving goals are effected at different stages of activity, will be summarised in a table in Appendix 4. Our conclusion will make reference to key points based on this table.

## 6.2 The Design model

The Design model is the conceptual model of the system (Norman, 1986), so will be determined by the designer and developers of the system. As discussed in the introduction, the Home heating system is a composite of a number of different components (boiler, programmer, thermostat etc.), often made by different manufacturers. All of these different components have their own 'design model' at the component level, as well as a composite design model at the system level, based on how the components are combined within a household. Whilst design models of specific components could be inferred from user instruction and installation manuals, these tended to discuss device function in isolation, or at most, with very general reference to connecting devices. This presented a problem when seeking a design model for the central heating system as a whole, which could be compared with User Mental Models of a specific system.

To overcome this difficulty, an expert that could give an overview of a specified central heating setup, was interviewed. The expert approached had 40 years' experience with home heating systems and worked for the manufacturing company that produced the key control devices present in the case study households. To enable direct comparison with the householders' data, the expert was interviewed using the QuACK method (chapter 4). For reference, the

## Chapter 6 – A case study of the gulf of evaluation and execution of home heating systems

expert was provided the layout and specification of the components present in the case study households so he could keep this in mind when describing his mental model of the system. To provide an example of ‘appropriate’ behaviour with this heating system, the expert was asked to respond to questions, as if he was making recommendations to a member of a family with school age children, with one adult at home during the day, and the other working outside the home. This reflected the family structure of householders in the case study.

### 6.2.1 The design model expressed as an expert ‘user mental model’

Figure 47 depicts the mental model description produced using the QuACK method (Revell & Stanton, 2013 and chapter 4), which has been redrawn for clarity. It shows at a system level, the different components, connections and rules associated with the central heating system from the case study. Each box in Figure 47 represents a component of the central heating system with the benefit of the system to effect ‘room temperature’ (in dotted lines). The boxes outlined in bold, represent home heating controls that a user could interact with. The boxes with a light outline represent ways in which devices indicate the state of the system. The arrows between boxes represent the direction of ‘cause and effect’. Rules and functions of elements and links are annotated with text.

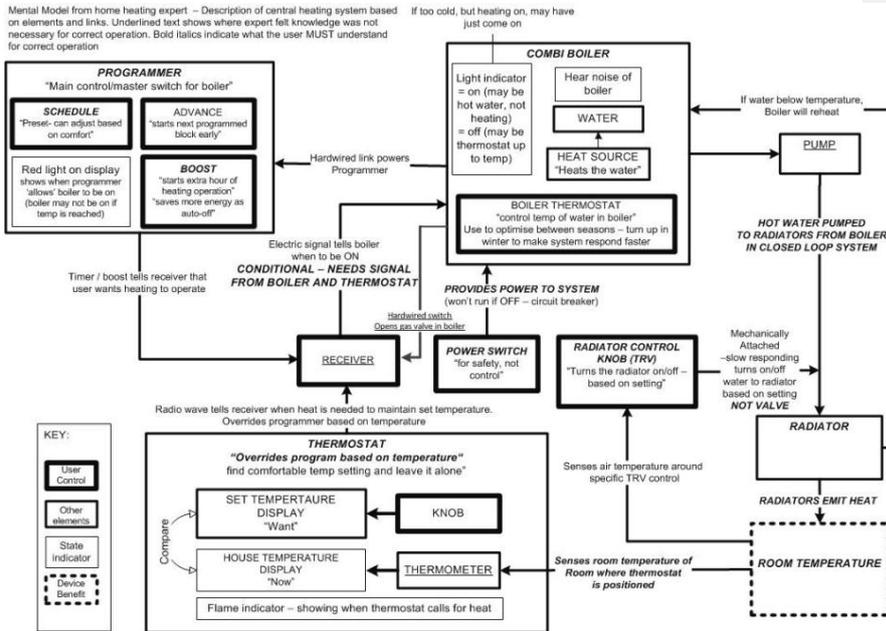


Figure 46 - The home heating system 'Design Model' represented as an Expert User Mental Model description

Figure 47 illustrates an interrelated relationship between heating controls and the system benefit. This design model is far from straight forward, but Norman (1986) does not consider it necessary for a householder to understand the full complexity of the design model of a device, in order to use it effectively. Norman (1986) does require that the user mental model is 'compatible' with the design model, however. Following discussions of appropriate operation with the heating system, the home heating expert was asked to identify which parts of the design model shown in Figure 47 he thought were necessary. That is to say, what 'compatible' mental model would allow a householder to operate the system appropriately. These are identified in Figure 47 with bold italics and tabulated with explanations in Table 13 - Expert considered 'essential' components of compatible user mental model for appropriate operation of heating system. It should be emphasised that as the opinion of the home heating expert, these components provide a starting point, rather than prescriptive guidance on how to build a compatible user mental model of a home heating system.

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Table 14 – Expert considered ‘essential’ components of compatible user mental model for appropriate operation of heating system

<b>Essential Components</b>	<b>What user needs to understand for appropriate operation</b>
<b>Programmer Schedule</b>	Master control for the heating system
<b>Programmer Boost</b>	Override for schedule that automatically switches off after 1 hour
<b>Thermostat</b>	Only calls boiler for heat when set point temp > temp of room
<b>Room Temp</b>	Only room temp where thermostat is situated is used to control boiler
<b>Boiler</b>	Heats and pumps hot water around system
<b>Conditional rule in Boiler</b>	To operate, boiler requires both programmer AND thermostat to call for heat
<b>Pipes &amp; Radiators</b>	Contains hot water in closed loop system (helps user understand operation)
<b>Thermostat Radiator Valve (TRV)</b>	Not for frequent adjustments - slow response control, used for limiting heat long-term, turns radiator on when set point > sensed temp, and off when set point < sensed temp
<b>Master ON/Off switch</b>	Not for heating control, but safety (electrical isolation) when maintaining system

To provide a visual example of what a compatible user mental model to the 'Design Model' would look like, the essential components of the design model in Figure 47 have been redrawn in a simplified form in Figure 48.

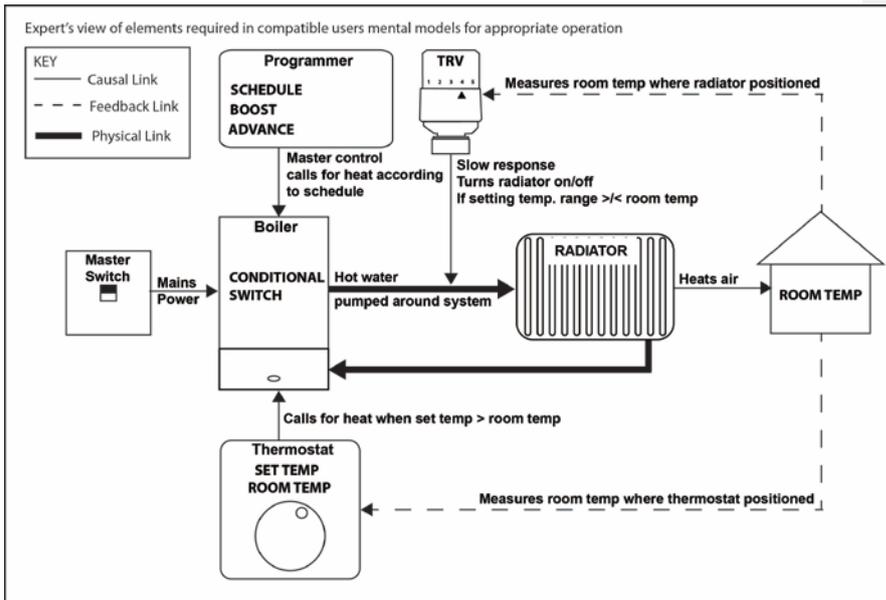


Figure 47 - The elements of the design model that should be evident in compatible user mental models of a home heating system.

Figure 48 depicts (from the left), the Master Switch that supplies electricity to the heating system, linked to the boiler. It shows the boiler with two controls attached to it, the programmer (with schedule/boost/advance features) and the thermostat control. The programmer schedule calls for heat to the boiler at specific times. It has a boost button that adds an ad-hoc single hour to the schedule from the time pressed, and an advance button, that will set the next part of the schedule to start immediately. The boiler has a conditional switch that requires the programmer and the thermostat to both be calling for heat before it will pump hot water around the pipes to the radiators. The radiators emit heat to the air in the room, resulting in a change in room temperature. The thermostat takes an estimate of the house temperature from the room where it is positioned. It compares this room temperature to its set temperature value, calling for heat from the boiler only if this is higher. Before

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reaching the radiators, the TRV can control if the hot water will enter the radiator. This is a crude slow response control and works like the thermostat. If the room temperature measured by the TRV is higher than the temperature range associated with its set point, then it will allow hot water to flow into the radiator. If lower, the TRV will slowly block access, so hot water must bi-pass that particular radiator, and that room will no longer continue to receive heat from the radiator.

6.2.2 What does ‘appropriate’ home heating control look like?

What an expert in home heating considers a ‘compatible user mental model’ to look like, has been shown. Based on the behaviour output of QuACK, Figure 49 depicts the expert recommended use of heating controls over a typical week in winter. This reflects the desired state of the system that would result from stages 3 and 4 of Normans’ (1986) 7 stages of activity (how householders specify and execute their heating goals with their home heating system). The recommendation will represent a ‘standard’ to which householders reported behaviour will be compared.

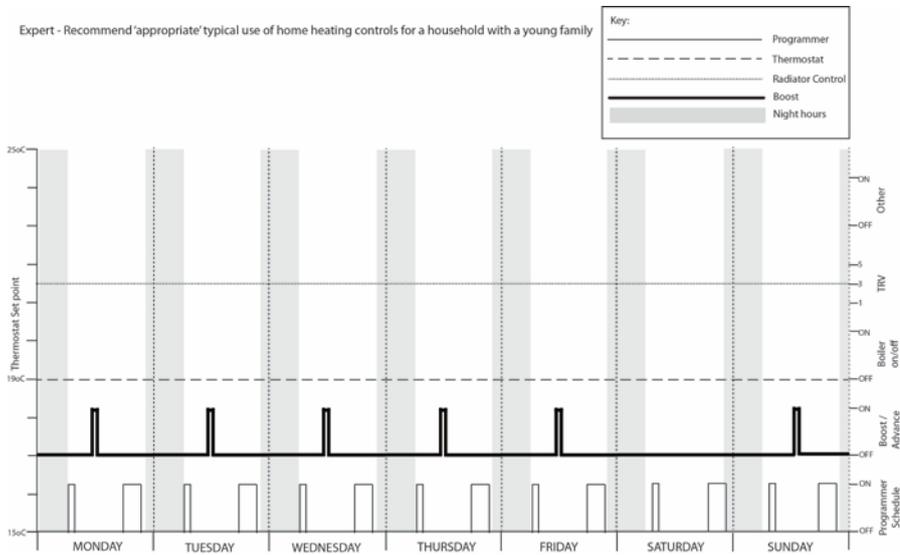


Figure 48 - Recommended state of the home heating system - stage 3 of Norman's 7 stages of activity.

### **6.2.3 7 stages of 'appropriate' activity with a home heating system**

Stage 1 of Norman's (1986) 7 stages of action represents goals. The heating goals assumed by the expert for a family with young children were to 1) enable the house to be comfortable during routine times (e.g. in the morning on waking and getting ready to leave the house, and at the end of the day when returning & relaxing before bed) 2) to have ad-hoc comfort on demand when the house is occupied (e.g. by parent during the week, or whole family at weekend) and 3) to avoid wasting money on heating the home when it is not needed (e.g. when the house is unoccupied, or when occupants have high activity levels, doing exercise or housework). Norman's (1986) second stage of action, Intentions, are closely related to goals and represent the decision to act, to achieve the goal. The intentions described by the expert, were to use specific control devices of the central heating system to appropriately achieve these goals. For goal 1, the expert's intention was to set the long-term heating controls and for goal 2, the intention was to override these pre-set heating controls. The intention to avoid heating the home when not needed, (goal 3) was to utilise residual heat, to avoid heating long-term unused rooms, and to check if comfort levels are the result of the room temperature, or activity levels, before deciding to override the system. How Norman's (1986) 7 stages of activity relate to these 3 home heating goals are summarised in Figure 50 below.

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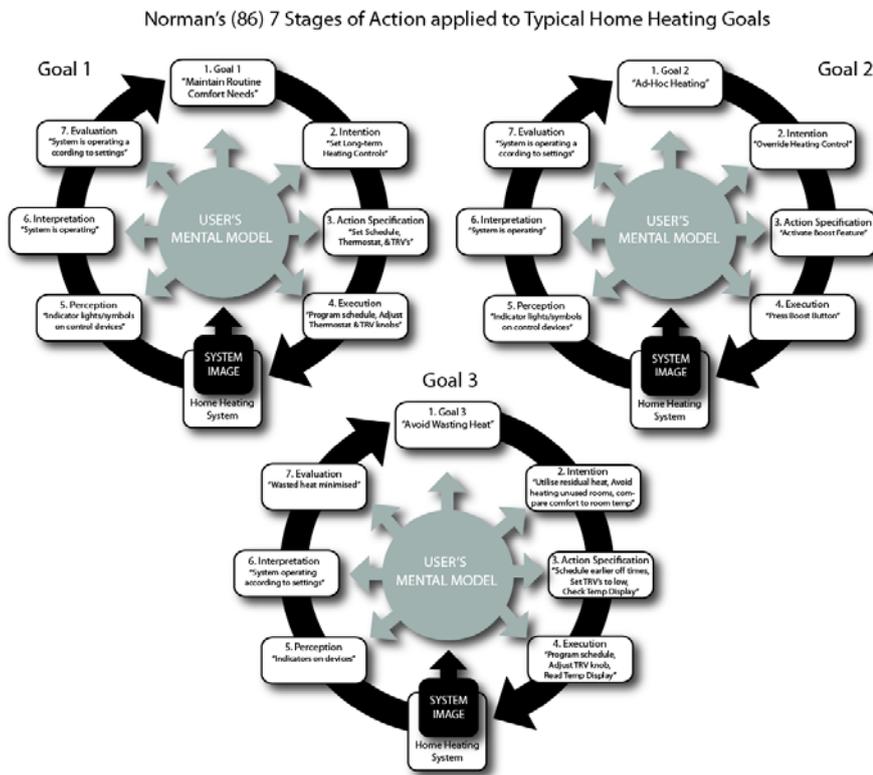


Figure 49 –The 7 stages of activity broken down by typical home heating goals

Stages 3 and 4 involve mapping the user goals and intentions onto a desired home heating 'system state'. In this context, it represented the required adjustments of the programmer, thermostat, boost and TRV to fulfil the goals, and the actions necessary for execution. Figure 49 depicts stage 3, the intended 'state' of the home heating system controls following this execution. To fulfil goal 1, the expert recommended 'action specification' was for the programmer to be used in conjunction with the Thermostat and TRV's. At the bottom section of Figure 49, the programmer timeslots are set from one hour before the household awakes during weekdays, to enable a comfortable temperature on waking. In the evening, the programmer timeslot is set from 30mins – 1 hour before occupants return from work or school, allowing time to reach a comfortable temperature when the house will be occupied. The expert

specification was to program a timeslot for 4-5 hours (depending on when the occupants go to bed). Figure 49 shows this pattern repeating daily during the week, and with timeslots shifted slightly later at the weekend as an example of 'appropriate' heating operation with the programmer to fulfil routine comfort needs (goal 1). It is important to make clear, that the programmer time periods do not represent 'boiler on' time periods. Heat energy is only emitted during these periods when the thermostat also calls for heat. As Figure 47 and Figure 48 shows, the programmer works in conjunction with other devices. According to the expert, industry recommendations state the thermostat set point should remain static at around 18-20oC (see Figure 49, dashed line). Due to variations in the structure of the houses, initial experiment is necessary to determine a set point that achieves a comfortable temperature in the most used rooms. Similarly, the TRV set points should largely be kept at static settings and should not be treated as a heating control, but a heat limiter. The expert action specification was for used rooms to adopt a moderate, static setting (see Figure 49, light grey line).

To fulfil goal 2, providing ad-hoc comfort, The expert recommended using the 'boost' button (Figure 49, bold line) This control over-rides the program schedule, inserting an instant extra hour where heat can be emitted (subject to the thermostat). Operating the boost does not interfere with any other long-term device settings, so the user does not have to reinstate original settings after use.

To fulfil goal 3, the expert specification relates to the other goals. When setting the programmer for goal 1, to fulfil routine comfort needs in the morning, the expert recommends the timeslot ends 30 minutes after waking (see Figure 49), as the comfort levels will be retained without further heating for the next hour (assuming reasonable insulation) keeping the home comfortable until they leave for work and school. This avoids wasting energy by retaining heat in an unoccupied house. When making long-term TRV settings, the expert recommended adjusting TRVs in long-term unused rooms, to a low static set point. When considering overriding the heating to fulfil goal 2, the expert strongly recommended that comfort levels should be compared to the air temperature before taking action, by referring to the 'room temperature' display on the thermostat device. Often, low activity levels, hunger or tiredness may make individuals feel cold, when the heating system

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has achieved the intended air temperature. The expert considered that energy is wasted if the air temperature is raised to compensate for these other variables, that would be more appropriately addressed directly (e.g. by increasing activity levels, eating, sleeping). The recommendation for using the boost (as opposed to other override options, such as on-off button, turning up the thermostat) also is linked to goal 3. The expert emphasised the feature of automatically switching off after 1 hour, prevents energy being wasted by being on for longer than needed through the risk of users forgetting to revert to the original settings (e.g. thermostat being left at a high setting, or on-off switch left to on).

The expert also emphasised that a benefit of opting to use the boost, is the ease in which the user can activate the setting (by pressing a button). This relates to stage 4 of Norman's (1986) stages of activity, how a user executes action specifications. To execute adjustments to the program schedule (for goals 1 & 3), required the householders in the case study to make various mode changes and adjustments on the programmer device. This was an involved process that would need the user to refer to instructions. To adjust the set temperature value on the thermostat (for goal 1), householders merely had to turn a dial. Similarly, to adjust the TRVs (for goals 1 & 3), householders were required to turn a knob with a scale ranging from 1-5. For goal 2, the boost button was a simple 'on/off' button positioned on the programmer device. The pros and cons of these ways in which these controls facilitate appropriate execution is discussed further in the next section.

The stages so far make up the gulf of execution (Norman, 1986). The 5<sup>th</sup> and 6<sup>th</sup> Stages encompass the perception of the system and the users' interpretation of what they perceive, in relation to their goal. In the design model represented in Figure 47, elements of the heating controls that feedback the state of the system, are shown with a thin border. The Programmer had a red indicator light that illuminates when during the set time periods where the boiler is allowed to be on (but may not be, if the thermostat has not called for heat). This is clearly relevant for goals 1 & 3, as is feedback from the thermostat device, which indicates with a flame signal when calling for heat (but does not indicate that the boiler will only come on during scheduled time periods). For all 3 goals, boiler activation is a key variable.

When active the boiler illuminated an indicator light and made a noise (though these also indicated hot water provision). For the benefit of goal 3, the thermostat also displayed current room temperature for the room in which it was located, and the set points of the TRVs in unused rooms could also be perceived.

Norman's (1986) 7<sup>th</sup> stage of activity captures when the user evaluates the outcome. This is achieved by comparing their interpretation of the perceived system state, with the original goals (Norman, 1986). In the home heating context, the point at which the evaluation may take place could vary. If the householder was feeling cold in the morning and evening they could evaluate if the system was operating as intended to achieve goal 1 (provide routine comfort needs) by checking the device feedback. Where the thermostat showed the room temperature value below the set temperature and the flame indicator symbol, the programmer indicator was illuminated, and the boiler could be heard and its indicator was illuminated, they could accurately conclude that the system was working to pursue their goal. If the indicators on these devices were not present but the room temperature display on the thermostat matched the set temperature throughout the day the householder could evaluate that the heating system had achieved the intended state (fulfilling goals 1 & 2). Outside the scheduled programmer periods, if the householder felt cold and had perceived from the thermostat that the room temperature value was below the set temperature value, then they could evaluate the need to provide ad-hoc heating (goal 3) and specify to execute the 'boost' button (goal 2) to achieve the desired system state. To evaluate part of goal 3, that residual heat is not wasted when the house is unoccupied, with the existing system, the user would need to perceive the programmer indicator unlit a set time before planning to leave the house. The final part of goal 3, that heat is not emitted into long-term unused rooms would result from understanding that a low set point on the specific TRV in the unused room would prevent hot water from entering that radiator.

This section has proposed a 'design model', 'compatible model' and recommended system state of a UK home heating system. How these allow the gulf of evaluation and execution to be bridged has been discussed. Norman (1986) proposed that the system image influences whether a compatible model is reinforced to the user when interacting with the system (Figure 45). How the

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system image of the heating system in the case study could influence the formation of a compatible mental model will be discussed in the next section.

### **6.3 The System Image of home heating**

Norman (1986) emphasized the importance of level when considering Gulf of Evaluation and Execution. In the home heating context, the system image was considered at the system level by envisioning the household as an ‘interface’, as well as at the device level, by examining the human-device interface for key home heating controls. Both levels are represented in Figure 51. At the system level, the consequences of the prominence, connection and distribution of devices will be described. At the device level, the cognitive and physical usability of individual control interfaces a, both cognitive and physical, will be considered. How these variables have the potential to impact the development of a compatible user mental model (Figure 48), as well as influence specific stages of Norman’s (1986) 7 stages of activity, is reflected upon in this chapter.

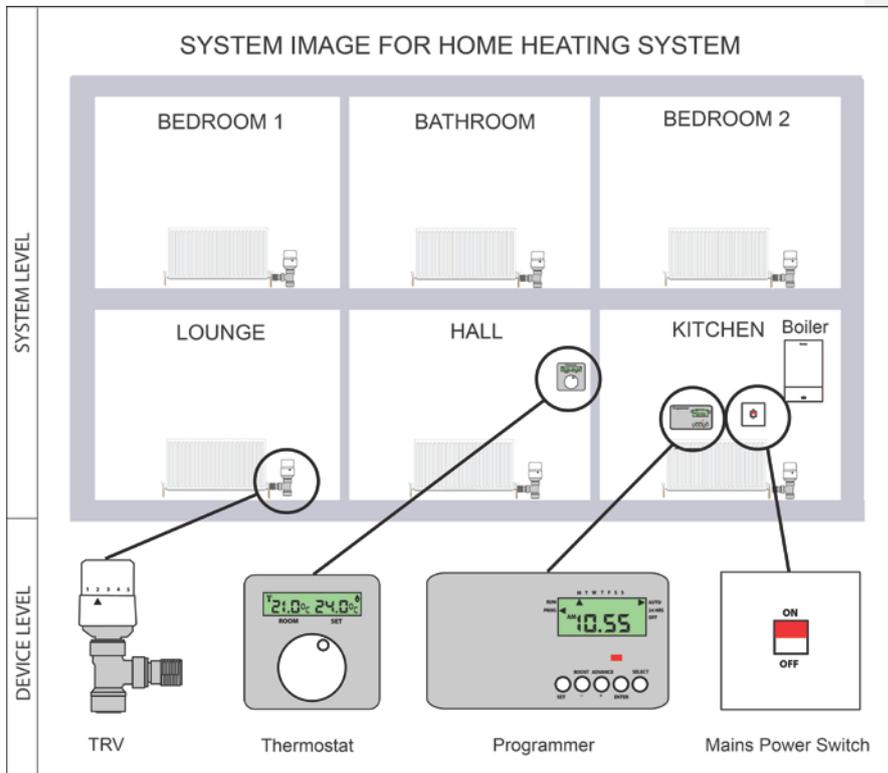


Figure 50 - The 'System Image' of the Home heating System, showing the layout and device interface of the home heating elements from the 'compatible mental model'

### 6.3.1 Home heating at the 'system' level

At the system level, Figure 51 shows control devices are distributed across the house, with different levels of prominence. The TRV's are positioned at ankle level adjoined to each radiator in each room. The central thermostat is positioned at eye level in the hall, exposed to high levels of traffic by occupants in the house. The Programmer and Master power switch are just below eye level and positioned in the kitchen near the boiler. The Boost button is a sub feature of the programmer (Figure 51).The differing prominence of the control devices in Figure 51 are summarised in Table 14 - Summary of analysis of the system image of the heating system, with possible misunderstanding by

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the user.. This variation may play a part not only in which devices ‘come to mind’ as part of the user’s mental model, influencing specification of the action sequence (stage 3) but which devices ‘come to sight’ when the user is perceiving and interpreting the state indicators on devices (stages 5 & 6). [In Chapter 3](#), Revell & Stanton (2013, 2014) depicts how information intake is filtered depending on the user’s background experience. Devices that users do not expect to be part of the heating system may be treated as not relevant.

Figure 51 shows a lack of visible ‘connections’ between elements in the home heating system. Whilst a simplified view of central heating at a system level, Figure 51 reflects reality in that some devices transmit wirelessly, and pipes and wires that connect elements of the system, are partially obscured by floorboards and walls, preventing continuous visual tracking from element to element. Cause and effect at a system level is not, therefore, explicit, which could prevent a compatible mental model being formed or reinforced. Johnson-Laird (1989) illustrates that where information is ambiguous, multiple UMMs can be formed. Variations in UMMs for a single system ultimately could lead to variations in the way users bridge Norman’s (1986) 7 stages of action (see Figure 46) resulting in differences found in users behaviour with heating system as identified in the literature (e.g. Lutzenhiser and Bender 2008)

The distributed nature of heating system elements (Figure 51) also affects the ease with which users can gain feedback of the system state from control devices. To evaluate appropriate functioning of the system, requires the user to relocate to the hall and kitchen to gain perceive and interpret indicator lights and icons on the thermostat, programmer and boiler (stages 5 & 6). To confirm the set point values on the control devices demands the user to be adjacent to the device, which in the case of TRV’s are distributed across the household and require bending or crouching to read the value. For the user to accurately evaluate the system state from the various control devices requires focussed attention and physical ‘effort’ from the user. Bainbridge (1992) proposes that ‘metaknowledge’, (a form of data learned through experience) is incorporated with mental model data to determine the chosen strategy. The ‘ease of evaluation’ of the functioning of a system based on the various controls that need to be referred to for perception and interpretation (stages 5&6) may be stored as ‘meta-knowledge’. This may result in ‘short-cuts’ or

estimates from limited data, being adopted by the user when performing their evaluation.

### 6.3.2 Home heating at the device level

Figure 51 highlights the key control devices identified in the 'compatible mental model' (Figure 48). The interface of each control device may support, mislead or fail to reinforce the way devices function in the model in Figure 48. For example, the TRVs (Figure 51), are attached to each radiator indicating custom control of the radiators within the system. The nature of the customisation possible is misleading from the system image. The user is presented with a scale from 1-5 and set point adjustments are made by twisting a knob (Figure 51). There is no indication on the device of the relationship between the 1-5 scale and the temperature range at which hot water will be prevented from flowing into the radiator. Nor is there an indication that the device responds to changes in room temperature, or that this is a slow responding device. Crossman & Cooke (1974) suggest that manual operators of slow response systems need to be taught the control characteristics in order to secure the best results. The name of the device (Thermostatic Radiator Valve) contains reference to the 'feedback' function of the thermostat, as well as the control of fluid flow function of the valve which reflects well the device function. However, the device is not labelled by name, and the idea of a valve that users may have may relate to experience with those that offer fast acting variable obstruction (like a gas valve) rather than a slow responding control that functions by allowing or blocking flow. The idea of variable flow is reinforced by the twisting motion of the knob, similar to that used on other variable flow devices (e.g. gas hob control, tap). Together, these elements seem to communicate to the user a 'natural mapping' (as described by Norman, 2002) between the 1-5 scale and heat output, rather than the ability to set a temperature range for automatic flow control.

Like the TRVs, the central thermostat in the case study households (Figure 51) also requires a twisting motion to adjust its set point. Kempton (1986)'s 'Valve' folk model of thermostat function may similarly be encouraged by this twisting motion. This could therefore have an effect on the action specification and execution of home heating goals (stages 3 & 4). On the thermostat interface, an LED display shows the chosen set point and the current room

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temperature (Figure 51). The room temperature label does not emphasise that this is the sole sample point used to calculate when to 'call for heat'. Whilst a 'flame' icon indicates when the thermostat calls for heat, there is nothing on the interface to communicate that boiler activation is also dependent on programmer scheduled time periods. Both of these attributes of the interface are state indicators available for perception (stage 5) but could result in problems of interpretation (stage 6), and ultimately evaluation of the ability of the system to achieve desired home heating goals (stage 7).

The programmer device (or timer) also does not identify its function by labels on the main casing. To set the scheduled time periods, requires an involved series of steps and mode changes obliging the support of a manual for first time (or infrequent) adjustment. The process requires time periods to be inputted for each day of the week. The user inputs times into the device, prompted by labels such as 'on' and 'off'. The device does not make the distinction that these periods are possible 'boiler on' times, subject to the thermostat, rather than actual boiler on/off times. This fails to reinforce the conditional nature of boiler activation required for a compatible mental model (Figure 48). The programmer also does not distinguish to the user the difference between scheduled times and comfort times, taking into account residual heat. A time lag in heating up and residual heat are characteristics of a slow response system (Crossman & Cooke, 1974). Whilst the Program schedule is an automatic system, the automation relates to time, not consideration of thermodynamics within the home setting. The householder remains the manual controller of this aspect when programming the start and end times. Crossman & Cooke's (1974) analysis that controllers need the necessarily information about the behaviour of the system to make adequate decisions for control. Even with automatic systems

The boost button is located on the programmer, but the button name is misleading in terms of its function. The meaning of the word 'boost' in the UK is associated with ideas of increase, enhancement or amplification, providing a misleading metaphor (Lakoff & Johnson, 1981). The user could reasonably believe more powerful heat flow, or higher temperatures will result, resulting in errors in the user's mental model. The term also fails to communicate effectively its function is to provide 1 hour of ad hoc program schedule, which

may influence decisions made at the action specification stage (stage 3). Like the program schedule, the boost button's dependency on the thermostat for boiler activation is not explicit. This may affect the compatibility of the resulting user's mental model, as well as prevent appropriate interpretation of the system state (stage 5). The programmer also offers other features such as 'on', '24', 'Advance' (see Figure 51), providing the user with a variety of options that may compete with Boost feature at the action specification stage (stage 3). The Boost feature is easy to activate requiring only a single press without the need to choose a set point, assisting the execution stage (stage 4)

The final device highlighted in Figure 51 is the Master power switch. This interface is a simple generic switch with on/off labels and red highlighting (meeting conventions for a power switch). Without awareness of the conventions for a mains power switch, users may believe this is a heating control, particularly if through experimentation, its influence of the heating system is evident. This could result in inappropriate action specification and execution (stages 3 & 4). Conversely, without experimentation, there is nothing on the device to indicate its link to home heating, as opposed to other devices (e.g. cooker or oven). As a result, some users may not incorporate this in their home heating mental model. Nevertheless, like the boost button, thermostat and TRV, it is easy to operate. Norman (1986:p.40) succinctly positions the effect of usability of input devices on the interactions people have with systems, *"Because some physical actions are more difficult than others, the choice of input devices can affect the selection of actions, which in turn affects how well the system matches with intentions"*. Easy to operate devices, therefore, may be operated more readily than more appropriate 'less easy' to operate devices (such as the programmer). This may explain device selection that does not follow from the user's mental model description. Bainbridges (1992) concept of 'metaknowledge', further supports this sentiment. The 'ease of operation' of a device may be stored as 'meta-knowledge' that ultimately influences the behaviour specified and carried out (stages 3 & 4). Table 14 summarises the user's experience of the system image of the home heating interface, based on speed and ease of adjustment, prominence and possible misunderstandings. This will be used in the next section to help explain differences in the user mental models or reported behaviour, from those recommended by the expert.

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Table 15 – Summary of analysis of the system image of the heating system, with possible misunderstanding by the user.

Control Device	Quick to Adjust	Easy to Adjust	Visually Prominent	Possible Misunderstandings (level: S=System, D=Device)
Programmer	X	X	✓	Not connected to heating system (S,D) Independent Device– not dependent on thermostat (S,D) Programmed times are the same as heat output times (D) Programmed times are the same as desired comfort periods (D)
House Thermostat	✓	✓	✓	Not connected to heating system (S,D) Independent Device– not dependent on programmer (S,D) Set temp knob ensures temperature of all rooms in house (D) Temp display measures temperature of all rooms in house (D) Varies temperature of boiler like variable valve control
Boost	✓	✓	X	Heat output from boiler is increased /amplified(D) Independent Device – not dependent on thermostat (S,D) Not time based control (D)
TRV	X	✓	X	Setpoint varies flow of hot water into the radiators (D) Fast responding control (D) Not feedback based control (D)
On/Off switch	✓	✓	✓	Control for heating demand (D) Not connected to heating system (S,D)

#### 6.4 The User’s Mental Model of Home Heating – Case study results and discussion

The previous sections have shown how Norman’s (1986) 7 stages of activity can apply to the home heating system. A design model (see Figure 47), and proposed ‘compatible’ mental model of the system (Figure 48) that could help users to appropriately operate the system have been depicted. The control devices and settings required to achieve a ‘system state’ that could support

assumed goals of householders with a young family has also been illustrated (Figure 49). The system image of the case study heating system (Figure 51) has been described at both the system and device level and inferences have been made as to how this may influence the development of users mental models, and where this may have an impact on Norman's (1986) 7 stages of action.

In this section, how householder's mental model descriptions compare to the expert's idea of a 'compatible' mental model, is shown. Householders' self-reported behaviour with home heating controls are also compared with the recommended execution from Figure 49. With reference to the inferences of the effect of system image, this data will be analysed according to Normans (1986) 7 stages of action to highlight difficulties real users have in bridging the gaps of evaluation and execution with their home heating system (Figure 46).

#### **6.4.1 How compatible were the case study user mental models of home heating?**

Norman (1983) argues the importance of understanding where users' mental models are erroneous and incomplete, and considers it the duty of designers to develop systems that aid users to develop coherent, useable mental models. To provide a visual comparison that illustrates how compatible the householders' user mental models were with the compatible model of home heating (Figure 48). Elements that match those in Figure 48 have been represented in Figure 52 in black. Omitted elements from the compatible mental model are shown in light grey.

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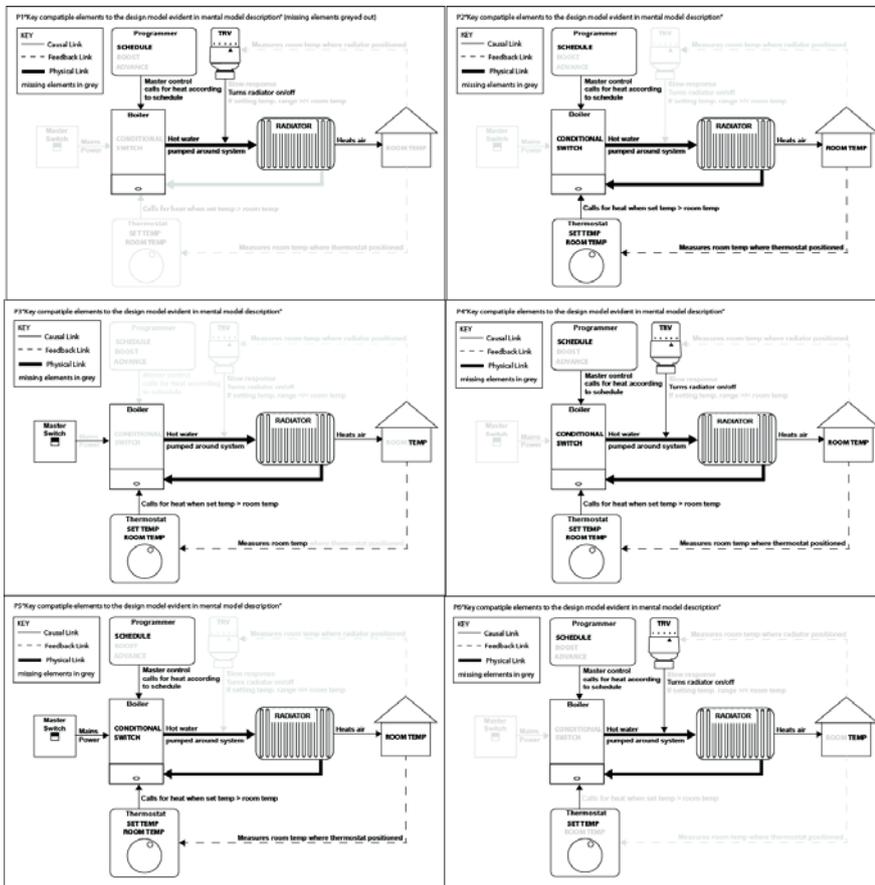


Figure 51 -Key elements compatible to Design Model, for each participant – greyed out areas are missing elements.

Figure 52 shows that householders from the case study varied in the key elements of the design model present in their mental model descriptions. The boiler, radiators and connecting pipes were evident in all, but the control devices, links and associated rules differed for each participant. The thermostat control was evident in all model descriptions except P1, though for P6, the room temperature display and the rule for ‘calling for heat’ was not depicted. The programmer device and schedule was evident in all but P3’s model description, but the boost & advance buttons were not depicted by any

participant. The TRV control was evident in half of the descriptions (P1,4 & 6) but the slow response, conditional rule for turning on and off, and the feedback link from room temperature was absent in all cases. Only participants 2, 4 & 5 depicted the conditional rule for the boiler, and only participants 3 & 5 depicted the master on/off switch. Half of the participants (P1, 3 & 6) did not specify that the heating settings were designed to influence 'room' temperature (rather than whole house temperature, or body temperature). Table 15 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model summarises which elements of householders user mental models match (to the right, in grey), or are missing (to the left, in black) from the expert recommended 'compatible' model (Figure 48). This table provides an indication of where the user interface of the home heating system in this study promotes, or fails to promote an appropriate user mental model.

Table 16 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model

Required Element	Connection/Function	Participants with missing elements						Participants with compatible elements					
Master Switch	Connected to--> Boiler		P6	P4	P2	P1	P3	P5					
	Electrical Isolation	P6	P4	P3	P2	P1	P5						
Boiler	Connected to --> Radiators						P1	P2	P3	P4	P5	P6	
	Pumps hot water around system						P1	P2	P3	P4	P5	P6	
	Conditional switch				P6	P3	P1	P2	P4	P5			
Radiators	Connected to --> Room Temp				P6	P3	P1						
	Heats air						P1	P2	P3	P4	P5	P6	
Room Temp	Connected to --> TRV	P6	P5	P4	P3	P2	P1						
	Connected to --> Thermostat					P6	P1	P2	P3	P4	P5		
	Provides sample of temp. value					P6	P1	P2	P3	P4	P5		
Thermostat	Connected to --> Boiler						P1	P2	P3	P4	P5	P6	
	Temp Set point						P1	P2	P3	P4	P5	P6	

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Required Element	Connection/Function	Participants with missing elements	Participants with compatible elements
	Room Temp display	P6 P1	P2 P3 P4 P5
	Calls for heat IF Room temp < set temp	P6 P1	P2 P3 P4 P5
Programmer	Connected to --> Boiler		P3 P1 P2 P4 P5 P6
	Schedule times		P3 P1 P2 P4 P5 P6
	Calls for heat during timeslots		P3 P1 P2 P4 P5 P6
	Boost - add 1 hour timeslot	P6 P5 P4 P3 P2 P1	
	Advance to next timeslot state	P6 P5 P4 P3 P2 P1	
TRV	Connected to --> Pipes	P5 P3 P2	P1 P4 P6
	Set points	P5 P3 P2	P1 P4 P6
	Blocks or allows hot water to radiator	P5 P3 P2	P1 P4 P6
	Allows access IF room temp < set point	P6 P5 P4 P3 P2 P1	
	Slow response	P6 P5 P4 P3 P2 P1	

6.4.2 How appropriate were case study self-reported behaviour of home heating operation?

To understand how householders specify and execute their goals with their home heating systems, Figure 52 compares their self-reported behaviour. The y-axis displays time divided by days of the week, with shading representing night (10pm-6am). The left x-axis measures the thermostat set point temperature that corresponds to the dashed line graph. The right axis displays a series of scales (on/off or 5 point scale) so multiple devices and their set points can be shown on one graph. The programmer schedule on/off times are displayed at the base with a solid graph, followed by boost/advance, programmer on/off button (in bold line). Towards the top, the TRV set points are displayed, and where different radiators have different set points, these are labelled.

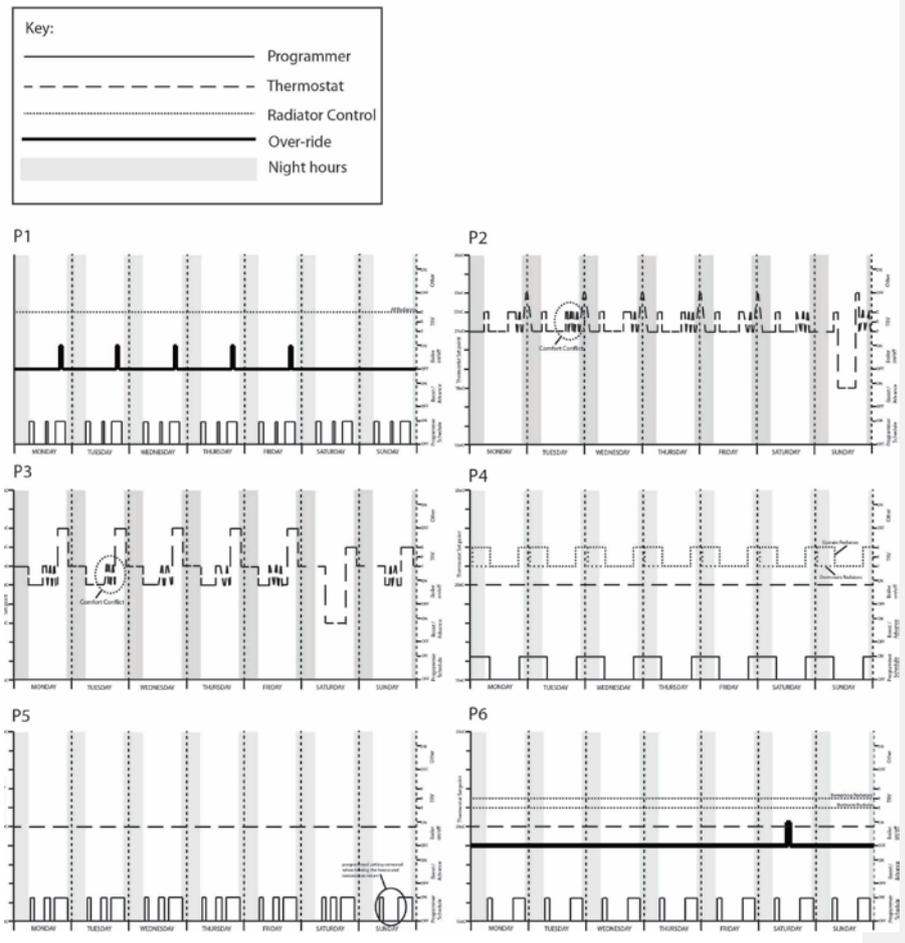


Figure 52 - Householder's self report of typical use of home heating controls over a week period.

From Figure 53 we can see participants 1, 4, 5 & 6 report that they use the programmer device to schedule routine periods of operation, as recommended by the expert. P5, however, also reports ad-hoc adjustments to the schedule to remove a time period when the house will be unoccupied. All participants, except P1, report use of the thermostat with participants 4, 5 & 6 keeping this at a constant setting. For participants 2 & 3, the thermostat is reported as the sole device that they use, with routine changes in set points, as well as 'ad hoc' changes (Figure 53). None of the participants report the use of the

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Boost/Advance button, as recommended by the expert for ‘ad-hoc’ changes to provide heating on demand between scheduled times. Participants 1 & 6 report the use of the programmer on/off button (absent from the ‘compatible mental model’) in order to fulfil this goal. Three participants report setting their TRVs; participants 1 & 6 use them as recommended by the expert, keeping them at a constant setting, and using a lower setting for rooms where heat needs to be limited. Participant 4, reports adjustment to all radiators in the household on a daily basis, with heat being limited from all radiators during the day, all radiators set to 3 during the evening, and some radiators set back to 1 during the night.

Table 16 was constructed with reference to householder’s transcripts and Figure 53, to understand how householders bridge stages 3 & 4 (action specification and execution) of the gulf of action, and provide a comparison to that recommended by the expert. For each goal, the expert recommended control device and actions specifications are shown on the left. Where householders agree with the recommendations is marked with a tick. Where the recommendations are partially followed, or an alternate cause of action is described, the amendment is shown in text. Recommendations that were not followed are marked with an ‘X’ (Table 16 - Comparison of householders actions to acheive goals, with Expert recommendations)

Table 17 - Comparison of householders actions to acheive goals, with Expert recommendations

Goal	Expert	P1	P2	P3	P4	P5	P6
1 – Meet routine comfort needs	Programmer	✓	X	X	✓	✓	✓
	Schedule used						
	Thermostat		✓	✓			
	Constant Set point (18°C-20°C)	X	Routine Adjustment	Routine Adjustment	✓	✓	✓
	TRV	✓	X	X	✓	X	✓
	Constant Set point (set to 3)				Routine Adjustment		

Goal	Expert	P1	P2	P3	P4	P5	P6
2 -Ad hoc heating	<b>Boost</b>	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>
	<i>Turn on when needed</i>						
	<b>Alternate where option absent from user mental model</b>	<b>Override</b>	<b>Thermostat</b>	<b>Thermostat</b>	<b>X</b>	<b>Schedule</b>	<b>Override</b>
<i>Turn on when cold for an hour</i>	<i>Turn up when cold</i>	<i>Turn up when cold</i>	<i>Turn up when cold</i>	<i>Add timeslot</i>		<i>Turn on when cold for an hour</i>	
3 -Avoid wasting heat	<b>Programmer</b>	✓			✓	✓	✓
	<i>Time slot ends earlier than comfort slots</i>	<i>Timeslot matches comfort slots</i>	<b>X</b>	<b>X</b>	<i>Timeslot matches comfort slots</i>	<i>Remove timeslot</i>	<i>Timeslot matches comfort slots</i>
	<b>TRV</b>				✓		
	<i>Reduce set-point for rooms unused long term</i>	<b>X</b>	<b>X</b>	<b>X</b>	<i>For rooms unused short term</i>	<b>X</b>	✓
	<b>Temp Display</b>	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	✓
	<i>Check before using override</i>						
	<b>Alternate where option absent from user mental model</b>	n/a	<b>Thermostat</b>	<b>Thermostat</b>	n/a	n/a	n/a
		<i>Turn down when house unoccupied</i>	<i>Turn down when house unoccupied</i>				

**6.4.3 A discussion of the 7 stages of activity when users operate their home heating system**

The aim of this section is to evaluate case study data presented in the previous section within the framework of Norman’s (1986) 7 stages of action. Reference will be made to the analysis of the existing interface to explain the user mental models and execution of heating controls.

**6.4.3.1 The gulf of execution**

Norman’s (1986) first two stages of activity are setting goals and intentions. Assumptions were made about the goals for this audience group. To check user goals were in line with the assumptions made by the expert, the

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transcripts from QuACk were analysed to identify and categorize householders' goals. Whilst a larger range of goals were identified, the 3 goals assumed by the expert were evident in the case study group. The outputs in Figure 51 were checked against the transcripts to ensure they reflected actions associated with these 3 goals, so confirm meaningful comparison could be made with the expert recommended actions (see Figure 49). The variations in the control devices depicted in Figure 51, shows the participants varied in their intentions when pursuing their heating goals.

Table 16 - Comparison of householders actions to achieve goals, with Expert recommendations is considered to represent how users specify actions (stage 3) and execution actions (stage 4) when bridging Norman's (1986) gulf of Evaluation and Execution. Table 16 - Comparison of householders actions to achieve goals, with Expert recommendations shows the householders in this case study were in most agreement with the expert recommendations when specifying actions to fulfil goal 1 (meeting routine comfort needs). Four of the participants used the program schedule to provide heating that met their routine comfort needs. Figure 53 shows that the time and number of repeated slots vary by participant, but, with the exception of P4 (who chose a single overnight timeslot), closely reflect comfort periods assumed by the expert. All these participants had the programmer in their mental model and understood the function of the programmer (see Figure 52, Table 15 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model). Participants 2 & 3, did not use the programmer at all. Participant 2's action specification is explained by the programmer being absent from their mental model (Figure 52, Table 15 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model) which is surprising given its prominent location. The lack of functioning labelling at the device level of the system Image, and no visual connection to other devices at the system level, may be responsible for this device not being considered part of the heating system (Table 14 - Summary of analysis of the system image of the heating system, with possible misunderstanding by the user.). Participant 2's mental model showed an appropriate understanding of the function of the programmer (Figure 52, Table 15 - Table to compare the elements of householders' user mental models with

those in the proposed 'compatible' model). The transcript revealed his choice not to use this control device is a usability issue. He described the device as "*too much hassle*" to operate, providing support to Norman's (1986) view of the importance of usability on the selection of actions.

To support goal 1, Table 16 - Comparison of householders actions to achieve goals, with Expert recommendations shows the expert specification to keep the thermostat at a constant setting between 18-20oC, was matched by participants 4, 5 & 6. Participants 4 & 5 contained an appropriate concept of the thermostat and its function (Figure 52, Table 15 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model), but participant 6 chose an appropriate specification despite lacking an understanding of the role of the thermostat. [In Chapter 3.](#) Revell & Stanton (2013, 2014) revealed their full user mental model promoted appropriate action through an alternately compatible model of the system. Participant 1 did not include the thermostat in their user mental model nor the action specification (Figure 52, Table 15 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model). Again, this omission is surprising given the prominence of the device (Table 14 - Summary of analysis of the system image of the heating system, with possible misunderstanding by the user.), but the lack of function labelling & visual 'connection' to other heating elements in the system image could provide the explanation. This lack of awareness, provides a positive unintended consequence, as it would ensure a 'constant' setting for the thermostat (though not necessarily at the appropriate set point). For participants 1 & 6, appropriate action with the thermostat could therefore arise from elements in their user mental models that differ from the 'compatible mental model' (Figure 48). Table 16 - Comparison of householders actions to achieve goals, with Expert recommendations & Figure 52 show that Participants 2 & 3 stand out by using the thermostat as their sole control. For goal 1, routine adjustments of the thermostat result in deliberate increase and decreases in set point as comfort needs change throughout the day. This action specification is explained by these participants choosing not to use the programmer schedule. Used as a sole device, routine adjustments of the set point would be an appropriate way to achieve goal 1 and is expected from users holding a 'feedback' mental model of home heating as defined by

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Kempton (1986). Figure 52 and Table 15 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model show both participants had a compatible understanding of the thermostat. This illustrates how recommendations for home heating controls, that assume a control is used in conjunction with another control (e.g. thermostat & programmer), would need amending for users who were using one of these controls in isolation.

The TRV was the final control recommended by the expert to achieve goal 1. A consistent midrange setting was suggested, which was adopted from participants 1 and 6 (see Figure 53, Table 16 - Comparison of householders actions to acheive goals, with Expert recommendations) despite a basic understanding of the way the device functioned (Figure 52, Table 15 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model). The lack of action may have reflected the effort (Table 14 – Summary of analysis of the system image of the heating system, with possible misunderstanding by the user.) required to change control devices in multiple locations. Participant 4 also had an equivalent understanding of the TRV, which omitted its role as a slow responding thermostat. This participant specified a labour intensive execution that required him to routinely adjust the TRV's on a twice daily basis so they were set low and moderate in unused and used rooms respectively. This approach would be appropriate for a fast-responding control, but for the TRV's installed in this household, the response time would result in occupants spending time in rooms that were uncomfortably cold, and leaving unoccupied rooms at a comfortable temperature, whilst the change in setting took time to take effect. The system image for the TRV appears similar to fast responding valves which may have contributed to this behaviour (Table 14 – Summary of analysis of the system image of the heating system, with possible misunderstanding by the user.). Participants 2, 3 & 5, did not report using the TRV to achieve their heating goals, nor had them as part of their user mental models. This absence may have been due to their low prominence due to the ankle level position (Table 14 – Summary of analysis of the system image of the heating system, with possible misunderstanding by the user.). Again, this omission implies

these devices are kept at a constant default setting, unintentionally complying with recommended advice.

For goal 2 (ad hoc heating between scheduled time), the action specification recommended by the expert was to press the 'boost' button. None of the householders had the boost feature in their user mental models (Figure 52, Table 15 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model), and this strategy was not evident in their behaviour (Figure 53, Table 16 - Comparison of householders actions to achieve goals, with Expert recommendations). This omission may have been due to lower prominence as a 'sub' feature of the programmer, or the he ambiguous label may have confused users, so they hesitated to operate this feature (Table 14 - Summary of analysis of the system image of the heating system, with possible misunderstanding by the user.). Participants instead chose to operate the manual override on the programmer (P1 & P6), increase the thermostat control on demand (P2 & P3), or access the programmer schedule to add a timeslot (P5). These strategies do fulfil goal 1, but may jeopardise goal 3, as they risk the user forgetting to reset the device to the original setting. This could waste energy by providing heat for longer or extra periods than required to meet comfort needs. The consequence of over-heating by thermostat control, could result in 'comfort battles', with frequent adjustments of the thermostat in opposing directions (Kempton, 1986), as seen in the output of P2 & P3 (Figure 53).

The action specification provided by the expert to achieve goal 3 (avoid wasting money on heating when not required) was to: 1) End scheduled timeslots earlier than comfort slots; 2) Reduce TRV set-point for long-term unused rooms, and 3) Check the temperature display before deciding to execute 'ad-hoc' heating. Whilst 4 of the participants used the programmer schedule, which contributes to this goal, their chosen 'off' time matched (rather than preceded) the end time of their comfort needs. This implies wasted energy where the home retains a comfortable heat level when this is not required. This applied even for participants whose understanding of the program schedule was compatible with the design model (P4, P5 & P6, see Figure 52, Table 15 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model). Participants 2 & 3, who used the thermostat as the sole control, fulfilled goal 3 by turning the

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thermostat device down below comfort levels, when away for the day, but also made these changes at the time of leaving the house, rather than a period of time before, so unused residual heat is still wasted. The action specification, of setting an earlier end time for heat output requires the user to incorporate an understanding of thermodynamics, with the functioning of the heating system. Compatibility with the design model alone is therefore insufficient, and the system interface at the device level for the programmer, fails to highlight the difference between heat output times and comfort levels periods (Table 14 – Summary of analysis of the system image of the heating system, with possible misunderstanding by the user.) reinforcing the view of Crossman & Cooke (1974) that operators of slow response systems need more state information or training to be able to make appropriate settings or adjustments. Participant 5 also described another strategy, by actively removing timeslots from the programmer when going out for the day (Figure 53). This is an effective and appropriate way of preventing wasted energy that conforms to a compatible underlying mental model of the system. However, there is a risk of forgetting to reset the routine settings that would result in comfort goals not being met. Strategies by participants 2, 3 and 5 all carry the risk that householders will forget to execute the initial action, allowing energy to be wasted.

Participant 6 adhered to the recommended action specification with TRVs, by adjusting rooms not requiring heating long-term, to a low setting, so saving energy (Figure 53, Table 16 - Comparison of householders actions to achieve goals, with Expert recommendations). Missing compatible elements in her mental model (Figure 52, Table 15 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model) did not *prevent* specification of this action. Participant 4, whose compatible elements of the TRV were identical to that of Participant 6 (see Figure 52, Table 15 - Table to compare the elements of householders' user mental models with those in the proposed 'compatible' model), intended to support goal 3 by minimising heat during the day and in unused rooms throughout the evening and night. The action specification used required routine daily adjustments, inappropriate for a slow response control (Figure 53, Table 16 - Comparison of householders actions to achieve goals, with Expert recommendations). This illustrates that the incomplete mental model of

the TRV is not sufficient to *ensure* appropriate action, particularly as the system image at the device level may encourage the idea of a fast-responding control (Table 14 – Summary of analysis of the system image of the heating system, with possible misunderstanding by the user.).

Participant 6, was also the only householder who stated (in transcripts) checking the temperature display on the thermostat device before executing ad-hoc heating (table 4). This is surprising since Participant 6's user mental model was missing the temperature display element, link to room temperature and function of thermostat. Again this reveals that appropriate behaviour can derive from a model that is not compatible with the design model in the way suggested by the expert (see Revell & Stanton, 2013, for more in-depth analysis of this participant).

#### **6.4.3.2 The gulf of evaluation**

So far, how user mental models and the system interface have influenced householders' activities to bridge Norman's (1986) gulf of execution, has been discussed. Norman's (1986) final 3 stages of activity bridge the gulf of evaluation, and involve perception, interpretation and evaluation (Figure 44). The system state is an information input for these stages (Figure 53), therefore how the system image provides feedback to the user about the system state is of particular importance in this analysis. Whilst manufacturers provide indicators on their devices to inform the user of the system state, the user may give greater importance to other forms of perceptible feedback when interpreting the system state. This may affect the appropriateness of their evaluations when determining whether the system has achieved their goals. Table 17 – Summary of perceptual cues used by participants to evaluate the state of the system. Cues in bold are recommended by the expert shows the feedback cues evident on the householders' mental model descriptions. Householders were not specifically asked which feedback they took on board when trying to achieve different goals, so this analysis will be more general.

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Table 18 – Summary of perceptual cues used by participants to evaluate the state of the system. Cues in bold are recommended by the expert

Participant	Feedback Cue						
	Thermostat Indicator	Programmer Light	Boiler Light	Temp Display	Boiler Sound	Radiator Warmth	Other
P1		✓				✓	Body Warmth
P2			✓			✓	
P3	✓				✓		Warmth of house
P4			✓		✓*	✓	Warmth of Pipes
P5	✓	✓	✓			✓	
P6				✓	✓*	✓	

\*participants aware that sound also indicates hot water

Table 17 – Summary of perceptual cues used by participants to evaluate the state of the system. Cues in bold are recommended by the expert shows that the feedback cues recommended by the expert for evaluating the state of the system, appear sporadically in the householders’ mental model descriptions. Participant 5 uses most of these cues, including the thermostat, programmer and boiler indicators in his model description, and is the only participant who would be able to evaluate the system state in the way suggested by the expert. His action specification in Figure 53, shows an appropriate use of devices. Participant 6 is the only one whose model description included the temperature display on the thermostat, but does not mention any of the other device indicators. Participants 2 & 5 produced model descriptions that included the boiler light, and participants 1 and 3 had model descriptions containing the programmer light and thermostat indicator respectively. Due to the minimal cues present, these participants would need to make assumptions about the system or use other cues to form their evaluation. Table 17 –

Summary of perceptual cues used by participants to evaluate the state of the system. Cues in bold are recommended by the expert shows that the warmth of the radiator is a perceptual cue that is used by all but participant 3, as feedback that the system is operating. This is not a reliable cue to determine if the action specification has been successful. A warm radiator does not necessarily imply that the boiler is active, or that the TRV is open (there may be residual heat). An already warm radiator can only inform the interpretation that hot water is currently in the radiator. A warming up radiator, on the other hand can be used to indicate that the TRV is open, and the boiler is active. It cannot accurately enable the evaluation that a set point value on the thermostat has been achieved, however. This means goal 1 is difficult to evaluate effectively with this cue. A cold radiator also does not automatically indicate that the programmer & thermostat are not operating, or that the TRV is closed. The room temperature in the hall may be at, or above the thermostat set point, preventing the boiler being activated, and water being sent around the system. This, therefore, is not a definitive way of determining that energy will not be wasted on leaving the house (goal 3). To evaluate if goal 2 (the need for ad-hoc heating) is required, a cold radiator could be used to evaluate that the boiler is not currently active only in rooms where the user knows the TRV setting is open. Further perceptual cues will need to be sought to determine the appropriate action specification for activating the boiler (e.g. thermostat set point, programmer status). Misunderstanding the meaning of the radiator temperature could result in users believing the heating is off when they leave a house unoccupied or assuming the heating has not achieved the temperature set by the thermostat, resulting in unnecessary override of the system. Both of these misunderstandings could result in wasted energy, jeopardising goal 3. Inappropriate override of the system could also result from the inappropriate interpretation of other cues. Participants 1 and 3 indicated on their mental model description, that they could tell the heating system was working based on the warmth of the whole house, or of their own body comfort level. Due to the effect of thermodynamics on how well different rooms in the house are heated, and the effect of activity levels, dress, and comfort preferences on body comfort level, both of these are poor ways for determining if the desired system state has been achieved. In the case of participant 3, this resulted in the thermostat set points being increased or decreased based on the felt temperature of different rooms in the house, rather than the desired set

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temperature (Figure 53, Table 16 - Comparison of householders actions to achieve goals, with Expert recommendations). Participant 1 also reported overriding a system during a scheduled time period when feeling cold and evaluating the heating had not achieved the set goal (Figure 53, Table 16 - Comparison of householders actions to achieve goals, with Expert recommendations). A full analysis of these participants responses are described in [Chapter 3 and Revell & Stanton \(2013, 2014\)](#). Participant 6 is the only participant who refers to the temp display before considering ad-hoc heating enabling her to evaluate appropriately if the system state has been reached. Despite not describing the other recommended cues, her operation fits the recommended pattern (Figure 53, Table 16 - Comparison of householders actions to achieve goals, with Expert recommendations) suggesting interpretation of this type of feedback is particularly useful for evaluating if goals have been obtained.

### 6.5 Conclusions

This chapter set out to apply Norman's (1986) gulf of evaluation and execution to the domestic heating system. It took a different approach to previous research, by examining the 'scaffolding' that underlies the bridges over these gulfs. User mental models from householders in a case study were used to inform analysis at each of Norman's (1986) 7 stages of activity. The analysis used a 'standard' derived from expert recommended examples of a 'compatible mental model' and 'action specification' to evaluate the appropriateness of the way householders think and behave with their home heating system.

The purpose of this analysis was to gain insights into why householders use their heating system inappropriately, often leading to wasted energy. These insights were thought to be important if considering the design of digital interfaces tasked with enabling users to better control their home heating systems. It is concluded that this approach was useful at identifying issues that hinder appropriate operation of home heating. As an aid to those considering the design of home heating interface systems, Appendix A shows a table that summarises how characteristics of the system image of the home heating system in our case study influenced the user mental model, with examples

taken from the case study data as to how for the 3 proposed home heating goals, this 'scaffolding' had an impact on Norman's 7 stages of activity.

Key findings that arose from analysis from the perspective of mental models were; 1) Users do not necessarily perceive all the available key home heating components in their home, 2) Users do not understand how all the key heating components are connected and 3) Users can misunderstand how key heating components function. These issues all contribute to poorer performance in terms of 'appropriate consumption', meaning energy is wasted, or frustration is caused as goals are not achieved. It was found, however, that a compatible mental model of how the heating system operates is not sufficient for the user to effectively achieve their heating goals. To ensure comfort and avoid wasting energy, expert advice recommended assigning end times for heat output at an earlier time than the end of a comfort period (so residual heat does not go unused). Also, for outlying rooms far from the thermostat, temperature values achieved may differ considerably from the temperature display, so 'comfortable' temperatures may not be possible in all parts of the house at the same time. For the user to be able to fully understand these issues at the time of execution, an understanding of thermodynamics of their home, over time, would also be necessary.

These findings have important implications, as current technology would be capable of addressing these issues. Efforts to address design issues at higher levels, may be ineffective, or at best less effective if these underlying issues are not taken on board. This may hinder well intentioned efforts from achieving the goal of reducing domestic energy consumption, or enabling user goals to be met. For example, improving the usability of the programmer, will have little effect if the householder does not contain this element in their mental model, and will still waste residual energy if they do not understand the relationship between the time periods set, heat output and comfort goals. Similarly, improving access to TRV controls may mislead users into thinking that these devices provide fast responding custom heating.

The findings related to home heating such as difficulty in operating controls (e.g. programmer), ambiguous labelling of device controls (e.g. Boost button), misleading control design (e.g. thermostat and TRV knob) and the dispersed, unconnected arrangement of related controls were all considered to contribute

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to issues with both the mental model adopted by users, and their subsequent interaction with the system to achieve their goals.

Normans' (1986) gulf of evaluation and execution to examine home heating systems at the mental model level, has provided insights that could help evaluate recent home heating system interface applications, as well as inform the design of a digital heating system interface that effectively puts householders in control of their heating goals, whilst reducing wasted energy.

Chapter 7 looks at how a 'control panel' style home heating interface could be designed that takes into account some of these recommendations, including promotion of the range of controls available, making explicit at the system level their interdependencies, and reducing ambiguities of function.

## 7. Using interface design to promote a compatible user mental model of home heating and pilot of experiment to test the resulting design.

### 7.1 Introduction

[Exploring the relationship between design and mental models described in hypothesis 3 in section 1.2.2, this chapter takes theory into practice. The design specification created in chapter 6 is applied in this chapter to the design of a home heating interface. This embodies the overriding aim of the thesis, to use the concept of mental models in design, to elicit behaviour change that results in increased achievement of home heating goals \(Hypothesis 4\). The effectiveness of the design changes are tested in an empirical study with a home heating simulation and the results reported in chapter 8.](#)

Domestic consumers contribute to over 25% of total UK carbon emissions (The UK Low Carbon Transition Plan, 2009). Large variations in domestic consumption are due to behaviour (Lutzenhiser and Bender 2008). Assumptions about the cause of excessive consumption may include ideas of 'autonomy' ("as long as I can pay for it I should be allowed to use as much as I want"), 'impulsiveness' ("I override the heating as soon as I feel cold"), 'apathy' ("I don't think anything I do makes a difference"), 'lack of confidence' ("It's too difficult to adjust the controls to conserve energy"), or 'confusion' ("I don't know what changes I should make, or the changes I make don't seem to have the intended results"). The first three assumptions relate to attitudes to consumption, but the literature struggles to show a strong causal link (e.g. Alwitt & Pitts, 1997; Sauer et al., 2009). The latter two assumptions relate to difficulties householders have when interacting with energy consuming devices, and is the focus of an ever growing body of research (e.g. Kempton, 1986; Vastamaki et al., 2005; Chetty et al., 2008; Lilley, 2009; Pierce et al., 2010; Peffer et al., 2011; 2013; Glad, 2012; Sauer et al., 2004; 2007; 2012,; Revell & Stanton, 2014)

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Domestic space heating accounts for 58% of domestic consumption in the UK (Department of Energy and Climate Change, 2011) and the central heating system is considered the most complex system in the home (Sauer 2009). Improving householders' confidence and reducing their confusion when operating heating devices would provide the opportunity to reduce wasted consumption. It may also go further and enable a positive attitude to energy use to show a significant effect in consumption, by overcoming the behaviour difficulties for those with pro-environmental behaviour intentions (Kaiser, 1999). As Lilley (2009) points out, responsible operation does not necessarily reduce consumption. To reduce consumption by promoting energy saving goals, it follows that systems would need to enable users to fulfil goals. A system that increased the ability of users to fulfil home heating goals is therefore desirable.

Lutzenhiser (1993) argues that technology-based efficiency improvements are amplified or dampened by human behaviour. Yet, Glad (2012) found when technology is introduced into homes, it does not always meet the user requirements (in terms of the type of technology and the interface). Pierce et al. (2010) argue that energy consuming behaviour is unconscious, habitual and irrational, and users ignore visible options. However, Crossman & Cooke (1974) showed slow response systems (such as home heating) are difficult to learn and control effectively, and Sauer et al (2009) argued that some users do not have adequate strategies available to manage a system more effectively even if aware of undue consumption. Chapter 3 found lack of awareness of device controls was responsible for inappropriate strategies with home heating. In addition, Peffer et al. (2011) makes the point that to save energy with home heating, the householder must actively select appropriate set point times and expend time and effort in programming devices, and highlights the difficulty users have in finding agreement on a programmed temperature.

At the device level, Glad (2012) found thermostats were not used as intended, negatively affecting performance and user satisfaction, making a prudent observation that smart technology is not that smart unless the user can effectively use it. Brown & Cole (2009) supports the assertions of Glad (2012) and cites responsiveness, lack of immediate feedback (or lack of relevant feedback), was responsible for poor comfort levels in green buildings. Peffer et

al (2011) found nearly half of users do not use programming features in home heating devices, and when they do, only half are programmed to make adjustments to correspond with night time or unoccupied times, limiting the energy saving benefits. They place the cause of misunderstandings of terminology (e.g. set point) and programming difficulties firmly as a result of poor design by designers and engineers. Additional support in the form of operating manuals for programmable thermostats, Peffer et al. (2011) found to be lengthy and obtuse, preventing users from easily learning how to operate their controls. This explains Sauer et al (2004)'s finding that home heating instructions manuals are often not read by users. Vastamaki et al. (2005) states that most existing temperature controllers do not provide initial feedback in a way that is understandable to the user, and temperature change feedback is delayed, resulting in trial and error behaviour, reducing comfort and wasting energy and reducing motivation to use the control again. They describe the temperature control as a seemingly simple everyday device that is difficult to use because 'everyday thinking' leads to the wrong conclusions about its way of working. This echoes the views of Kempton (1986) who found householders frequently developed an inappropriate 'mental model' of the thermostat, resulting in less appropriate behaviour with the device. It is hoped this chapter has painted a clear picture of the problems householders have when operating energy consuming technology in the home, and highlight home heating devices as presenting substantial difficulties.

Pierce et al (2010) claim behaviour is strongly influenced by the interface with energy consuming technology. Lilley (2009) proposes that to sustain change, behaviour steering should be the strategy adopted by designers. [In Chapter 3,](#) Revell & Stanton (2014) argue that designers should focus on misunderstandings and omissions in the user mental models of home heating to encourage users to hold more integrated functional models, and that design strategies could benefit from application of mental model descriptions. Papakostopoulos & Marmaras (2012) proposed that display units should be simplified to reflect the simplified view from expert users. Branaghan et al (2011) found that users were more effective at performing tasks using a redesigned interface based on expert knowledge, rather than a familiar interface. [Revell & Stanton \(Gulf Chapter\)Chapter 6 collected data from-used a](#) home heating expert to capture a simplified user mental model of the home

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heating system and identified how differences between this mental model and the user mental models of novice users led to less appropriate behaviour strategies with heating controls. This follows from Norman (2002) who argues that devices should ensure there is sufficient 'knowledge in the world' to promote appropriate behaviour.

Moray (1990) showed operators accessed mental models when controlling processes in complex systems. Sauer (2009) considers home heating to be the most complex system in the domestic domain. A mental models approach to home heating system design therefore warrants exploration. Sauer et al (2009) when considering instructional displays, emphasised that a poor mental model of system functioning would prevent an operator from knowing how to interpret the information available. Shipworth et al (2010) echoes this sentiment by stating that using controls without understanding how to use them is counter-productive. They propose that new controls should be developed that appeal to householders, are more intuitive to use and make it easy to reduce consumption. Peffer et al. (2011) proposes that user misconceptions that encourage incorrect usage cannot be easily overcome by better interfaces. Improved usability is essential but insufficient to encourage correct use, and advocates that a mental models approach to interface design that encourages a compatible user mental model at the system and device level could go some way to promoting appropriate conceptions.

Norman (2002) proposes that differences in user machine interaction are due to the gulf of evaluation and execution. He argues that interfaces should be designed to promote in the user, a compatible mental model to the design model of the system. To bridge the gulf of execution and evaluation Norman (2002) advises to 'make things visible' so people know what is possible and how actions should be done, and can also tell the effects of their actions.

Revell & Stanton (2006) applied Norman's 7 stages of activity to operation of a typical home heating system to understand how deviations in householders' user mental models from an 'expert' user mental model of the system could result in less appropriate behaviour strategies. The misunderstandings and omissions from these householders' models, were tabulated to form a design specification to focus improvements to the home heating interface with the view of including features that promote a compatible

user mental model (Revell & Stanton, [Gulf ChapterChapter 6](#)). Manktelow and Jones (1987) reiterates Norman's (1993) argument that good design should lead to a "single, coherent, and plausible mental model". They provided 24 recommendations for the design of user-system interfaces by reviewing research focusing on the ways that mental models are invoked and used, including the considered use of language, analogies, salient task features, and experience of the user.

This chapter describes the redesign of home heating controls in the form of a 'control panel' that promotes a Compatible User Mental Model (CUMM) of a typical home heating system, based on the design specification created [in by Revell & Stanton \(Gulf ChapterChapter 6\)](#). This chapter will highlight where the redesign follows generic recommendations from Norman (2002) and Manktelow and Jones (1987) to promote appropriate mental models of home heating in users. The intention is to use this redesign in a study that compares how interface design affects the mental models constructed by home heating users following from Norman (1986), and to compare the impact of mental models of home heating on energy consuming behaviour as proposed by Kempton (1986). The adaptations made following a pilot run will also be described, and screen shots of the resulting interface provided.

## 7.2 Concept Development

This section will summarise for each key device (Thermostat, Programmer, Boost and Thermostat Radiator Valves (TRVs) and for the system as a whole, the design specification from [Revell & Stanton \(Gulf ChapterChapter 6\)](#). The interface of standard controls, from which these recommendations were derived, will be illustrated and the redesign will be described and illustrated with reference to recommendations for evoking and triggering mental models by Norman (2002) and Manktelow & Jones (1987). The changes made following a pilot for an experiment designed to test the success of the redesign will also be presented.

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## 7.2.1 Design of key devices

### 7.2.1.1 Thermostat

The design specification from [Revell & Stanton \(Gulf ChapterChapter 6\)](#) identified that typical thermostat devices did not effectively communicate the 'feedback' function of the device, nor the temperature sample point. This led to inappropriate functional models of the thermostat and misunderstandings about the scope of temperature control (Revell & Stanton (2014); [Gulf ChapterChapter 6](#)). Figure 54 shows a typical thermostat (based on the Hortsman - HRT4-ZW Thermostat), but showing 2 temperature values rather than different modes). The control knob is analogous to those found on a 'gas hob' – according to Manktelow and Jones (1987), users' familiarity with this style of control, is can trigger a 'schema' that the device works in the same way, resulting in a 'valve' mental model of function. Kempton (1986) estimated up to 50% of users in the USA, at the time of his research, erroneously held a 'valve' mental model of the thermostat, resulting in less appropriate operation. Figure 55 shows the redesign of the thermostat to encourage the idea that existing temperature values fed back from a central temperature sample point are a key criteria for device function. Here the design capitalises on householders' likely familiarity with the form of a thermometer to trigger a schema relating to temperature measurement. Manktelow and Jones (1987) emphasised that ambiguous language should be avoided, for the development of coherent mental models. The Redesign of the thermostat is labelled a 'central' thermostat, and reference to 'room' is removed to avoid confusion with individual room thermostats. Norman (2002) recommends that users should know what actions are possible and actions should match intentions. The redesign in Figure 55 changes the interaction from a rotating knob to a selection of the desired temperature using a 'Want' button. Norman (2002) recommends that the system state is readily perceivable and interpretable and is a match to user's intentions.

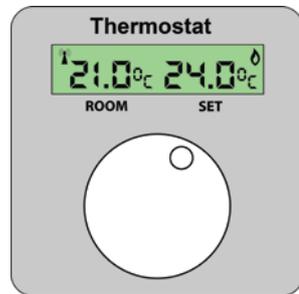


Figure 53 - 'Realistic' style thermostat interface with a 'flame' icon indicating boiler operation and ambiguous label 'room' to identify where temperature samples are fed back to the device.

The Redesign in Figure 55 indicates the current temperature measured by the central thermostat by increasing or decreasing the 'mercury' line within the thermostat analogy. In addition, the more meaningful label 'Got' (as opposed to 'Room') is used. By placing the 'Got' and 'Want' values on a single temperature scale, a concrete and immediate comparison of these values is apparent to the user. The functioning of the thermostat relies on this comparison of values (if the 'want' value is higher than the 'got' value, the thermostat 'calls for heat'). Norman (2002) recommends that the effects of their actions should be visible to the user. In the Redesign in Figure 55, the outline of the thermostat changes to green when calling for heat. The author's deliberately avoided using a flame icon (as with the typical design in Figure 54), to prevent users being misled that an 'active' thermostat alone, equates to boiler activation. Norman (2002) recommends that the outcome of users' actions should be obvious. As boiler activation relies on additional devices, how the redesign follows this recommendation is discussed in the 'system' section.

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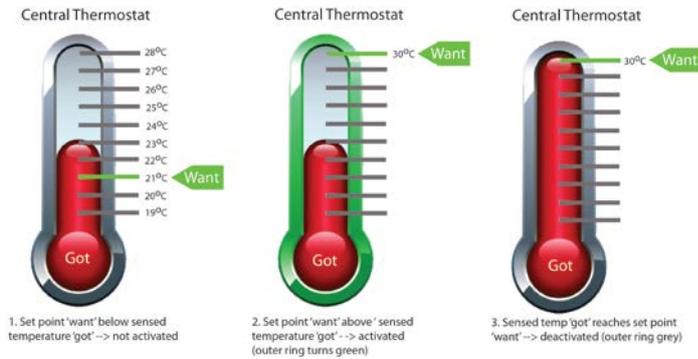


Figure 54 - Redesign of Thermostat Interface to promote appropriate device model to users

7.2.1.2 Programmer

The design recommendations from [Revell & Stanton \(Gulf Chapter Chapter 6\)](#) for the programmer identified that the usability issues of typical programmer devices create ‘metaknowledge’ (Bainbridge, 1992) in user mental models (UMMs) that dissuades the inclusion of programmers in the behaviour strategies formed by users, as they require too much effort for operation. In addition, the conditional link to the thermostat for operation is not clearly communicated, which can lead users’ to assume that scheduled times equate to boiler on times (Revell & Stanton, 2014). Finally, the difference between scheduled end times and continued comfort levels due to residual heat is not highlighted, preventing thermodynamic lag times forming part of UMMs that could promote shorter programmer schedule times. Figure 56 shows a typical programmer (based on a Horstmann CentaurPlus 17).

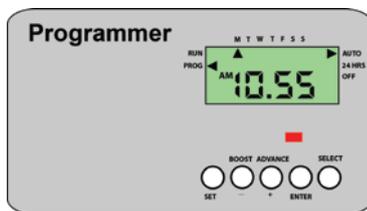


Figure 55 - 'Realistic' Home Heating Programmer Interface. Red indicator illuminates during scheduled ‘on periods’.

Figure 57 shows a redesign of the programmer to overcome lack of use due to usability issues (ADD REF as based on Alex's design). Norman (2002) suggest the structure of tasks can be simplified by minimising the amount of planning necessary, and changing the nature of the task. The redesign in Figure 57 changed the nature of the task from navigating through a series of modes and options to input start and end times, to a simple 'point and click' task to select hour slots of operation. Following from Norman's (2002) recommendations, it makes visible the actions that are possible, how the action is to be done, and unlike traditional programmers (e.g. Figure 56), it visibly displays the programmed schedule resulting from their actions by changing the timeslots to green. To indicate the system state, when a scheduled timeslot is 'active', the outline of the programmer is highlighted in green (Figure 57), supporting evaluation of system state. Promotion of the conditional link and thermodynamic lag times are discussed at the 'system level' as they relate to other devices and target rooms respectively.

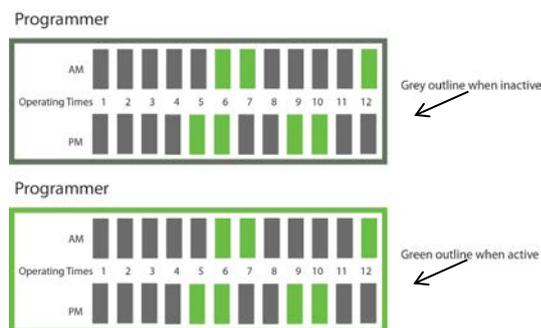


Figure 56 - Redesign of programmer to simplify schedule input, to encourage inclusion in behaviour strategies.

### 7.2.1.3 Boost

The design recommendations from [Revell & Stanton \(Gulf ChapterChapter 6\)](#) identified that the function of the Boost button was not communicated clearly, nor was its conditional link to the thermostat for boiler operation. The former explained the boost button being absent from UMMs or avoided in behaviour strategies, resulting in strategies at greater risk of energy waste (Revell & Stanton, [Gulf ChapterChapter 6](#)). Figure 58 shows a typical Boost button, as part of the features on the programmer (again based on the Horstmann

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CentaurPlus 17). When pressed, ‘BOOST’ text is shown on the LED for the duration of operation (1 hour).

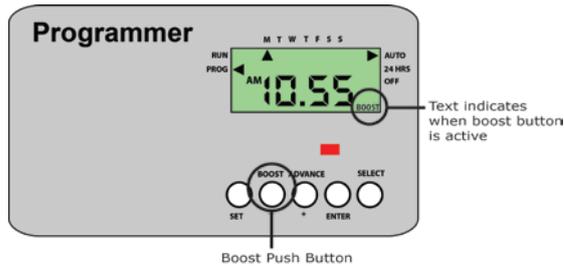


Figure 57 'Realistic' Boost Button, as a feature on a programmer device. Boost text appears in the LED display when active.

Figure 59 shows a redesign of the Boost feature to increase its prominence as a key control, and communicate its one-hour operation. Following from recommendations by Manktelow & Jones (1987) the analogy of a clock face is used to trigger in the user a schema relating to time passing and a label of '1 hour' is present to avoid ambiguity in the time period of activation (Figure 59). This also supports Norman's (2002) recommendations to make visible to users what actions are possible (only a 1 hour option). When activated, the time remaining for operation is displayed in green, following Norman's (2002) recommendation to make visible the effect of user's actions to enable easy evaluation of the system state. Promotion of the conditional link represented at the 'system level' (see Figure 63 and Figure 64).



Figure 58 - Redesign of Boost button to promote 1 hour operation

#### 7.2.1.4 TRV

The design recommendations from [Revell & Stanton \(Gulf Chapter Chapter 6\)](#) highlighted problems in the design of traditional TRVs in the communication of the feedback function, the mapping between set point and room temperature values, and their slow responding nature. This was found to result in an inappropriate device model and action specification (Revell & Stanton, Under Review) for the TRV. In addition, the distributed ankle height positioning was thought to encourage metaknowledge (Bainbridge, 1991) in UMMs that dissuade inclusion in users' behaviour strategies due to the physical effort involved in adjustment (even if the correct device model was held). Figure 60 shows a typical TRV control (based on a 15mm Ravenheat Thermostatic Radiator Valve). The set point scale shows markings from 1-5 without mappings to temperature values. This control suffers from the same difficulties as the central thermostat, in that a rotating knob is likely to evoke schema's based on users' experience with alternate devices that function like a value (e.g. Gas hob, basin tap). According to Manktelow & Jones (1987), the consequence of this could be the development of an inappropriate mental model (e.g. Valve), as was found in Revell & Stanton (Under Review).

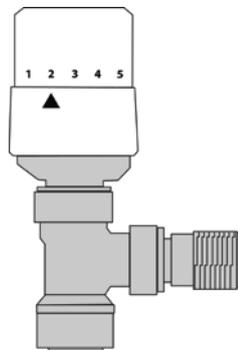


Figure 59 - 'Realistic' style of TRV control, with ambiguous 5 point scale

Figure 61 shows a redesign of the TRV device, following recommendations from Norman (2002), the mapping between set points and approximate room temperatures are made explicit, to better match enable users to match actions to intentions. Echoing the redesign of the central thermostat and following from Manktelow & Jones (1987), the image of a thermometer is used to evoke

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the concept of temperature measurement, emphasising data fed back to the device is essential for operation. To distinguish its operation from the way the thermostat functions, the set point button is labelled 'Limit' to communicate that the devices limits rather than achieves room temperatures. To promote that TRV controls act on individual rooms, the target room is labelled in the mercury line to indicate the temperature value in that room. Similar to the central thermostat, the comparison between the room temperature in the target room and the temperature at which heat output from the radiator will be limited is visually emphasised (Figure 61). Recommendations from Norman (2002) to make visible the possible actions is clear from the choice of 5 settings. The effects of users' actions is displayed visibly by highlighting the chosen setting, and where this has not been reached by the 'mercury line' for the target room, the outline of the thermometer, as well as the radiator image, are highlighted in green, providing a visible and readily interpretable state of the device. The slow responsiveness of the TRV was emphasised by operation instructions on the interface and in the user manual. Negative metaknowledge was expected to be overcome by a control panel interface where all TRV controls can be accessed without extensive physical effort.

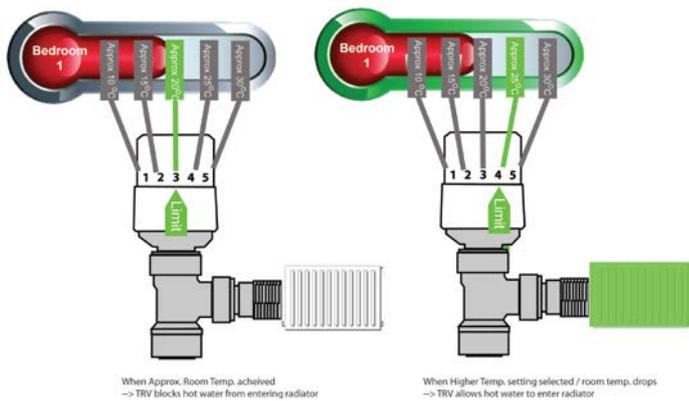


Figure 60 - Redesign of TRV controls to promote heat limiting feedback device model

### 7.2.2 Design of System view

The design recommendations from [Revell & Stanton \(Gulf ChapterChapter 6\)](#) highlighted how a typical system view of home heating has characteristics that impeded development of an appropriate UMM by householders. Presenting a range of different controls of varying prominence distributed around the house, risks some controls being overlooked (e.g. Revell & Stanton, 2014), the hierarchy of controls being misunderstood (Revell & Stanton, Under Review) and metadata for effort involved in controlling or checking device status preventing appropriate actions with, and evaluation of, the heating system (Revell & Stanton, [Gulf ChapterChapter 6](#)). The lack of household thermodynamic data in typical home heating systems hinder this concept becoming part of UMMs affecting expectations of performance (Revell & Stanton, [Gulf ChapterChapter 6](#)). A lack of clear visible connections between devices prevent interdependency of devices being emphasised and cause and effect rules being developed (Revell & Stanton, [Gulf ChapterChapter 6](#)). A typical distribution of controls is shown in Figure 62 and Figure 63. Access to these controls, as well as feedback of their status, and the status of comfort levels in each room is experienced by the user, in what is best described as 'tunnel vision'. The householder can only be present in one room at a time, meaning they can only access devices for control and feedback, when present in the same room. Similarly they can only evaluate the progress with comfort levels for the room in which they are situated, limiting an overview of variations in comfort levels across the house. This potentially hinders the development of UMMs a conceptual representation of thermodynamic variations.

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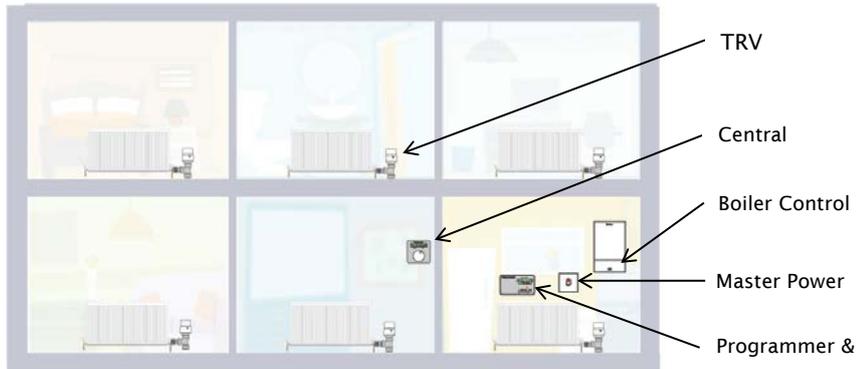


Figure 61 - Distribution of typical home heating controls across the home (but users can typically only see one room at a time)

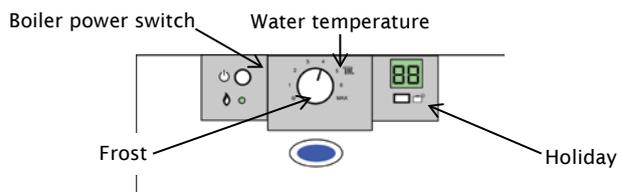


Figure 62 - Boiler controls hidden from user behind panel

Norman (2002) emphasises that to bridge the gulf of execution and evaluation, the outcomes of an action should be obvious. Figure 64 and Figure 65 show the redesign of the home heating interface to display the link between distributed physical control devices around the home (Figure 64) and to emphasise the 'conditional rule' that integrates set point choices for key controls (thermostat, programmer and boost) at the point of action (Figure 65) when controlling boiler operation.

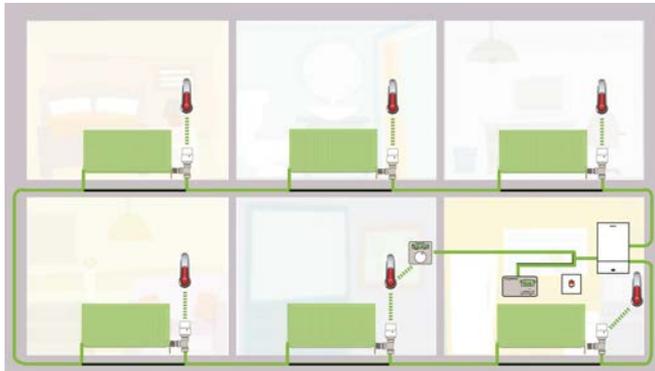


Figure 63 - Redesign of interface to display distributed control devices with cause and effect links

Following recommendations by Manktelow and Jones (1987) an analogy of a 'switches in a circuit' is used to trigger a schema that guides the development of a functional user mental model (Figure 65). Boiler activation is made visible (highlighted green) when the programmer or boost is active (closing left switch) *and* the thermostat is active (closing right switch). If one or both of these conditions are not met, one or both switches will be open and the boiler icon will remain inactive (grey).

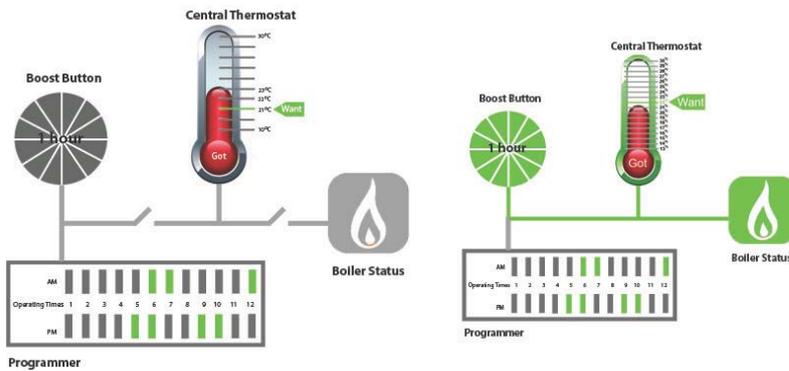


Figure 64 - Control panel for key controls emphasising link between set point choice with key controls and boiler status

To aid discoverability of controls - redesigning the interface as a 'control panel' enabled access to all controls from a single point. Manktelow & Jones

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(1987) emphasizes that if appropriate dominance is not emphasised, correct assumptions about dominance in development of user mental models is unlikely. The hierarchy of controls was emphasised by placing the key controls visible on the main panel. The only exception to this was the TRV controls. As slow responding long-term controls, they are not suitable for frequent adjustments. Norman (2002) advocates deliberately making things difficult if there are undesirable consequences for operation. Access to the TRV controls were therefore placed with the Advanced controls via a button on the main panel. This button categorized lesser used controls by their function with the option to place further text instructions at the point of action (see final design of the main panel shown in Figure 67). In the redesign of the interface, ‘tunnel vision’ is removed by showing the comfort levels of all rooms in a single view. This follows from Norman’s (2002) recommendation to ensure the system state is visible and readily interpretable. The intention of the design is that variations in comfort levels across the house will promote an understanding of lag times and thermodynamic variations in user’s mental models of home heating. The rooms overview in Figure 64 also displays the location of physical controls within the home and makes the invisible, visible (Norman, 2002) by showing the links between devices. Thermometer icons linked to the TRVs and central thermostat are also indicated to reinforce the feedback function of these devices relies on temperature sensing. To make visible the outcomes of users’ actions with TRVs following recommendations from Norman (2002), the radiators are highlighted in green (Figure 64) when water can flow, but not when the TRV acts to limit heat. In the final iteration of the simulation design a text label ‘water flow allowed’ or ‘water flow blocked’ is also added to the simulation design via a text label to reinforce the TRV function (Figure 67).

### 7.2.3 Creating a Simulation

A simulation was created to enable the redesigned controls and interface to be compared in operation, to a more realistic interface (based on the typical controls and interface described). The simulation presented two versions of a home heating interface, with controls providing the same function ‘behind the scenes’. The realistic interface replicated the ‘tunnel vision’ experience by presenting a single room to users at a time, meaning feedback of the devices

available, and the comfort levels achieved was only possible for the visible room (see Figure 66). To reflect users' need to deliberately approach a device before operation, the representation of typical devices in the typical room, could only be accessed when the user clicked the correct room (e.g. 'entered the room') and the specific device (e.g. approached the device). A larger version of the device was then presented that allowed adjustment with the mouse. This is in contrast to the redesigned simulation that provides visual feedback of all rooms and access to key controls by default (Figure 67).

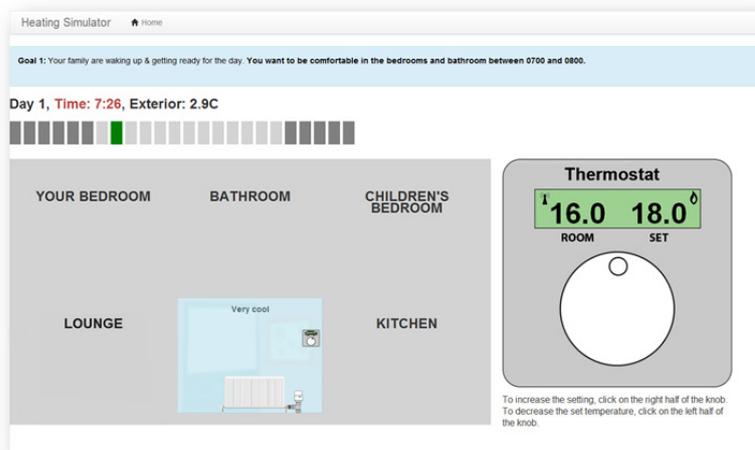


Figure 65 - Interface created to represent a typical home heating interaction

To avoid differences in opinion by users as to what temperature values constituted 'comfortable' - feedback was provided with descriptions ranging from very cold, cold, too cool, comfortable, too warm, hot, and very hot. The room temperature range for each of these descriptions was adjusted to ensure the user could not achieve comfortable temperatures too easily. This was necessary as a link between mental models and behaviour was under investigation, so a motivation for adjustment was needed to capture any differences. A simple thermodynamic model was included whereby the rooms adjacent to outside walls lost heat at a higher rate than central rooms, and included changes to heat loss rates based on variations in external temperatures throughout the day. Some elements of the interfaces shown in Figure 66 and Figure 67 do not relate to promotion of compatible user mental

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models, but are purely a component of the experimental setting. These include the text presentation of goals, and the ‘ticker’ below this that shows progress through the experiment.

**7.2.4 Pilot**

Initial informal pilots were undertaken to identify and mitigate initial usability issues during interface develop. Following this, a formal pilot for each condition was undertaken. This ran through the whole experimental procedure, and provided feedback about the experience from a participant’s point of view. The pilot candidates were both PhD students in Engineering and the Environment in their mid 20s. The issues and mitigation strategies that came out of these formal pilots are summarised in Table 18 below.

Table 19 - Summary of issues and changes to experimental procedure, interfaces and setting, following pilot run

Setting	
Issues:	Mitigation:
1. Awkward orientation to screen	1. Position Monitor face on to participant
Procedure	
Issues:	Mitigation:
<ol style="list-style-type: none"> <li>Key Elements of the simulation (Unaware / unclear about the purpose)</li> <li>Interaction with Simulation (prevalence and functioning of goals)</li> <li>Manual Use (Unsure of expectation)</li> <li>Goals (Concern over expectations, Disbelief about achievability)</li> <li>Stressful experience</li> </ol>	<ol style="list-style-type: none"> <li>During ‘Play mode’ explain layout, accelerated time, Changing goals, Temperatures in rooms changing is also due to thermodynamic model, and purpose of ‘Ticker’ show progress through simulation. Make goal change more noticeable with screen flash/colours and make key goal information bold.</li> <li>During ‘Play mode’ make clear there are controls in each room and that all controls represented, can be interacted with and are working.</li> <li>Emphasise that manuals are there to explain control operation and can be used as much or as little as needed in the ‘play’ and ‘main’ experiment.</li> <li>During ‘play mode’ – talk through goal example. Make clear prior to experiment condition that i) Goals are achievable but can be difficult ii) All goals should be attempted, iii) If goal is already achieved or existing settings are appropriate, no action is necessary.</li> <li>Prior to experiment condition and during debrief, reassure participant that goals may be difficult to achieve but that the aim of the experiment is to see the controls used as settings chosen, rather than if the goals were achieved.</li> </ol>

NaturalisticRealistic Interface	
<b>Issues:</b> <ol style="list-style-type: none"> <li>Usability of interaction for adjusting Thermostat, Boiler water control, TRV</li> <li>Mismatch between room labels and goal reference</li> <li>Misleading feedback of room comfort levels</li> </ol>	<b>Mitigation:</b> <ol style="list-style-type: none"> <li>Put text instructions next to controls and warn participant that some controls are difficult to operate with the mouse.</li> <li>Change room labels to match goals (e.g. 'Bedroom one' = 'Your bedroom')</li> <li>Change labels to 'too warm' and 'too cool' rather than 'warm' and 'cool' so participant knows that goal has not been achieved.</li> </ol>
Design Interface	
<b>Issues:</b> <ol style="list-style-type: none"> <li>House image too cluttered – difficult to know what to focus on.</li> <li>Boost label misleading</li> <li>TRV purpose not clear</li> <li>Not clear you can interact with thermostat</li> </ol>	<b>Mitigation</b> <ol style="list-style-type: none"> <li>Remove from house image: thermometers and black line link to the radiator controls, lines linking programmer/thermostat to boiler, and programmer and power switch icons.</li> <li>Rename Boost as 'override'</li> <li>Label TRV control so function explicit</li> <li>Emphasise thermostat buttons</li> </ol>
Achievability of task	
<b>Issues:</b> <ol style="list-style-type: none"> <li>Goals too easy/hard to achieve</li> <li>Boiler 50C working – makes accidental messing around have too high an effect.</li> </ol>	<b>Mitigation</b> <ol style="list-style-type: none"> <li>Experiment with parameters for 'comfortable' temperature setting.</li> <li>Make boiler 50C setting a 'dummy' so pressing it can be recorded as an action, but it does not have an effect on the simulation</li> </ol>

The resulting interface design for both the realistic and redesigned versions are shown in Figure 66 and Figure 67. The intended redesign for the Boost button (relabelled 'Override') and shown in Figure 59 was not possible to implement in the time allocated. The resulting design showed all segments highlighted as green when active, with the remaining time displayed on the text label (Figure 67).

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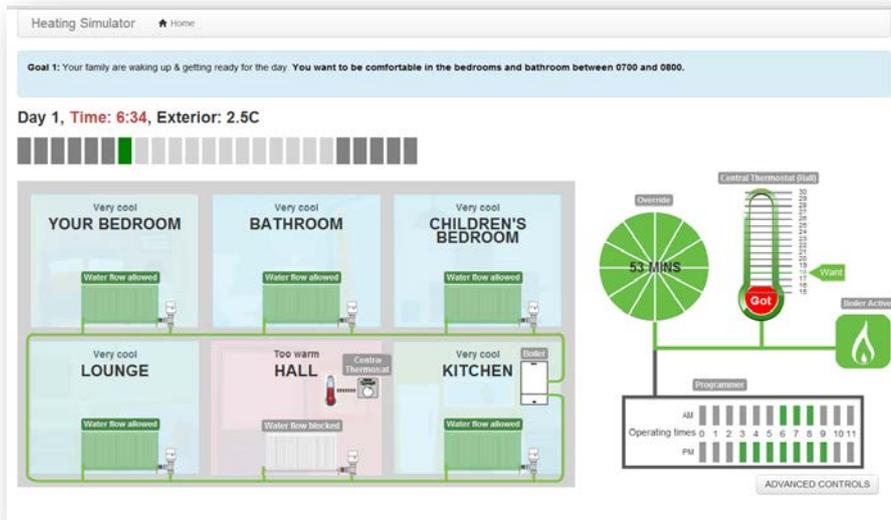


Figure 66 - Interface designed to promote Compatible User Mental Model of Home Heating System

### 7.3 Discussion

Home heating control, like other devices in the domestic domain, suffer from the difficulty that users are given no formal training on operation and instruction manuals may not be consulted, are too difficult to understand, or missing (Kempton, 1986; Sauer, 2009). Whilst the impetus for this research is to help reduce energy consumption due to space heating, the focus in this chapter is considered to be the first step towards this goal. The aim of the research is to change users' mental models through the way in which heating controls are presented to householders. It is hypothesised that the design and controls will promote more compatible models than traditional interfaces.

The design decisions made were directed from the design specifications to improve mental models of home heating, provided by [Revell & Stanton](#) (Gulf Chapter 6) and design recommendations to evoke mental models in general, by Norman (2002) and Manktelow and Jones (1987). Some aspects of

the designs intended could not be fulfilled (e.g. Boost (Override) redesign). Other design elements that made sense 'on the drawing board' did not work in practice (e.g. providing a link between key control devices on the house display, as well as a feedback link from thermometer icons to TRVs), highlighting the benefit of piloting design concepts. Other design considerations were made to ensure the use of a simulation for an experiment to test differences in behaviour resulting from altered user mental models provided sufficient data. This included not only potentially narrower than necessary criteria for room temperature values labelled as 'comfortable', but also a deliberate decision to enable unhindered access to the thermostat and programmer controls. These specific controls are considered long-term controls requiring initial and considered setup (Revell & Stanton, [Gulf Chapter 6](#)). For application in a genuine domestic setting, it is recommended that different modes of access to these controls, depending on whether the user is using trial and error to determine appropriate set points to meet their needs (full access), or if long-term set points had already been established, and the user intends only to make adjustments for atypical goals (restricted access).

The body of literature referred to in the introduction, focusing on problems with energy consuming devices in the home, also offered up a number of recommendations for improving users interactions with technology. It is put forward that a mental models approach to design at both the system and device levels is likely to address a number of these. For example: realtime feedback, in this design, relating to comfort levels and boiler on periods (Sauer et al., 2004; Chetty et al., 2008); Clear display of device status (Sauer et al., 2007); improved discoverability and intuitive design of controls (Glad, 2012); understandable temperature scales, in this case for the TRV controls (Vastamaki et al., 2005); preference for auto-reset features, supported in this design by providing increased prominence of the boost button (Sauer et al., 2004); peripheral positioning of controls (in this case TRV and advanced controls) to reduce frequency of adjustment (Sauer et al., 2004) and application of information proximal to controls (Sauer et al. 2004). In addition, Pierce et al. (2010) and Peffer et al. (2013) validate the relevance of generic design recommendations by Norman (2002) by advocating designers make use of affordances and constraints, visibility, feedback, natural mappings and

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consistency when ensuring householders effectively operating domestic energy consuming devices. These, together with other recommendations in the literature, can be an asset. However, designers need to ensure that seemingly separate devices that in practice, have to be operated with consideration of the impact on each other, are ‘improved’ with consideration of the user’s mental models at a system level.

### 7.4 Conclusion

This chapter has highlighted how domestic technology, particularly the central heating system, is problematic for the user. A case was made for redesigning the home heating interface so that an appropriate user mental model was projected to the user. A redesign of home heating controls at the system and device level was undertaken, based on a design specification [by-developed in Revell & Stanton \(Chapter 6\)](#). Recommendations by Norman (2002) and Manktelow and Jones (1987) for evoking appropriate user mental models were applied to the designs. A brief description of the development of a simulation to test the effectiveness of the redesign, as well as changes resulting from a pilot were provided. Limitations of the design, as well as further enhancements were explored. How the existing design meets recommendations for improving interaction with energy consuming devices in the home was discussed. It is proposed that designer consider the redesign of home heating controls at the system level to evoke functional mental models in the user. These ideas are tested in chapter 8.

## 8. Mental Model Interface Design – putting users in control of their home heating systems.

### 8.1 Introduction

[This chapter focuses on the key aim of this thesis and brings together all the hypotheses described in section 1.2.1 in the introduction. It explores how a mental model driven design can influence the model held \(Hypothesis 3\), which in turn influences behaviour patterns \(Hypothesis 1\) to improve the achievement of home heating goals \(Hypothesis 2\). Linking these hypotheses together with the same data source provides evidence to test Hypothesis 4. This chapter performs statistical tests on data collected through application of QuACk developed in Chapter 4, as well as automated data collected from a home heating simulation. The simulation design is documented in Chapter 7 and is based on the design specification produced in Chapter 6, based on evaluation of the omissions and errors in householders' mental models of home heating described in Chapters 3 and 5.](#)

Energy consumption due to home heating is a key contributor to climate change, making up 58% of UK domestic energy consumption (Department of Energy and Climate Change, 2011). It is easy to save energy in the home - just don't turn the heating on (Sauer, 2009). The real challenge is *using* energy effectively and efficiently, not just saving it. Using energy effectively to meet realistic heating goals is no mean feat (Revell & Stanton, 2014; chapter 4). Doing so in a way that minimises waste is rife with difficulties when using devices that were not designed with this emphasis (Sauer, 2009; Revell & Stanton, chapter 6).

Occupant behaviour is a key variable affecting the amount of energy used in homes (Lutzenhiser & Bender, 2008; Emery & Kippenham, 2006; Guerra -Santin & Itard, 2010; Dalla Rosa & Christensen, 2011; Raaij & Verhallen, 1983). Kempton (1986) discovered variations in the way occupants behaved with their home heating thermostat could be explained by differences in their 'mental model' of its function. Different types of mental models held by occupants

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encouraged different behaviour strategies for saving energy overnight.

Kempton (1986) estimated considerable energy savings could result if specific mental models of thermostat function were promoted to domestic users.

Householders' misunderstandings about thermostat function and the workings of the heating system as a whole is still a problem today (Brown & Cole, 2009; Revell & Stanton, 2014; Under Review, Shipworth et al., 2010). Revell & Stanton (2014; Under Review) extended the findings of Kempton (1986) to consider functional mental models of all home heating controls present in the home, as well as their interactions at a system level. In addition to inappropriate mental models of device function, [in Chapter 3](#), Revell & Stanton (2014) found incomplete mental models at a system level explained differences in behaviour strategies that either wasted energy or jeopardised comfort goals.

Mental models are described as internal representations of the physical world (Veldhuyzen and Stassen 1976, Johnson-Laird 1983, Rasmussen, 1983) and can act as an internal mechanism to allow users to understand, explain, predict and operate the states of systems ( Craik 1943, Gentner and Stevens 1983, Kieras and Bovair 1984, Rouse and Morris 1986, Hanisch et al. 1991). The link between mental models and the operation of states of systems, allows these 'internal representations' to help explain human behaviour (Wickens, 1984; Kempton, 1986; Gentner & Stephens, 1983). There are many definitions of mental models and different perspectives from which to consider them (Revell & Stanton, 2012, Wilson & Rutherford 1989, Richardson & Ball 2009), so specificity in definition is key (Bainbridge 1992; Revell & Stanton, 2012). In this chapter, the concept is best understood in terms of a user mental model (Norman, 1983) and device model (Keiras & Bovair, 1984). That is to say, a mental model held by a user of a specific technology, that contains information about the operation and function of that device, and has been accessed and described by an analyst.

Lutzenhiser (1993) argues that human behaviour limits the efficiency of technology introduced to reduce consumption. However, it is often the choice and positioning of technology, as well as usability issues, that impedes discovery and use by householders (Glad, 2012). Poor discoverability of controls was also found by Brown & Cole (2009), Shipworth et al. (2010) and in chapter 6, and is a credible cause of incomplete models (Revell & Stanton, 2014). Usability issues of home heating controls is prevalent in the literature

(Brown & Cole, 2009; Peffer et al., 2011; 2013; Combe et al., 2010; Shipworth et al., 2010 & Glad, 2012). These can result in lack of use due to inconvenience (chapter 5) or fear of complexity (Glad, 2012). As background knowledge gained from experience, affects the formation of the users mental model (Johnson-Laird, 1983; Moray, 1990; Bainbridge, 1991), lack of experience can further impede appropriate models of heating controls, leading to inappropriate behaviour that impact home heating goals (Kempton, 1986).

Norman (1986) proposed that designers could help users operate technological systems more appropriately by designing interfaces that encourage a 'compatible' mental model of the way the system functions. Norman (1986;2002) proposed that a compatible mental model was necessary to enable users to successfully navigate the 'gulf of evaluation and execution' when interacting with a system. In chapter 6 the home heating system was considered the perspective of Norman's (1986) 7 stages of activity, to determine the components necessary in a compatible mental model for typical home heating goals. Norman (1983;1986) emphasised that whilst underpinned by their mental model, users' interaction with technology, are ultimately driven by their goals. This is supported by Bainbridge (1992) and Moray (1990) who argue that users' mental model of the system constrains the performance with the system, but user goals influence the resulting strategy adopted.

The review so far has touched on system device design (in terms of discoverability and usability of controls), mental models (at a device and system level), user goals (both for comfort and energy saving) and the strategies adopted (in terms of operation of controls). These are all variables that influence the observed user behaviour with home heating systems (for a simplified view of how these variables interact, see figure 68). The consequences of user behaviour need to be understood in relation to the intended goals. However, as both Kempton (1986) and Sauer et al. (2009) note, goal achievement is also subject to variables acting in the broader system (e.g. building structure, infiltration, insulation, thermodynamics of the house, external temperature) as depicted in Figure 68.

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Figure 67 - Different variables that effect home heating behaviour and its consequences

In a [naturalisticrealistic](#) setting, there are clear barriers to controlling householders' goals and broader system variables, limiting the insights that can be drawn about the cause of differences in occupants' behaviour. Sauer et al. (2009) overcame these issues with a central heating system simulator that enabled control of house structure, external weather conditions, occupancy and regularity of arrivals and departures. Sauer's (2009) study compared the provision of different types of feedback on consumption levels (revealing predictive feedback to be the most effective at reducing consumption). Sauer's (2009) participants were all university students, and were tasked with creating heating profiles for each room within the simulation, by selecting heating periods on a graph-style interface. This differed to the nature of typical home heating goals and for greater generalizability of results, Sauer (2009) highlighted that a broader age group and more realistic goals were needed.

Previous work has revealed insights about user mental models of home heating, at the individual level from a small, atypical, sample selected for minimal experience with home heating control (Revell & Stanton, 2014; In Press). Use of a simulation in this study was adopted to allow a larger sample of typical home heating users in the UK, enabling greater generalizability of

conclusions. In addition, the simulation allowed control of goals, broader system variables and heating system type.

This chapter investigates how differences in interface design affect user mental models of home heating systems. Using data from a simplified home heating simulation, it explores how resulting changes in user mental models affect user behaviour with home heating controls. Finally, differences in goal achievement as a result from different behaviour strategies enabled by different interfaces are compared. Classic studies focused on manipulating users mental model and comparing their behaviour and performance (e.g. Keiras & Bovair, 1984; Hanisch et al., 1991) with a single device. Using an extensive 'training' stage to alter the mental model, change is presumed to have occurred if the expected performance was observed. This study differs in that it is relying not on prior training, but on the interface design (plus manuals) to alter the mental model held *at the time of interaction with the system*. This study also measures the success of this manipulation by analysis of user-verified User Mental Model (UMM) descriptions captured post study, behaviour related to statistically significant differences in UMMs, and overall goal achievement. Following from the work of Norman (1986; 2002), the premise of the study predicts that an interface designed to promote a compatible mental model of the heating system, better enables users to achieve their home heating goals.

## 8.2 Method

An overriding assumption for this study was that the contents of UMM descriptions captured by the Quick Association Check (QuACK) (see chapter 4) were linked to behaviour with Home heating controls following from Kempton (1986). This study provided an opportunity to test this assumption for both conditions. The key focus, however, predicted that participants presented with the 'Design' interface; 1) Would have a greater range of heating controls in their mental model description (following enhanced discoverability recommended by Revell & Stanton, 2014); 2) Were more likely to hold an appropriate functional model of key devices (through redesign of controls, recommended by Norman (1986;2002)); 3) Would describe mental models with a greater number of key home heating system elements (through redesign of the home heating interface at a system level, following recommendations by

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Revell & Stanton (2014; In Press; Chapters 3, 5 & 6); 4) Would adopt more appropriate behaviour strategies where significant differences in a) the presence of specific devices in UMMs and b) the appropriateness of functional models at the device and system level were found. Differences in behaviour would be in terms of a) inclusion of specific devices in behaviour strategies and b) the adoption of more appropriate set point values and frequency of adjustment for specific devices (following from Kempton (1986) and Norman (1986; 2002), and; 5) Duration of goal achievement would be greater for participant in the Design condition, than for participants presented with the 'Realistic' interface (following from Norman, 1986; 2002; Moray, 1990; Bainbridge, 1992). For both conditions it was predicted that where a control was present in a UMM, it was more likely to be used as part of a behaviour strategy. It should be noted that the goal achievement variables are dependent upon the outcomes of the behaviour variables, which are in turn dependent upon the mental model variables. An unexpected outcome from the mental model or behaviour variables, would therefore alter expectations for behaviour and goal achievement outcomes respectively.

### 8.2.1 Participants

40 participants took part in this experiment, 20 per condition. 10 males and 10 females were in each condition from ages ranging between 23 and 70 years ( $M=38$ ). Pairs in each condition were matched by gender, age category, and the number of years' experience with central heating ( $\pm 2$  years). Experience with gas central heating (with radiators) ranged from 4 to 40 years, with a median of 12 years. Participants were all native English speakers and were recruited from staff, students, and residents local to the University of Southampton. Participants were recruited through posters on University notice boards and website.

### 8.2.2 Experimental Design

The experiment was a between-subjects design. The independent variable was the version of the interface to the simulation presented to participants; either 'Realistic' or 'Design' (see Figure 69). Dependent variables related to participants' user mental model, their behaviour with controls to achieve goals, and the level of goal achievement. Dependent variables relating to users'

mental models included: 1) the range of heating controls present in participants' UMM description; 2) the number of appropriate functional models of key controls; and 3) the number of key mental model elements for home heating operation, present in participants' UMM descriptions. Dependent variables relating to users' behaviour with the simulation included: 1) the range of controls used in participants strategies, and; 2) the number and value of set point adjustments time. Dependent variables relating to goal achievement included: 1) the proportion of time target room temperatures were within the target temperature range; and 2) total boiler on periods.

### 8.2.3 Apparatus & Materials

Development of the simulation allowed automatic data collection of energy use and behaviour strategies, and enabled two different interface views to be presented to participants. The simulation versions were presented on a Samsung LE40M67BD 40" TV monitor attached to a DELL Latitude E6400 laptop connected to the internet page hosting the simulation and controlled with a mouse. The 'realistic' version reflected the design of a typical gas central heating system, using the setup described in [Chapter 3 & Revell & Stanton \(2014\)](#). The 'design' interface was constructed to promote a compatible mental model of the home heating system following recommendations from [Revell & Stanton \(Revell & Stanton, cChapter 6\)](#). The duration of the simulation activity, goals presented, and duration of goals, were matched for both conditions. The simulation automatically collected data relating to: 1) set point adjustments; 2) "boiler on periods" and "device control mouse clicks". A 'play mode' was available for each version of the simulation that did not collect data. User manuals specific to each simulation version were provided. A consent form, participant information sheet, and participant instructions were provided along with a pen for the subject. Parts 1 and 3 of the Quick Association Check (QuACK) interview script (Revell & Stanton, chapter 4) was used to interview participants to collect background information and elicit the users' mental model. The former was recorded using a pen, and the latter was recorded on A3 plain paper and square post-it notes, using a marker pen. The interview was recorded on a Olympus VN-2100PC audio recorder.

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### 8.2.4 Procedure

Participants were run individually in a room with the subject sat at a desk in front of the monitor. After providing health and safety information, the subject was asked to fill in the consent form, read the instructions for participation (see Appendix 5) and fill in the demographic information section on this sheet using the pen provided. The experimenter then checked understanding, verbally reiterated the key points of the experiment, told the subject which condition they were allocated to, and collected the completed consent forms.

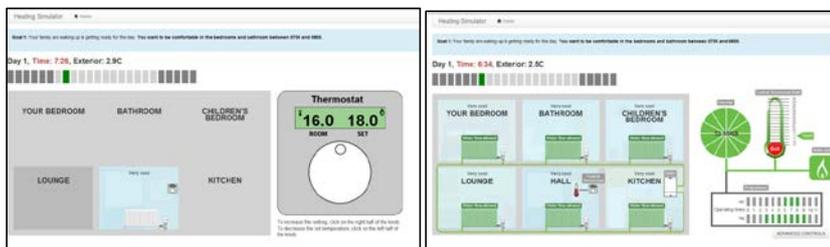


Figure 68 - Screen Shots of Realistic Interface (left) and Design Interface (right)

Before starting data collection, the participant was provided with the user manuals for their experimental condition and exposed to a 5 minute practice session, using their simulation version in 'play' mode. At the start of the practice session, the experimenter pointed out key elements of the interface with reference to a script appropriate to the experimental condition (see appendix 6). For those in the 'Realistic' condition, they were asked to imagine they were operating the home heating controls as if they were in their own home setting. For the 'design' condition, they were asked to imagine they had been provided with a digital interface to control the existing heating controls in their home setting. The experimenter then remained at a desk behind and to the left of the subject to allow the subject to practice independently. During the practice session only, the experimenter responded to any questions by the participant about the procedure for the study or layout of the controls and displays. Participants were referred to the user guides provided (see Appendix 7) if they asked any questions about the function or operation of control devices. At the end of 5 minutes, the experimenter stopped the practice session and asked the subject if they understood what they were required to do and clarified any confusion.

The simulation appropriate to the experimental condition was then started by the experimenter. The simulation ran for 22 minutes with a home heating goal presented textually at the top of the screen, every 2 minutes. The goals represented typical home heating goals for a family with young children and were the same in each condition. To direct action, specific timeframes, rooms, or objectives were provided in the goal description (refer to Appendix 8) for the goal list). The screen flashed yellow to signal a change of goal. On reading the goal, the participant was required to decide what adjustment of heating controls was necessary to achieve the goal, and perform any operation they thought appropriate (even if this resulted in no adjustment). If a subject had not completed their intended adjustments before the next goal was presented, they were to move onto adjustments for the new goal. At the end of the experiment, the screen flashed yellow and text (where the goals had formally been presented) informed the subject that the experiment was complete.

Once the paper-based questionnaires had been completed the experimenter turned off the TV monitor and removed the questionnaires and user guides to prevent them acting as prompts to the structured interview. The experimenter sat to the right of the subject at the same desk, to conduct the structured interview. The audio recorder was switched on and placed on the desk. The experimenter explained the structure and purpose of the interview using the instructions for interviewer provided on QuACK (see Appendix 9). During part 1 of QuACK, the participants' answers to questions about their background experience with home heating systems, attitudes to home heating use, was recorded by pen on the interview script by the experimenter. The participants preferred terminology for home heating components were written on individual post it notes on marker pen. During part 3 of QuACK, the experimenter made clear to the subject that they should answer questions based on their experience with the simulation, not their own home heating system. Participants were told they could refer to their own heating system as a means of comparison, (e.g. "like my heating system, it worked like...." or "unlike my thermostat at home, it worked like....") but only descriptions relating to the simulation would be represented. Following the interview prompts, a diagram was constructed on the A3 paper by positioning post it notes and linking and annotating by pen, to represent the participants' user mental model of the heating system presented on the simulation. On completion of this diagram,

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the experimenter paraphrased the mental model description to check for understanding and provide an opportunity for amendments. When any amendments were complete, a verification stage was undertaken whereby each element, link and rule on the diagram was considered in turn, and the subject asked to identify how confident they were that this represented what they believed. On completion of the verification stage, the subject was debriefed and paid £10 for their participation.

### 8.3 Results

This section describes data gathered from user's mental model description, variables relating to their behaviour with heating controls in the simulation, and goal attainment based on room temperatures. The presentation of information will be split into three sections relating to these areas. In each section, the key hypotheses will be explored by tabulating descriptive statistics then applying the Mann-Whitney U test for non-parametric data to determine the significance of differences in the realistic and design group. Non-Parametric test were necessary as the data was not normally distributed (Field, 2000). To drill into the detail of any significant differences, the data was illustrated in graphs and diagrams. Where graphs revealed the likely focus of differences, the Pearson's Chi-Square for categorical data was used to check the statistical significance. Where the data did not meet the criteria for Pearson's Chi-Square (i.e. expected values per cell were less than 5), the Fisher's Exact test was applied.

#### 8.3.1 User Mental Models of Home Heating Simulation

##### 8.3.1.1 Hypothesis 1 – Greater Range of Home Heating Controls present in participants UMMs when exposed to the Design Condition

To determine if the Design interface increased the discoverability of the home heating controls, hypothesis 1 predicted that the Design condition would promote a greater range of heating controls in participants' UMM descriptions. Figure 70 shows a boxplot illustrating the median, interquartile range and minimum and maximum of the number of controls described by participants in their UMM descriptions. Using the Mann-Whitney test, it was found that the number of heating controls captured in participants' UMMs was significantly

greater in the Design condition than in the Realistic condition ( $U=124.5$ ,  $z=2.092$ ,  $p<0.05$ ,  $r=-0.33$ ). The Design condition therefore encouraged participants to include a greater range of heating controls, supporting hypothesis 1.

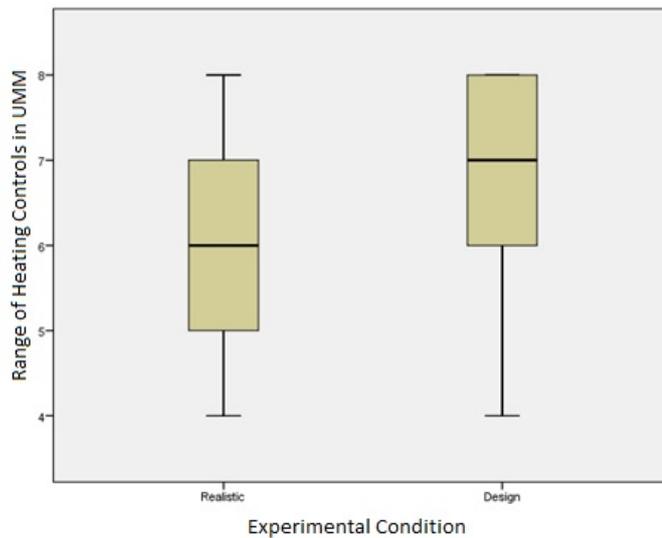


Figure 69 – Range of Heating controls found in User Mental Models.

Figure 71 and Figure 72 group data indicating the presence of heating controls in UMMs by 'key controls' and advanced controls. Whilst Figure 71 revealed little difference in the discoverability of key controls between conditions, greater variation was seen in number and type of advanced controls present in UMMs (Figure 72). Chi-Square tests revealed a significant greater use of the Holiday Button ( $\chi^2=10.99$ ,  $d.f.=1$ ,  $p < 0.001$ ) and Frost Protection ( $\chi^2=32.40$ ,  $d.f.=1$ ,  $p < 0.0001$ ) controls in the design condition.

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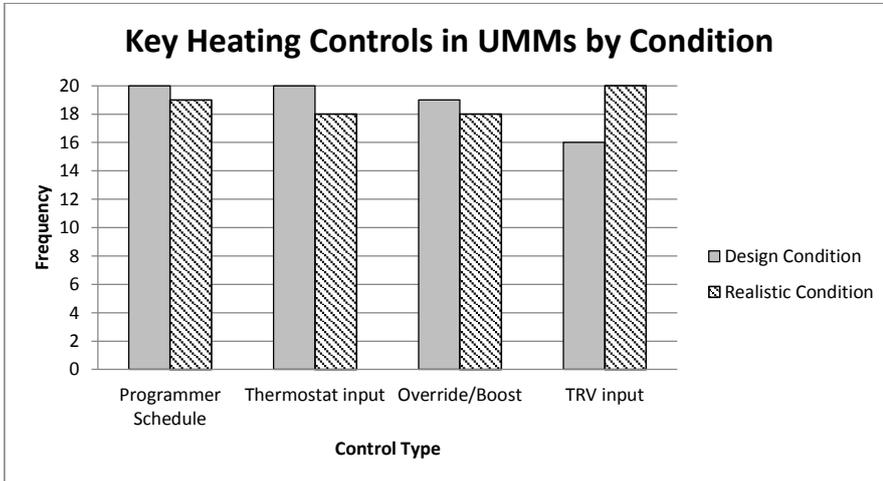


Figure 70 - Frequency of participants who described key heating controls in User Mental Model descriptions.

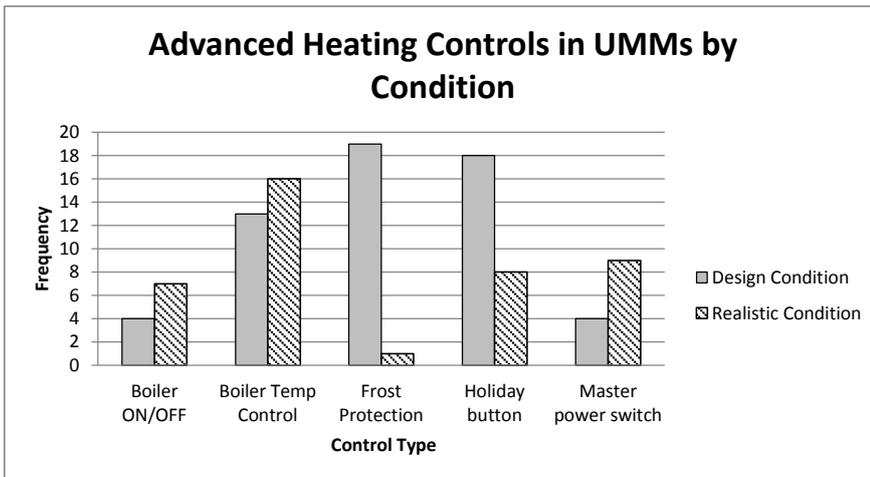


Figure 71 - Frequency of participants who described Advanced heating controls in User Mental Model description.

**8.3.1.2 Hypothesis 2 - Improved Functional Models of Key Devices held by participants in the Design Condition.**

Hypothesis 2 predicted that participants in the Design condition would hold more appropriate functional models of key devices, than those in the Realistic condition. Figure 73 shows a boxplot illustrating the median, interquartile range and minimum and maximum of appropriately functions described by participants to key controls in their UMM diagrams. Results of the Mann Whitney U test, found the number of appropriate functional models of key controls captured in participants UMMs was significantly greater in the Design condition than in the Realistic condition ( $U=108.00$ ,  $Z=-2.617$ ,  $p < 0.01$ ). To take into account variations in the number of key controls present in UMMs, a Chi-Square test was also performed comparing appropriate and inappropriate models (Appendix 10), revealing a statistically significant difference ( $\chi^2=7.335362$ ,  $d.f=1$ ,  $p < 0.01$ ). Both tests support hypothesis 2, that participants in the design condition were more likely to have an appropriate functional model of key devices.

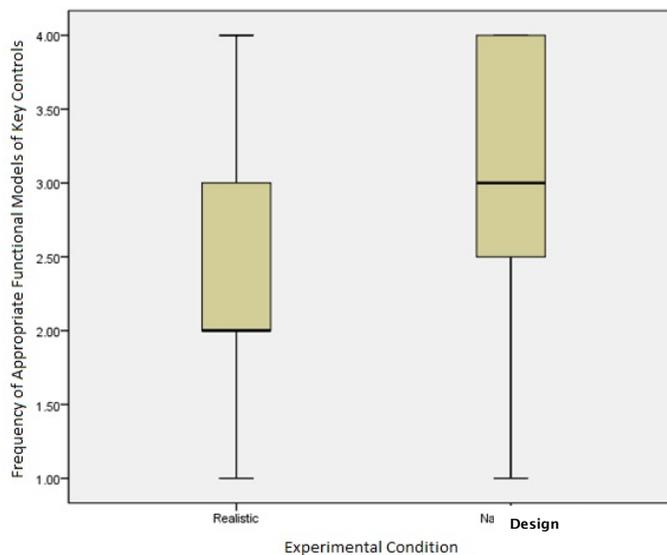


Figure 72 - Frequency of Appropriate Functional Models for Key Controls

The graph in Figure 74 illustrates differences in the appropriateness of functional models for the different controls described in UMMs. This shows

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that the programmer schedule is functionally understood by all participants, regardless of condition. In this sample, more participants in the Design condition held an appropriate functional model for the boost and thermostat controls, but in both conditions, the majority had an appropriate model. Figure 74 shows a statistically significant difference was found in the functional model held for the TRV control ( $\chi^2=9.60, d.f.=1, p < 0.01$ ). Almost half of participants in the Design condition had an appropriate device model of the TRV however, compared to a single participant in the Realistic condition.

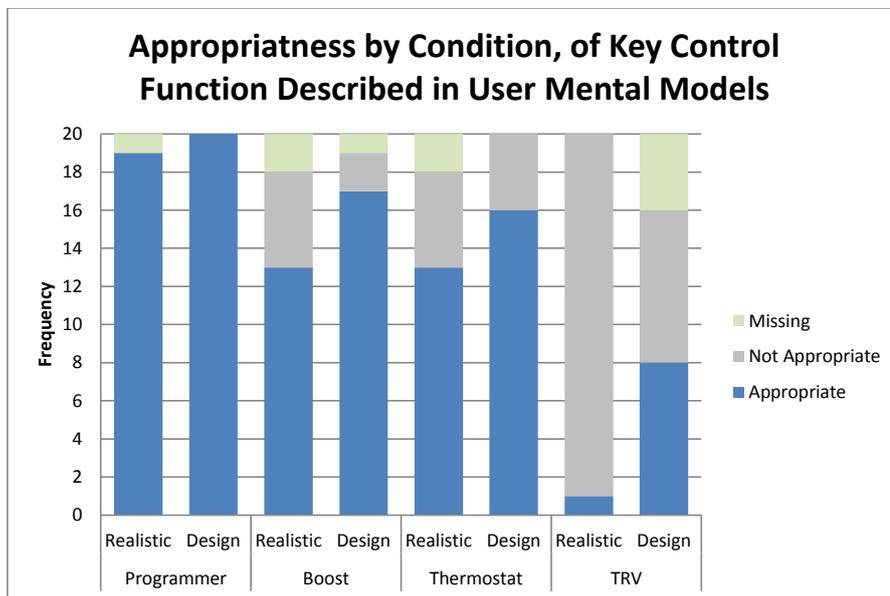


Figure 73 - Graph to compare the frequency of appropriate and inappropriate functions assigned to key controls

**8.3.1.3 Hypothesis 3 - Improved Number of Key Home Heating System Elements described in UMMs of participants in the Design Condition**

Hypothesis 3 predicted that participants from the design condition would describe a greater number of Key Home Heating System elements. Figure 75 shows a boxplot illustrating the median, interquartile range and minimum and maximum of key system elements described by participants in their UMM diagrams. It was found, using the Mann-Whitney test, that the number of key

system elements present in UMMs was significantly greater in the Design condition than in the Realistic condition, ( $U=124.5$ ,  $z=2.092$ ,  $p<0.05$ ,  $r=-0.33$ ), supporting hypothesis 3.

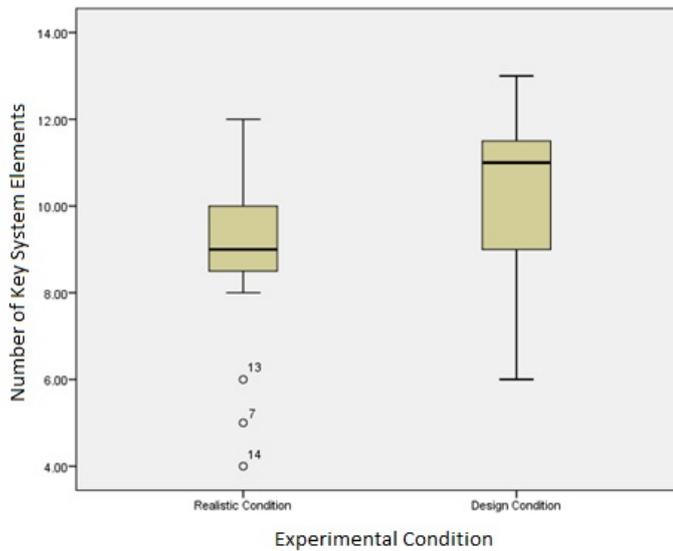


Figure 74 - Number of key system elements present in UMM descriptions.

The graph in Figure 76, compares the frequency of each Key element found in UMMs. The largest differences relate to increases in Design condition in the presence of the 'Conditional Rule', 'TRV Feedback link', and TRV Active Indicator. Chi-Square tests showed these differences were significant for the Conditional Rule ( $\chi^2=5.226667$ ,  $d.f.=1$ ,  $p < 0.05$ ) and the TRV Feedback Link ( $\chi^2=7.025090$ ,  $d.f.=1$ ,  $p < 0.01$ ). Fisher's Exact test showed a significant difference for presence of the TRV Active Indicator in UMMs ( $p < 0.01$ ). This indicates the design condition was more effective at encouraging increases in the presence of these elements.

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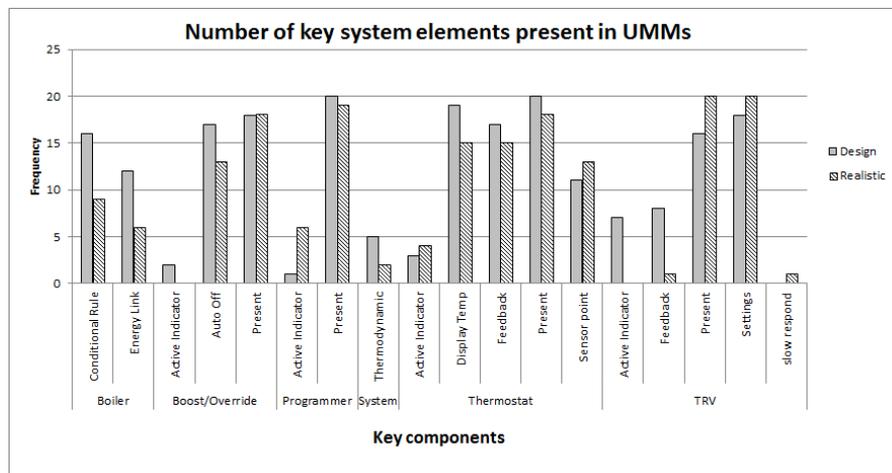


Figure 75 –Frequency of Key system elements present in UMM descriptions

### 8.3.2 Hypothesis 4 – Would adopt more appropriate behaviour strategies where significant differences in UMMs were found

#### 8.3.2.1 Data relating to User Behaviour with Home Heating Controls

This study is underpinned by an assumption that if a control is present in a UMM description, that this control is available for participants to include in behaviour strategies. Hypothesis 4 predicted that participants in the Design condition would adopt more appropriate behaviour strategies in line with the content of UMMs. For this study, significant differences were found between conditions with the prevalence of the Frost Protection and Holiday Buttons devices in UMMs. Hypothesis 4a therefore predicts that the i) Frost Protection and ii) Holiday buttons are included in more behaviour strategies in the Design condition than in the Realistic condition. Significant increases in the appropriateness of the functional model (at the device level) of the TRV and inclusion of the TRV feedback link (at the system level) were found in the Design Condition. Hypothesis 4b i) predicts that the TRVs in the design condition will be operated in a way consistent with a temperature sensing feedback device. Finally, a significant increase in the occurrence of the 'Conditional Rule' at the system level was found in the UMMs of participants in

the Design condition. Understanding the conditional rule enables deliberate control of boiler activation. Hypothesis 4b) ii) therefore predicts that effective boiler control would occur more in the Design condition.

#### **8.3.2.2 Underlying Assumption - Controls present in UMMs indicate presence in Behaviour Strategies**

The underlying assumption to this study predicted that if a heating control is present in a UMM, that it predicts (where the goal requires), its presence in a home heating behaviour strategy. Chi-Square tests revealed a highly significant difference for both the Design condition ( $\chi^2=78.268, d.f.=1, p < 0.0001$ ) and the Realistic condition ( $\chi^2=90.496, d.f.=1, p < 0.0001$ ) (see Appendix 10). For the Design condition, 133 control elements were present in UMMs and 90.2% of these controls were used during the simulation. 47 controls were absent from UMMs, of which 76.6% were also absent in participants behaviour in the simulation. The same trend was found in the Realistic condition, with 89.7% of 116 controls present in UMMs being used in the simulation. Similarly, of the 111 controls absent from the UMMs, 77.9% were also missing from behaviour strategies (see Figure 77). This supports the assumption that contents of UMM descriptions captured by QuACK are linked to behaviour with Home heating controls.

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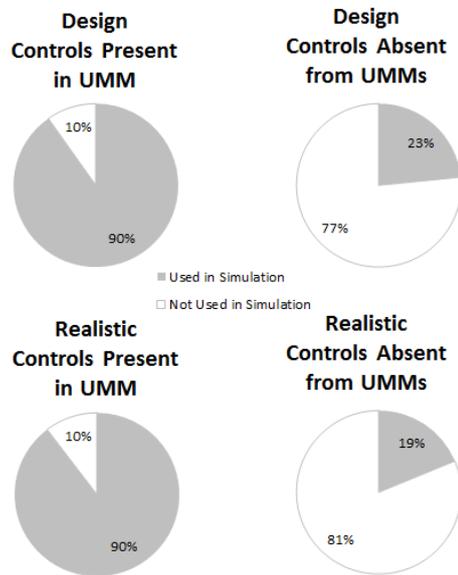


Figure 76 - Proportion of controls used in Simulation, depending on presence in UMM

### 8.3.2.3 Hypotheses 4a i) & ii) - Differences in the Inclusion of Specific Devices in Behaviour Strategies

The graph in Figure 78 shows that the majority of all participants used all four Key controls (Programmer, Thermostat, Boost, TRV). It also reveals a considerable difference in use of the Frost Protection and Holiday Buttons. No participants in the Realistic condition used the frost control button, compared to almost all participants in the design condition. Chi-Square tests showed these differences were statistically significant for the Frost Control button ( $\chi^2=36.190$ , d.f.=1,  $p < 0.0001$ ) and for the Holiday button ( $\chi^2=7.619$ , d.f.=1,  $p < 0.01$ ), supporting hypotheses 4a i) & ii).

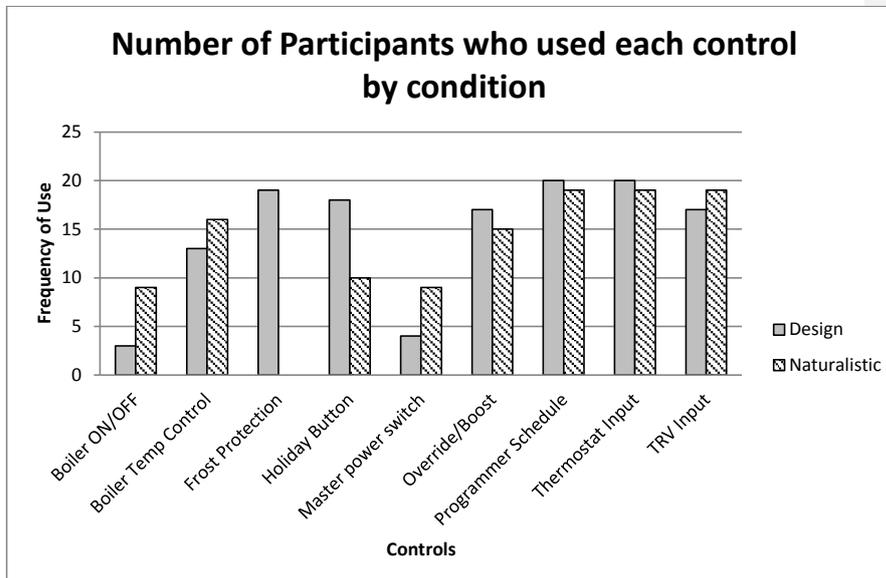


Figure 77 - The frequency of use for controls

#### 8.3.2.4 Hypothesis 4b - The adoption of more appropriate set point values and frequency of adjustment for specific devices

##### 8.3.2.4.1 4b) i) - TRV operation consistent with a temperature sensing feedback device.

Hypothesis 4b) i) predicted that TRV operations in the Design condition will be operated consistent with a temperature sensing feedback device. Less frequent and less extreme set point adjustments are more consistent with appropriate operation of a temperature sensing feedback device for typical home heating goals (Kempton, 1986).

Figure 79 and Figure 80 show boxplots illustrating the median, interquartile range and minimum and maximum of the total frequency of TRV set point adjustments, and mean range of TRV set point choices, respectively. Performing a Mann-Whitney test for non-parametric data failed to reveal a significant result ( $U=158.000000$ ,  $Z=-1.137224$ ,  $p=\text{not significant}$ ) for frequency of adjustment, however, but showed a statistically significant difference in the range of TRV set points ( $U= 110.500$ ,  $Z= -2.428742$ ,  $p < 0.05$ ).

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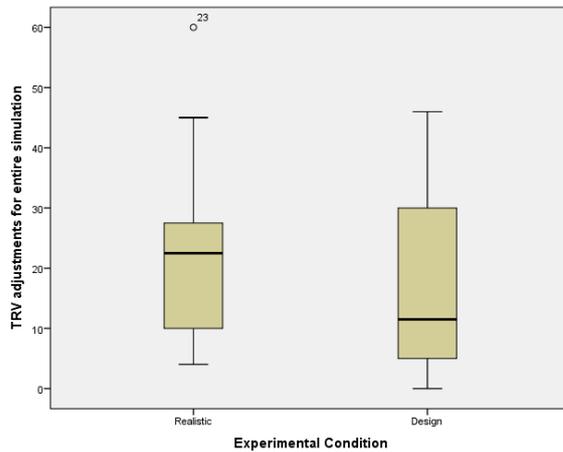


Figure 78 -Frequency of TRV set point adjustments

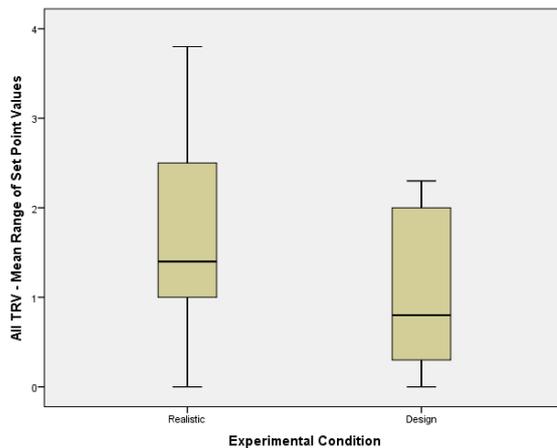


Figure 79 - Mean Range of TRV Set-point Values

Figure 81 shows the adjustment strategies of TRVs for each condition. The set point choices in the realistic condition are more extreme and vary in direction far more than in the design condition, which shows a more subdued pattern. Greatest variation can be seen with the Lounge, Kitchen and Children's Bedroom, reflecting the target rooms in the majority of the provided goals.

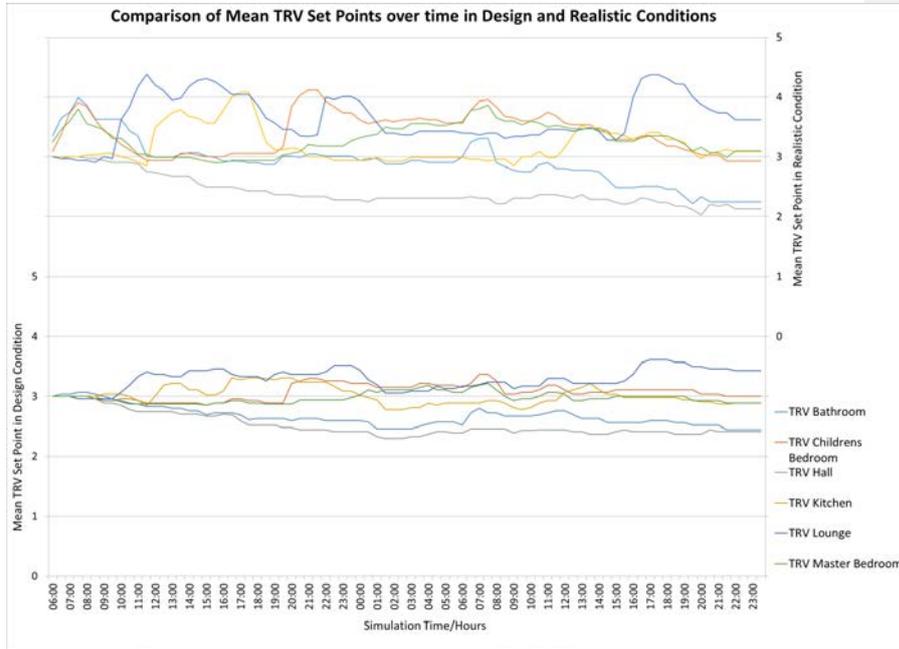


Figure 80 - Frequency of use and set point choice over time of TRVs.

8.3.2.4.2 Hypothesis 4b) ii) - Differences in Control of Boiler Activation

Hypothesis 4b) ii) predicts that effective boiler control would occur more in the Design condition. An essential pre-requisite for boiler activation is for the thermostat to hold a higher set point than the hall room temperature, and a lower set point for deactivation. To test the statistical significance of this hypothesis, an independent samples t-test for parametric data was performed to compare the percentage of thermostat set point value changes that crossed the current hall temperature value. The results showed a statistically significant increase in control of boiler activation in the Design Condition ( $t=3.296$ ,  $d.f.=37$ ,  $p<0.01$ ), than in the Realistic condition, supporting Hypothesis 4b)ii).

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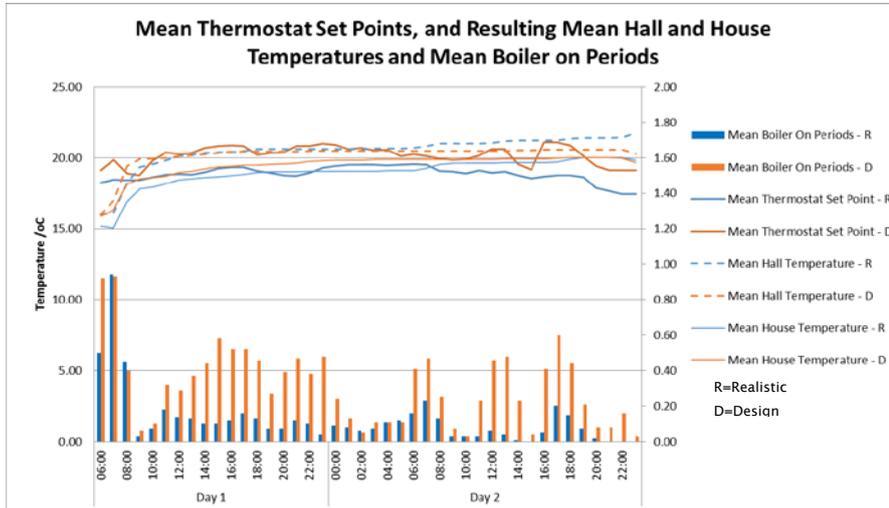


Figure 81 - Control of boiler activation by thermostat adjustments

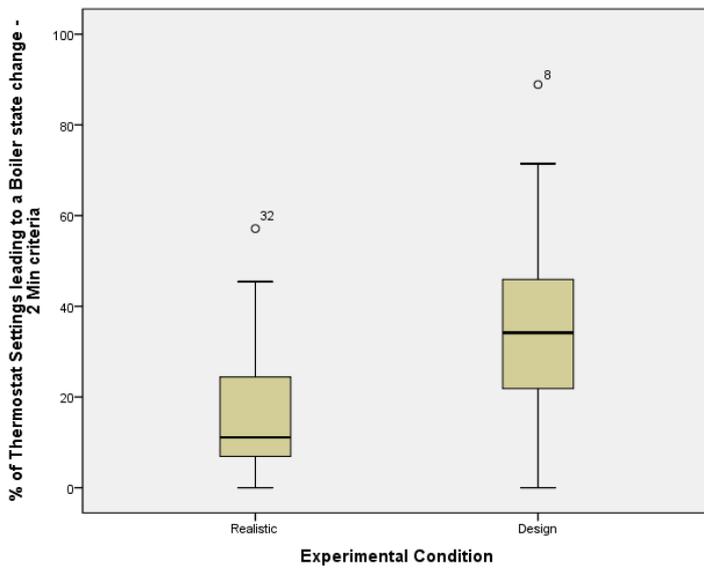


Figure 82 - Percentage of thermostat set point choices leading to boiler state change

**8.3.3 Hypothesis 5 - Data relating to Goal Achievement through target temperature durations.**

Goal achievement was based on target rooms achieving room temperatures within a target temperature range during a target time period. Details are in Appendix 11. Where the target related to multiple rooms, the median room was used as the basis for measuring the duration of goal achievement as it reflected central tendency for non-normally distributed data. As target goal durations differed, to prevent this becoming a confounding variable, the proportion of time each goal was achieved was used. These were summed for 18 goals [meaning and converted into a percentage a 100% goal achievement score would be 18 of overall goal achievement](#). Figure 82 shows boxplots illustrating the median, interquartile range and minimum and maximum of goal achievement. A Mann Whitney test was undertaken, showing a statistically significant increase in goal achievement in the design condition (U=125.500, Z=-2.015, p < 0.05), supporting hypothesis 5.

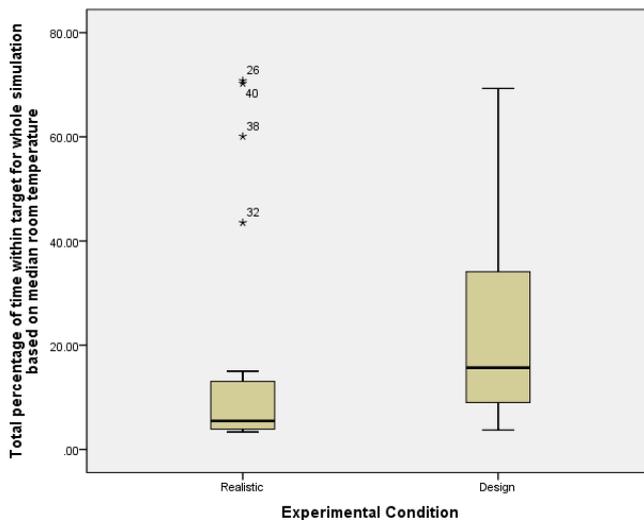


Figure 83 – Total proportion of time within goal temperature range

## 8.4 Discussion

The underlying assumption for this study derives from Kempton (1986) and extended by Revell & Stanton (2014) [in Chapter 3](#), that householders' UMMs of their home heating system affects their behaviour with that system. This underlying assumption was supported, by comparing the presence of heating controls in participants UMMs together with at least 1 instance of adjustment during the experiment. The statistically significant difference between the use of controls based on presence in UMM descriptions was not reliant on the type of interface presented as comparable results were found for both conditions (see Figure 77). Identification of a link between UMMs and behaviour complements previous literature from other domains (Wickens, 1984; Gentner & Stephens, 1983; Keiras & Bovair, 1984; Hanish et al., 1991). The QuACK method for capturing UMMs is proposed as a useful tool in understanding and predicting whether a device is likely to be used. The level and appropriateness of use is subject to more detailed analysis, however, and the subsequent hypotheses go some way to exploring the value of the method in that respect.

### 8.4.1 Improved discoverability of home heating controls

The greater range of heating controls present in UMMs of participants in the Design condition (supporting hypothesis 1), suggests the changes in the home heating interface improved the discoverability of controls overall (see Figure 70). The difference in discoverability of home heating controls in the Realistic condition supports findings by Shipworth et al (2009) and Revell & Stanton (2014) [in Chapter 3](#). When polling 427 English homes, Shipworth et al. (2009) found many people did not recognize many of their home heating controls. [In Chapter 3](#), Revell & Stanton (2014) found key heating controls were missing from UMMs of occupants new to heating control. Similarly, Brown & Cole (2009) who compared heating controls in standard and 'green' office buildings, found that the highest reason occupants had for not using controls was 'Controls don't exist' followed by 'I don't know where they are'. The implications of a greater number of controls described in UMM descriptions in the Design condition, are that the appropriate control(s) are available in the UMM to draw upon when determining an action specification to fulfil a given goal (Norman, 1986). However, it should be noted that since both conditions had a high prevalence of the key heating controls (see Figure 71), the

differences in the inclusion of controls in behaviour strategies, attributable to discoverability alone, would be most marked when attempting to fulfil goals met by 'advanced controls' (in particular, in this case, the Frost Protection and Holiday Button). Improvements in discoverability of less familiar controls by representing physically distributed devices in a single 'control panel' could hold the key to fulfilling the potential of energy saving systems and monitoring technology (e.g. Smartmeters). Glad's (2012) study on the benefits of new energy systems in Swedish housing cited lack of discoverability of devices thwarted expected improvements in CO2 saving.

#### **8.4.2 More appropriate mental models**

Participants from the Design condition were found to have more appropriate functional models of key heating controls, and key system elements supporting hypothesis 2 (users were more likely to hold an appropriate functional model of key devices) and hypothesis 3 (users would describe a greater number of key mental model elements) respectively (see Figure 73 and Figure 75). These results are particularly encouraging, given the lack of formal 'training' to promote specific model types in comparison to studies like Kieras & Bovair (1984) who provided extensive training, followed by a test for comprehension and a re-test a week later to ensure knowledge retention, and Hanish and Moran (1983) who provided 30 minutes training in advance of their experiment. Both of those studies were using novice participants who did not have to 'overcome' an existing mental model of the test device. This study, in comparison, comprised of participants with between five and forty years' experience of home heating controls, so existing knowledge structures would need amendment (Johnson-Laird, 1983). The largest difference between conditions was found with the functional model of the TRV as a feedback device and the conditional rule for the boiler, that requires both the thermostat and the programmer (or Boost control) to be 'calling for heat' to trigger boiler activation. The function of the TRV was misunderstood by most participants, supporting the findings found in (Chapter 6). Improvements in the appropriateness of the TRV functional model supports the view by Kempton (1985), that when operation of controls is 'visible', the correct model is adopted. Improvements in the presence of the 'conditional rule' element, reflects advice from Keiras & Bovair (1984:p.271) that the most useful

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information to provide users is “specific items of system topology that relate the controls to the component’s and possible paths of power flow”. Contrary to the work by Kempton (1986), Norman (2002) and Peffer (2011) but in support of Revell & Stanton (2014) [described in Chapter 3](#), most participants provided an appropriate functional model for the thermostat device (see Figure 74) suggesting present day UK householders do understand this device. The programmer control was not only included in all but one of participants UMMs, but its purpose was well understood. No inappropriate functional models were given by participants for this device, so issues with operation are likely to result from inappropriate models at a system level, or the known usability issues with typical device designs seen in the literature (e.g. Combe et al., 2010; Peffer et al. 2011). That amendments to existing UMMs of home heating systems can be achieved within a very short period of time (25 minutes of accelerated interaction) without ‘formal instruction’ and has favourable implications for using UMM based design for home heating systems or other systems where inappropriate UMMs have been shown to result in inappropriate behaviour.

### 8.4.3 Increased use of Frost Protection and Holiday Button

Hypothesis 4 represented differences in behaviour with heating controls following from statistically significant differences in UMM content. At the device level, this focused on difference by condition in the use of the Frost Protection and Holiday button. As expected, the Design condition encouraged significantly more interaction with these controls than the Realistic condition. Whilst the former device is concerned with safety, increased use of the Holiday button (that replaces the existing programmer schedule with minimal on periods to reflect lack of occupancy) is clearly relevant in terms of reducing energy consumption. How significant this is in terms of other recommended behaviour requires further research. That lesser known controls are used when present in UMMs, and accessible on an interface, lends support to the view that increasing the discoverability of energy saving technology could indeed increase inclusion in behaviour strategies, potentially realising the energy saving potential promised by technology. This would, however, still rely on the adoption of corresponding energy saving goals (Norman, 1983; Moray, 1990; Bainbridge, 1991, Chapter 6).

#### 8.4.4 More appropriate behaviour with TRV controls

Following from analysis of the appropriateness of functional models of Key Control devices, corresponding differences by condition, in the behaviour patterns relating to TRVs were expected. Figure 81 showed TRV adjustments over time for both conditions and it was clear that Expert advice promoting static set points (Revell & Stanton, [Gulf ChapterChapter 6](#)) were not evident in either condition. However, this can be explained by the style of the prescribed goals for 'comfortable' conditions in specific rooms, which may have convinced participants that this level of custom control was possible, as well as the lower effort levels necessary to make changes to distributed controls when presented on a single interface. The results in this study showed increased interaction with TRVs in the Realistic condition, but this was not statistically significant (see Figure 79). A statistically significant difference was found, however, in the mean range of set point adjustments (see Figure 80). The more extreme set point choices found in the Realistic condition are reminiscent of the behaviour pattern described by Kempton (1986) for 'Valve' model holders of a central thermostat, whilst the moderate adjustments made in the Design condition are more in line with Kempton's (1986) behaviour pattern corresponding to a 'Feedback' model. Further examination of the data revealed that a 'Valve' functional model for the TRV was held by the majority of participants in the Realistic condition. This supports the view [given in Chapter 3](#) by Revell & Stanton (2014; Chapter 4), that Kempton's insight can be applied to alternate control devices, and suggests that differences in UMMs in terms of function can explain behaviour patterns. Whilst TRV is not cited in the literature as a key player affecting domestic energy consumption (plus the physical effort involved in adjusting multiple distributed controls) issues of unnecessary adjustment may not be considered a problem at the device level. However, when viewing heating controls as an integrated system, chapter 5 (Revell & Stanton, In Press), showed that inappropriate UMMs of other controls, such as the TRV, can have a significant negative impact on both comfort and energy consumption.

#### 8.4.5 Greater control of boiler activation

The final part of hypothesis 4, examined differences in boiler activation predicted from significant differences in the presence of the 'Conditional Rule'

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in UMMs. To intentionally fulfil heating goals and manage energy consumption it is necessary for the participant to have an understanding of the link between the set points of the thermostat, its relationship to sensed temperature in order to ‘call for heat’ and its dependency on the setting of the programmer and boost for boiler activation. The graph in Figure 82 showed the mean number of thermostat adjustments over time for both condition. Whilst a static thermostat set point is encouraged in manuals and by Expert advice (Revell & Stanton, [Gulf ChapterChapter 6](#)), the appropriate set point choice requires an appreciation of the thermodynamics of the house structure. Crossman & Cooke (1974) emphasise that operator control of dynamic systems requires sufficient time for experiment and observation, which was not provided to participants in this experiment. In addition, the (unintended) non-typical thermodynamic model for the simulation resulted in particularly high temperatures in the hall where the central thermostat was located. This meant that far higher set point values would be necessary to activate the boiler, than participants would be used to selecting at home. Expectations for a static thermostat pattern was unreasonable in these circumstances. The mean data represented in Figure 81, suggests that participants in the design condition were able to influence boiler activation by varying the thermostat set point (thick orange line) above and below the hall temperature value (dashed orange line). Participants in the realistic condition display very little influence over boiler activation as after 0800, day 1, the mean thermostat set point (thick blue line) remains below the mean hall temperature (dashed blue line). For the majority of participants in the Realistic condition, therefore, the boiler would be inactive for a substantial part of the simulation despite repeated set point adjustments in both directions. Results from a t-test supported the hypothesis that participants in the Design Condition operated a greater level of intentional control over the boiler. This result supports the findings of Keiras & Bovair (1984) who found that participants with an appropriate UMM of the system engaged in very few ‘nonsense’ actions, favouring behaviours that were consistent with the device model. This result further supports Revell & Stanton (2014) [described in Chapter 3](#), that UMMs of home heating must be considered at the system level, since the majority of participants in the realistic condition had an appropriate functional UMM for the thermostat device in isolation. Usability or Mental Model promoting design initiatives focused solely at the single device level

(e.g. programmer, thermostat, TRV) are unlikely to maximise desired benefits for comfort or consumption goals.

#### **8.4.6 Increased goal achievement**

Participants in the Design condition were also significantly more successful at achieving the goals provided. This result supports the work of Keiras & Boivair (1984) and Hanish et al (1991). To be as realistic as possible, comfort goals made up a large part of goals and energy conservation was only the focus when the house was to be unoccupied. The proportion of goal achievement was relatively low in both conditions compared to the results of Sauer et al. (2009) who found between 73% and 94%. Sauer et al. (2009)'s study, tasked participants with choosing setting in advance to achieve a specific daily profile, allowing greater opportunity for planning and amendment. In contrast this study presented a succession of changing goals that incorporated not only typical planned changes in comfort goals, but a more realistic 'ad-hoc' adjustment of goals throughout the day, which were not necessarily achievable. This study also placed participants with greater time pressure to make their heating adjustments. Previous work in chapters 3 and 5, has led to the conclusion that a 'gap' between heating expectations (in terms of speed of achieving comfort goals, consistency through the house in space heating temperature, and effectiveness of 'custom' room heating) and what typical UK heating systems can deliver has a large influence on encouraging inappropriate behaviour. Greater generalizability of the results to every-day behaviour is therefore possible by providing 'realistic' goals in the simulation. The measure for goal achievement was based on temperature values for rooms rather than consumption or deployment of appropriate action sequence with controls. This meant that appropriate choices in behaviour (e.g. programmer settings, or deployment of the Frost Protection and Holiday Button) did not get recognized unless there was an impact on room temperature values within the target time period. Further analysis that matches behaviour strategies to specific goals will be the focus of further work. The most important aspect of this study, is that performance improvements can be explained by better control of boiler activation following from increased understanding of the conditional rule, resulting from design changes in the interface and instruction manual. This

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result is highly encouraging as it demonstrates that home heating performance can be affected through design, for a given set of goals.

### 8.4.6.1 Limitations of study

There were limitations of the thermodynamic model used for the simulation. The mean house temperature over time for each condition, shows a gradual increase in value throughout the simulation (see Figure 82). Given the variations in the controls used and boiler on periods, this suggests the insulation parameters were unusually high, preventing heat loss from occurring. This has implications in terms of energy saving goal achievement based on room temperature, since a deliberate drop in room temperature cannot be contrived by behaviour strategy. The thermodynamic characteristics of the simulation were therefore atypical and limits the generalizability of goal achievement findings, particularly relating to comparison in energy conservation. To reduce the variables under analysis, the simulation did not allow the participant to control ventilation or heat flow within the house through opening and closing of doors and windows. Comments from participants indicated that this would have made up part of their strategy for controlling room temperatures, suggesting that restricting behaviour to heating controls only may not be representative for how people manage space heating in the home.

## 8.5 Conclusions

Differences in the design of an interface have been shown to change the content of mental model descriptions. The hypothesis that correspond with the Design condition to improve the functional mental model of heating controls, the discoverability of heating controls and the number of key system elements, was supported. Key differences in users' mental model descriptions focused on the TRV control (appropriate model and feedback link), an awareness of the Conditional Rule for the boiler and the presence of the Frost Control and Holiday Buttons. Differences in the content of mental model descriptions was found to correspond with differences in operation of the heating simulation. Inclusion of controls in a mental model was a highly significant predictor of whether that control would form part of a behaviour strategy. The action specification with controls was also seen to vary between conditions in line

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with the key differences found in users' mental models, significantly improving TRV set point choices and control of boiler activation by the central thermostat, in the Design condition. Participants in the Design condition achieved significantly greater proportion of the experimental goals than those in the Realistic condition. It is concluded that a control panel interface that promotes a UMM integrating heating controls with energy monitoring and predictive technology will help users to have more control over heating consumption. This simulation focused on communicating control device models and interdependency of devices. The promotion of appropriate UMMs of home space heating within the broader context of thermodynamics, weather conditions, and house structure would be the natural next step.



## 9. Conclusion

### 9.1 Introduction

The aim of this research was to investigate how the concept of mental models could be used to encourage behaviour change with home heating controls. Whilst the impetus of the work was to reduce consumption, it is the relationship between householders' mental models of the home heating system and resulting behaviour that has been the focus. The key findings are summarised below, followed by a discussion of the core issues underlying the research. Finally key recommendations and areas for future work are presented.

### 9.2 Summary of Findings

This thesis explored how Kempton's (1986) insight that folk models of the home heating thermostat were associated with energy wasting behaviour patterns. Considering bias in its development, a semi-structured interview was constructed to elicit, describe and analyse householder's mental models of home heating systems and self-reported behaviour. It was found that present day householders used a range of strategies including multiple controls to manage home heating. Considering mental models and behaviour patterns of thermostats in isolation was no longer appropriate, a systems view was proposed to understand domestic home heating behaviour and its effect on consumption. Analysis of mental models and behaviour strategies at the level of the whole heating system, revealed gaps and misunderstandings that hindered appropriate behaviour. Differences in householders' goals also affected the behavioural strategies adopted. A design specification was developed by comparing the gaps and misunderstandings in novices' mental models of the home heating system, to that of an expert. For optimal consumption, it was recommended that householders incorporated in their mental model, broader variables that impact consumption rates. A study comparing a control panel interface developed to promote a Compatible User Mental Model (CUMM), with a more typical interface, found more users described more appropriate mental models at the device and system level, greater control of boiler activation, and greater goal achievement.

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### 9.2.1 Bias must be considered in mental models research.

As mental models cannot be accessed directly, methods for eliciting, describing or interpreting related data is subject to bias. Confidence in application of findings is limited unless the impact of bias is made explicit. A method for considering bias in mental model research was not evident in the literature, so the 'Tree-Rings' framework was developed in Chapter 1. This method allowed systematic consideration of bias in definition, capture, analysis and representation of mental models. This method enables researchers to graphically represent the relationship between the mental model source, intermediaries and recipients when conducting mental models research. Analysts are then prompted to consider the background, social and cognitive artefact biases that come into play. By translating these diagrams to 'tree-ring' diagrams, key characteristics of the type of knowledge structure captured, and the layers of bias to which it is subject could be visualised. This technique is a tool that can aid researchers when constructing methods or undertaking studies involving knowledge structures. The tree-ring method also offers a novel way of gauging the commensurability of existing mental models research.

### 9.2.2 Outputs from QuACk help explain energy consuming behaviour

The Tree-Rings framework was used to develop a systematic method to capture user mental models of home heating and associated behaviour. The Quick Association Check (QuACk) is a semi-structured interview script developed with consideration of bias for data collection, representation and analysis. QuACk was applied in this thesis, first to 3 pilot participants (chapter 3), then to 6 householders in matched accommodation (chapter 4, 5, 6), as well as 40 participants of a home heating simulation (chapter 8), and to 1 expert of home heating controls (chapter 6). Evidence of differences in user mental models of the thermostat and other control devices were found, extending the work of Kempton (1986) (chapters 3, 4, 5 and 8). The shared theories (valve, feedback, timer, switch) described in the existing literature (Kempton, 1986; Norman, 2002; Peffer, 2011) to the thermostat device, were useful in a 'generic' capacity to describe functional models and behaviour for alternate devices (Chapters 3,4 and 8). Self-reported behaviour with home heating controls (depicted in graphical form using a QuACk template) were helpful for

understanding variations in users' energy consuming behaviour strategies (Chapters 5 and 6). The content of mental model descriptions explained differences in householders' behaviour with heating controls. Omissions of control devices in users' mental model descriptions explained omissions in users self-reported behaviour (chapters 3, 4 and 5) and actual behaviour in a home heating simulation (Chapter 8). Differences in the functional models of the thermostat control, explained differences in the way householders reported operating the device (Chapter 3). Similar results were found for the TRV controls and actual behaviour shown in the home heating simulation. Householders with the same functional model of the thermostat, but differences in the range and functional models of other home heating devices, showed considerable variations in their reported behaviour strategies and recorded consumption levels (Chapter 5). Differences between the content of householders' mental model descriptions and that from a home heating expert, highlighted common misunderstandings and omissions relevant for targeting energy saving strategies. The method for categorizing outputs has been validated by 2 Human Factors analysts (Chapter 3)

### **9.2.3 We need to think beyond the thermostat - home heating behaviour should to be understood at a system level**

The focus of past literature on mental models of home heating and associated behaviour, focussed on the thermostat device. Chapters 3, 4 and 5 revealed other devices were used as the main control (e.g. programmer, on/off switch, or TRVs), resulting in static or very infrequent thermostat set point adjustments. To understand the home heating behaviour strategy adopted by a householder, set point adjustments need to be viewed for the whole heating system, not just a single device. Home heating controls are integrated in function, so set points on one device affect operation of other devices. Mental model descriptions by householders and participants revealed misunderstandings about how controls are integrated (Chapters 3, 4, 5 and 8). These misunderstandings explained non-optimal operation of controls by householders, leading to compromised comfort (Chapter 3 and 8) or wasted consumption.

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### **9.2.4 Broader system variables need to be understood for optimal consumption, but are not promoted by existing technology**

To balance comfort and consumption with home heating controls, expert recommendations revealed that users' mental models needed to include concepts relating to the context of use (Chapter 6). To select an appropriate thermostat set point, householders need to be aware of variations in comfort levels throughout their home. To select appropriate programmer start and end times, they need to be aware of, and able to quantify, lag times in heating and cooling. To appreciate energy consumption over a particular time period is greater at night, or when internal doors are open, an understanding of how household thermodynamics are affected by infiltration of warm air throughout the home, and temperature differentials, is needed (Chapter 5). These types of concepts extend beyond the heating system as they relate to variables associated with house structure and weather conditions. Kempton (1986) highlighted how the feedback 'folk model' of the thermostat could result in wasted energy because it did not incorporate these broader variables. Typical home heating technology in the UK does not make this visible nor communicate the influence of these variables on comfort or consumption (Chapter 6), hindering the formation of CUMMs for optimal home heating.

### **9.2.5 Mental Model driven design helps users achieve more heating**

Norman's (1983) 7 stages of activity, and gulf of Execution and Evaluation, were applied to the home heating context. This resulted in a design specification to promote a CUMM that enabled recommended operation of the home heating system (Chapter 6). This design specification was used to develop a concept for a home heating control panel that: 1) improved discoverability of all controls; 2) improved the functional model for key controls; 3) promoted the inter-dependence of key controls; 4) highlighted the influence of control set point choices on radiator output and boiler activation; and, 5) provided real-time thermodynamic feedback. Compared to a more traditional design, the control panel design significantly improved the understanding of the range of heating devices, the appropriateness of their functional model, and understanding of the way key devices were integrated in users mental models. Significantly greater control over boiler activation and

achievement of home heating goals was observed with the control panel design.

## 9.3 Core Issues

### 9.3.1 Optimal Home Heat Control is a complex task

Sauer (2009) described central heating as the most complex system in the domestic domain. Mental models are accessed when users try to interpret complex systems (Moray, 1990). The central heating system is a slow responding system and inherent in systems of this type, cause and effect is difficult to gauge by observation alone (Crossman & Cook 1974). In addition, the user is faced with multiple distributed controls that vary between households in their location, interface and functionality. Optimal comfort and consumption levels are dependent on the compatible adjustment of integrated controls. Additionally, they are effected by variables relating to the environmental setting. These include static variables such as house structure and level of insulation, as well as changing variables within the control of the user (infiltration due to door and window positions) and outside the control of the user (external temperatures varying throughout the day and over changing seasons). For optimal heating control, users have a number of different levels of understanding to navigate: 1) Awareness of controls and the correction functional model at the device level; 2) Awareness of how controls are integrated at the system level; 3) Awareness of House Structure characteristics on comfort and consumption; and, 4) Awareness of Climate characteristics on consumption. But this is only one side of the story. For optimal heating control, householders also need to match this understanding to an understanding about their own lifestyle. This means that they need to have an appreciation of their occupancy levels, and those of others within the household, as well as the different needs of different members of the household (e.g. greater comfort levels for vulnerable occupants, lower room temperatures when cooking, exercising or doing housework, night time comfort for those studying late). This is no mean feat, and Sauer et al. (2009) found it was far more difficult to conserve energy with variable daily routines. Given the barriers to forming a CUMM, householders are faced with matching their unique lifestyle goals with the demands of home heating control, by

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referring to, what is often, an incomplete mental model of the system. It is therefore unsurprising that the behaviour specifications that result are far from optimal.

### **9.3.2 Existing technology does not support a ‘systems UMM’ of home heating**

The home heating systems typically found in UK homes were designed to provide ‘space heating’, rather than an ‘optimal balance between comfort and consumption’. However, through rising fuel prices and environmental concerns, householders are being tasked with operating a system designed for one purpose, to achieve another purpose. To achieve optimal control, householders need to hold mental models of technology at a system, not device, level. However, the modular nature of home heating devices hinders this goal. The controls, radiators and boiler found in typical households are manufactured by different companies. The companies themselves do not know the range or type of controls that will integrate with their device, so can only provide generic guidance outside the feature of their product. Boilers vary in their efficiency, whilst controllers vary in their interface, features and location within the home. In the UK, heating systems are generally inherited, rather than chosen. Unless aware of a certain controls through prior experience, it is not surprising that some householders are wholly unaware of their existence. Heating controls and components are also limited in the type of feedback they give to users. Generally, this is limited to the set point, status and where appropriate, temperature measurements. Feedback that would allow an understanding of cause and effect of their behaviour, the functioning of the heating system as a whole, and the impact on heating goals, is missing. Even at the device functional level, user manuals are often verbose, difficult to understand and if not lost, filed away never to be read. Whilst technology has been used as a tool to encourage energy conserving behaviour in the home, there has been a tendency to focus at the device level. Programmable thermostats have been adopted to help save energy at night or when the house is unoccupied, but do not emphasise the conditional nature of set point choice for boiler function. Neither do they facilitate users choosing appropriate start and end times that fit their lifestyle and the heat lags associated with their own house. Smartmeters and energy monitors have been introduced to make

householders aware of their consumption, but these initiatives rely on the user being able to interpret data at a system level in order to specify an appropriate behaviour strategy. This is a tall order without a fully CUMM and a highly routine lifestyle. By failing to help householders interpret these strategies at the 'system level', householders will refer to and amend their own mental models of their heating system to inform their behaviour strategy. Given the misunderstandings and omissions in user mental models of home heating systems revealed in this thesis, strategies to reduce consumption positioned at the 'device' level are at risk of *compromising*, rather than *optimising* the balance between comfort and consumption. It is not surprising that the EnergyStar rating for programmable thermostats have been removed (Energy Saving Trust, 2013) and the benefit of a SmartMeter roll out in the UK is being questioned (BBC, 2014). Householders currently have the wrong tools for the job of optimal consumption.

### **9.3.3 We cannot control all the variables that effect optimal home heating control**

There are a number of broader system variables that influence comfort and consumption levels include people's lifestyles, the climate, and the structure and insulation levels of the house. Whilst householders have some control over their lifestyles – they may not be able to dictate the regularity of their occupancy if this is linked to work and school obligations and other commitments outside their home. Although they can make choices relating to internal and external infiltration of air around the home, and the installation of insulation, it is more difficult for householders' to make adjustments to the structure of the house to better support thermodynamics and evenly distributed heat. Without moving some distance, householders have no control over the external world climate to which they are subjected. Householders will always be subject to variations that make it difficult to ensure comfort or avoid wasting energy. Similarly there is a limit to what government initiatives can do to control these broader variables, although subsidised insulation and the building of 'greener' buildings are positive steps. This thesis has focused on the problem of influencing householders' *behaviour* with home heating controls, rather than these outside variables. But it is important to appreciate that how appropriate householders behaviour with controls is subject to many

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other variables. A good choice of set point at one time of day, is a poor choice at another time of day. A programmed set of times optimally fits a lifestyle one week, but wastes energy the next week. What is considered a comfortable temperature for occupants sitting and watching TV in the evening, is different when doing the housework. The provision of ‘One-size-fits-all’, prescriptive advice on how to manage home heating systems is therefore unrealistic.

### Recommendations

#### **9.3.4 Recognize the complexity of the task for householders, when embarking on strategies to reduce home heating consumption**

The complexity of the task that householders face to optimise consumption needs to be recognized before effective guidance can be provided. Whether technology-driven guidance, or Government campaigns; simplistic, generic advice is inappropriate given the variations effecting householders. Tailored guidance that takes into account differences in householders’ lifestyles and the influence of broader variables is more likely to result in appropriate home heating management. Device certification (e.g. Energy Star) of devices that rely on the adoption of specific behaviour habits should be tested in the context of use to gain robust indications of energy savings.

#### **9.3.5 Use system level strategies for encouraging appropriate home heating consumption**

A systems level approach is prevalent in Human Factors research in a wide range of domains. The findings of this thesis indicate that a systems approach to tackling home heating use in the domestic domain would be beneficial. Before embarking on a strategy targeted at the device level, an understanding of the interdependency of this device at with other devices in the system is necessary. Ensuring the ‘user’ understands these dependencies is crucial for success. This applies not only for the redesign of existing home heating controls (e.g. improving the usability of programmable thermostats), but also the introduction of new technologies designed to aid energy reductions. For example, the introduction of energy monitors with a strategy that effectively communicates to householders how consumption feedback relates to chosen settings of key controls in different circumstances. System level strategies that

go beyond the central heating system controls to include broader variables are likely to be even more effective to householders, as they would promote a CUMM that enables appropriate consumption. In addition, providing householders with a systems level view that considers heat loss rates could have 'knock-on' effect of making explicit the benefits of investing in low tech improvements such as insulation & draft excluders. It may even positively influence behaviour by making explicit the effect of leaving doors / windows open for longer than necessary.

### **9.3.6 Use a mental models approach when seeking to encourage appropriate behaviour in complex systems**

A Mental Model approach to system control has the benefit of aiding learning and facilitating troubleshooting (Norman, 1983). Where an operators holds an appropriate mental model of a system, variations in their goals can be accommodated (Moray, 1990). This in turn can facilitate appropriate behaviour when undertaking tasks. In the case of home heating, this could lead to systematic improvements in goal achievement. Householders whose goals include reducing waste (e.g. energy or money) could systematically reduce consumption with. Helping users to hold an appropriate 'picture in the mind' of cause and effect at the point of set point adjustment is possible through design driven by mental models research.

### **9.3.7 Design future heating systems with optimal consumption as the primary goal**

Ultimately, the way in which legacy home heating technology is presented to householders, is no longer 'fit for purpose'. Designers for devices, such as home heating controls, which currently rely heavily on human behaviour for energy efficiency, have a responsibility for enabling energy efficient behaviour in the context of use. New home heating technology needs to be designed so optimal consumption is its primary goal. To do so effectively, the broader system variables need to be taken into consideration in their design.

## **9.4 Areas of Future Research**

### **9.4.1 Extension of the ‘Tree-Ring’ method for considering bias**

The tree ring method was applied in this thesis to the home heating and a bank machine. Application to other contexts where knowledge structures are being explored would further validate its generalizability. Further population of the types of bias that are likely to act at different levels, and guidance of typical biases found in particular circumstances would help analysts mitigate for bias in their research, improving confidence in results. Assessment of a significant number of different studies involving knowledge structures using the tree-ring method would provide an opportunity to appreciate their commensurability.

### **9.4.2 Extension of the QuACk method for exploring association with mental models and behaviour**

The QuACk method was developed for the home heating context in this thesis and has also been used by another researcher at Herriot-Watt University in this context. Application by additional researchers would validate its usefulness as a method for this domain, as well as studies of reliability and validity. Adjustment of the questions for another domain of study where mental models are likely to link to behaviour would test its generalizability.

### **9.4.3 Tailored Guidance for Optimal home heating behaviour in different circumstances**

Application of Norman’s (1986) ‘Gulf of Evaluation and Execution’ in chapter 6, considered simplified recommendations for generic home heating goals to understand where householders deviated from expectations. Tailored guidance for appropriate behaviour based on householders’ specific goals, that allowed householders to ‘preview’ predicted consumption could better support optimal consumption, or encourage goals that better fit the installed heating system. Research focused on modelling optimal behaviour in different types of structures, with different environmental conditions, heating system setups against a variety of user goals would be highly beneficial. Further work that looked at how best to communicate the recommended behaviour changes at

the point of action would be a considerable step towards providing highly effective guidance.

#### **9.4.4 Enhancement to home heating control panel & testing in domestic setting**

To upgrade the design of the home heating control panel, different modes would present different controls during setup and for ad-hoc adjustment. Formal user testing would be undertaken at the device and system level. Advanced features such as predictive guidance for different circumstances would be the ultimate goal. The control panel would need to be tested in a real-life setting to determine if improvement to user mental models and achievement of home heating goals held 'outside the lab'.

### **9.5 Concluding Remarks**

This approach to home heating control is highly pertinent given the level of consumption and potential environmental consequences. This research investigates a 'retrofit' to technology that is no longer fit for purpose as its purpose has changed from space heating for comfort, to energy conservation. Similar approaches could be adopted to other domains where devices are designed for a benefit rather than conservation and require active judgements relating to broader systems for efficient operation (e.g. motor vehicles, aviation vehicles, air conditioning). As pervasive computing / intelligent computing advances in its ability to tailor home heating to peoples' goals and expectations, the need to actively manage heating control may become a thing of the past. The literature often cites human behaviour as a barrier to reduced consumption, but this is an unfair charge. The barrier to reduced consumption is the design of technology that does not enable optimal operation and not the user of it. This thesis has shown how advances could be made in understanding behaviour as well as bringing about behavioural change through interface design using mental models.



## Appendices

Appendix 1 - QuACk data collection method

Appendix 2 Part 1 - Output 1 Analysis Table for categorizing behaviour patterns of home heating

Appendix 2 Part 2 - Output 2 Analysis Table for categorizing mental model descriptions of home heating

Appendix 2 - Part 3: Walk-through questions to guide analysts when categorizing output 1 from QuACk

Appendix 2 - Part 4: Walk-through questions to guide analysts when categorizing output 2 from QuACk

Appendix 3- Part 1: Example Categorization of Output 1 using Updated Analysis Reference Tables

Appendix 4 - Table to show how system image of the home heating system can effect user mental models that underpin Norman's (1986) 7 stages of Action

Appendix 5 - Instructions for Participant

Appendix 6 - Example Script for instructions during 'Play' section of Experiment

Appendix 7 - User Guides for Home Heating Simulation

Appendix 8 - Home Heating Simulation: Goals presented to participants

Appendix 9 - Amended QuACk Interview Script for Simulation

Appendix 10 - Chi-Square Test Results

Appendix 11 - Goal Achievement Criteria



## Appendix 1 - QuACK data collection method (comprising: 'Instructions for Interviewer', 'Participant information sheet' and '3 part Interview script')

### 1. Instructions for Interviewer

#### 2.1. Background

The QuACK interview script is separated into 3 areas:

1. Background experience in Home heating /capture of participant's home heating terminology – Questions and probes to guide the positioning of the interview, and understanding of participants responses.
2. Behaviour with home heating system – Questions and scenarios to collect data relating to devices used, and the set points chosen over time. These are then used to populate a diagram of self-reported behaviour.
3. Mental model of Home heating system – Questions and probes to identify home heating components, their function, and the rules and relationships between components. These are used to build up a diagram describing the participants 'mental model' of the home heating system.

Each area will start with 'verbal positioning' to the participant. It is important that this is not missed out, even if it seems repetitive. Throughout the interview script, there will be instructions to the interviewer **in bold** to provide guidance. Depending on the answers to section 1 – some questions may need to be skipped (e.g. if they do not use a particular device) or adjusted (e.g. the terminology used to describe a device, or based on demographic information). The interview should be in a relaxed conversational style, so the participant is allowed to continue a train of thought where it relates to the data sought, but is brought back to the questions if it goes off track. Be aware that some participants, when discussing heating, will have a preference for discussing temperature settings in °F rather than °C.

#### 3.2. Preparation

The following equipment is needed to conduct the QuACK for home heating

- Participant information sheet
- Interview script
- self-report template
- audio recorder & batteries
- pens
- A3 paper
- Square post-it notes.

#### 4.3. Provide Participant Information sheet:

Prior to the interview, the participant should be given the 'participant information sheet' and asked to read the positioning text and fill in the demographic information.

#### 5.4. Verbal Positioning

Before starting the recording, the interviewer should verbally set expectations to the participant by:

- reiterating the 'positioning' text from the 'participant information sheet'

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- stating the interviewer's expert knowledge is on data collection, not home heating systems, so they should not assume any verbal/facial cues relate to the accuracy of their answer
- describing the 3 different sections in brief, and explain that there will be paper based activities where together, the interviewer and participant will 'draw a diagram' to represent how they use, and think about home heating.
- reassure the participant that the best contribution they can make to the research, is to express their own thoughts and experiences with home heating, rather than try to present 'perfect understanding' or 'ideal usage'
- emphasise to the participant that there will be opportunities to amend or change their answers throughout the interview, if they feel they haven't described something the way they intended.

#### **6.5. What to expect & how to deal with it**

- a) When providing a response, participants may answer questions that belong to different sections. The interviewer should follow the participants train of thought rather than cut them off. ***If a question has already been addressed in a different section, the interviewer should state the question, then refer to the answer already given to show they were listening.***
- b) Participant answers may be contradictory as the interview progresses. ***This is expected, and the participant should not be challenged on their inconsistencies. Peoples models or behaviour may vary when presented with different contexts, and this could be a useful research insight.***
- c) The length of the interview may vary depending on the age and experience of the participant. Older participants may drift off subject and will need to be tactfully returned to the questions. Older/more experienced participants may take longer in the mental model section as they may have a more detailed / complete understanding of the number and role of heating components. Younger/less experienced participants may take less time as they have a basic / incomplete understanding of the heating system. ***Allocate longer time periods for older participants. Avoid leading / putting younger participants under pressure to produce more detailed/complete mental model descriptions.***
- d) Throughout the interview, participants may feel embarrassed when confronted with their realisation that they may use the system in a non-optimal way, or may have less understanding of the heating system than they thought. ***Repeat verbal positioning and reassure participant by reminding them there is no reason that they should have expert knowledge.***
- e) In the mental model section, more experienced, or older participants, may fall into the role of trying to 'teach' the interviewer how the heating system works and then may get frustrated that the interviewer (who may appear to them as an intelligent adult) is not 'grasping' what they are saying. ***Remind the participant that to avoid misunderstandings, it is important they describe what they think, even if the interviewer may know what they mean. Sometimes it helps to ask them to explain what they mean, as if they were talking to a teenager, or adult from a hot country, who has not used home heating before.***

## 7.6. Interview Outputs

8.7. Diagram of a participant's self-reported 'typical weekly schedule' of home heating use. Created with, and validated by, the participant.

9.8. Diagram of the participants mental model of how the home heating system functions - showing the components and the relationship between components. Created with, and validated by, the participant.

10.9. Audio recording of interview – allowing in depth analysis of transcripts if required

## ++ Participant Information Sheet

*We are interested in how people think about home heating, and how they use home heating devices. We think that heating devices can be difficult to understand and/or that it can be difficult to heat your home in the way that you want.*

*We are not testing you about your knowledge of energy or mechanical systems, but we will ask you questions about how you think things work, to see if this affects the way you use heating devices.*

*We will ask you about how you use heating for your particular lifestyle. This is to see how well it matches the energy data we have collected, and to understand better your needs and how you use heating devices to meet those needs.*

*We will also suggest situations to you and then ask you to imagine the effect on heating your home and the way heating devices should be used.*

*Home heating is a complicated subject. We do not expect anyone to know the most energy efficient way to run their home. Your answers will help the design of heating and energy monitoring devices to make it easier for people to be energy efficient in a way that fits in with their lifestyle.*

All your answers will be kept confidential and stored securely.

### **Please fill in the following information and bring this sheet with you to the interview.**

1. Gender (please circle) Male/Female
2. Age Group (please circle) 20-35 36-45 46-55 56-65 66-75 Over 75
3. Occupation.....
4. Country of origin (where you spent most of your childhood).....
5. If you have lived outside of the UK, how long have you lived in countries where it is normal to heat the home? (approx. no years) .....
6. How long have you lived in your current accommodation (approx. no years).....
7. What type of Accommodation do you currently live in (please circle)  
flat terrace house semi-detached house detached house other.....
8. How many bedrooms in your current accommodation?.....
9. Do you own your current accommodation? (please circle) Yes / No / shared ownership
10. How many people live in your current accommodation?  
No. Adults (over 18)..... No. Children (under 18).....
11. Does your know accommodation have insulation? (please circle) Y / N / Not Sure
12. If Yes/Not sure , please indicate which of the following apply (please circle):  
Cavity Wall Insulation Loft Insulation Double Glazing Other .....

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## 12.10. Interview Template for home heating based on Kempton (1986) and Payne (1991).

### 13.11. 2.0 Background Experience in Home Heating

*“For this first section, I will be asking about your past experience with home heating systems so that I get an idea of what may have influenced your ideas about home heating. We will also ask about your attitude to home heating and talk about the names you give to different parts of the home heating system, so that I can make sure that we are talking about the same thing”*

1. Do you have any specialist knowledge about heating, energy use or thermodynamics of buildings?
2. Have you had previous experience of home heating devices? If so,
  - a. What sort of devices were they - can you describe them, or do you know the make?
  - b. Approximately how long have you had experience of home heating devices?
  - c. What type of device you are most familiar with? ***If they struggle – suggest a couple to get them going (e.g. central heating with radiators, electric fires)***
3. Which of the following statements best reflects you attitude to energy over the last 3 months?. ***If the participant looks hesitant, verbalise that the study is not aligned to a particular viewpoint, but is interested in how people think and use heating systems and understanding attitudes to heating may help explain this. If the participant cannot choose, ask them to put them in order of importance***
  - a. I want to save money
  - b. I want to protect the environment
  - c. I want to keep warm
  - d. other (e.g. I want to balance cost/comfort).....
4. What home heating devices do you have in your current accommodation (I will write these down on post-it notes so we can use them later, and so I know what you are referring to in the interview)? ***(give an example of ‘radiator’ if they seem unsure. For each device, ask them to describe what they look like and what they refer to them as. Agree a terminology that they are comfortable with, but you are clear on the meaning– e.g. ‘heating control’ for thermostat, ‘heating switch’ for boiler override, ‘big box’ for boiler, ‘blower’ for hot air heater – write BOTH terms on each post it notes to avoid confusion)***

**CHECK ALL QUESTIONS ANSWERED IN SECTION 2.0**

### 14.12. 3.0 Behaviour

*“For this section, I’m going to first be asking about how you use the heating system in your current accommodation over a typical week. I’ll use your answers to create a diagram on this template [show template]. Throughout this section, or at any time in the interview, you can make changes to this diagram, if, for example, you remember something you haven’t added, or you do not feel it reflects what you do. After this, I’m going to describe some typical home heating scenarios to you and ask you what you think you would do in each situation”*

1. **When asking the questions – replace the terminology in the questions with that agreed with the participants**
2. **If questions have been covered in previous answers, acknowledge the question by verbalising the answer given previously, to show you were paying attention.**
  - **When you get a sense of the pattern of use (e.g. which devices, and what settings used over time), start representing this on the template as they talk. Prime the participant verbally, e.g. “What I’m going to do now is draw what I think is the typical way that you use home heating in your home over a week, so you can tell me if you think I have the good idea about what you do”**
  - **Draw out a basic idea of what they have said over a week – separating weekday with weekend if different. On the y-axis, choose the appropriate scale for the devices. If there is a combination of devices – you may need different versions of the scale for different devices (e.g. temperature scale, as well as an on/off scale). As you are drawing, talk through what you are doing so the voice recorder can pick up exactly what you mean, and if there is agreement from the participant).**
3. **Allow the participant to draw on the diagram to show what they mean, if they find this easier.**

#### 15.13. 3.1 Self report on usage

1. How do you turn the heating on? (which device, describe the steps)
2. When do you normally turn the heating on? **(make a note of the times of day, and duration to use for the template)**
  - a. Is there a difference in the way you use heating at the weekend? if so, please describe.
3. Who normally turns the heating on? Is it more than one person, or typically one person?
  - a. If more than one person, could you describe when each person normally turn it on? (e.g. times of day, how often, how long for, what controls and steps are used) **(when annotating different agents on the template, agree a key with the participant, and label the behaviour patterns to distinguish between them)**
4. Do you ever use the thermostat? If so,
  - a. Who normally uses the thermostat?
  - b. When do you normally turn it up/down?
  - c. Why do you normally turn it up/down?
  - d. Are there any other situations in which you use the thermostat? If so, what are they? how often does this happen (every day, every week, or rarely)?
5. Do you use the thermostats on the radiators? If so,
  - a. When do you do this (every day, every week, or rarely)?
  - b. How do you make adjustments?
  - c. Why would you make adjustments?
6. Have you/someone programmed the programmer? If so,
  - a. What times and durations is the programmer set to come on & why?
  - b. Have you ever bypassed the programmer to turn heating on/off? If so,
    - i. What sorts of situations (when & why & how often?)
    - ii. What did you do to bypass the programmer?

**Paraphrase what you have understood from this section to allow participant to agree/amend.**

**CHECK ALL QUESTIONS ANSWERED IN SECTION 3.1**

**16.14. 3.2 Response to Scenarios**

*“In this section, I’m going to describe some home heating scenarios to you. These may, or may not, reflect what happens in your own life. If it doesn’t reflect your own life, please imagine what you think you would do in this situation. Afterwards, I will ask you how likely this scenario is for your lifestyle. This section often reminds people of ways that they use their home heating, that did not come to mind in the previous section. If this happens, we can make adjustments to the home heating template to better reflect this”.*

1. **Scenario 1:** It is winter, you come home to a cold house and want to put the heating on to warm up. What do you do? **(let the participant answer freely, then use the following probes if they have not already been answered)**
  - a. Describe what device you use and how you adjust it?
  - b. Why do you use that device, and why do you adjust it in that way?
  - c. You want to warm up quickly– would you do anything different?
    - i. How likely is this? (every day, every week, rarely...?)
  - d. You want the heating to stay on for a long time - would you do anything different?
    - i. How likely is this? (every day, every week, rarely...?)
  - e. You want the heating to come on straight away – would you do anything different?
    - i. How likely is this? (every day, every week, rarely...?)
  - f. You want the house to warm up to a specific temperature – would you do anything different?
    - i. How likely is this? (every day, every week, rarely...?)
  - g. How typical is scenario 1 for your lifestyle during winter? (every day, every week, rarely...?)
2. **Scenario 2:** You have been working on your laptop all morning and are feeling cold from sitting at your desk for too long. What do you do? **(let the participant answer freely, then use the following probes if they have not already been answered)**
  - a. How likely are you to turn on the heating to warm up? (every day, every week, rarely...?)
  - b. How typical is scenario 2 for your lifestyle during winter? (every day, every week, rarely...?)
3. **Scenario 3:** The heating is on at the usual time and you have been rushing around (e.g. doing housework, playing with the children, cooking in a warm kitchen, or doing exercise). You now feel uncomfortably warm. What do you do? **(let the participant answer freely, then use the following probes if they have not already been answered)**
  - a. How likely are you to turn on the heating to warm up? (every day, every week, rarely...?)
  - b. How typical is scenario 3 for your lifestyle during winter? (every day, every week, rarely...?)

4. **Scenario 4:** You are relaxing with your spouse in the evening, the house is pleasantly warm and the heating is on. What do you do?
- How likely are you to turn the heating off? (every day, every week, rarely...?)
  - How typical is this scenario? Every day, every week, rarely....?

**Paraphrase what you have understood from this section to allow participant to agree/amend.**

**CHECK ALL QUESTIONS ANSWERED IN SECTION 3.2**

**Give participant opportunity to make any changes to their typical behaviour diagram (verbalising adjustments so they can be understood when listening back to the audio recorder)**

#### **17-15. 4.0 Mental model of Device Function**

*"In this section, I will be asking you how you think the home heating system in your current home works. We are not interested in knowing the 'correct' answer. We are looking to understand what you imagine happens, as this is more likely to affect your behaviour when using heating in the home. Please say what you think, or have a 'guess'. Afterwards you will be asked how sure you are. Don't worry if things you say do not match things you have said before, it is normal for people to think differently about how things work, when presented with different situations. As you answer the questions, I will write your answers down on the post it notes and paper, and arrange the post it notes and draw lines between them. This will help me to build up a picture of what you imagine."*

- **Take the A3 plain paper and place the annotated post it notes next to it.**
- **When the participant mentions elements in the post it notes in their response, add this to the paper in an appropriate place.**
- **If the participant mentions new terms / devices /concepts – add this to a new post it note and place on the paper in an appropriate place**
- **If the participant gives further details or information about a concept – annotate the appropriate post it note or paper to reflect this.**
- **For questions 2, 3 and 4, substitute the concepts in brackets, and repeat the question, for each relevant post it note.**

- How can you tell when the heating is on/off?
  - What do you see, hear, feel, smell?
- What is the job of this [device]( **Use the following prompts to draw out the different elements of the system and the different conduits and dependencies**)
  - What do you think happens when you [adjust] the [device]? (e.g. "...turn up/down the thermostat)
  - What do you think the [device] is connected to? (e.g. thermostat)
  - How does the [device] know when to [operate]? (e.g. "... the boiler know when to come on/off?)
  - What happens when you override the [device]? (e.g. programmer)?

**After each post-it note has been through this process, paraphrase using the diagram what you think the participant means, and ask them to confirm/amend, before going onto the next post it note.**

3. If you [adjusted] the [device] to its [extreme maximum] setting – can you explain using the diagram, what would imagine happens? (e.g. “... turned the thermostat to its maximum temperature”)
4. If you [adjusted] the [device] to its [extreme minimum] setting – can you explain using the diagram, what would imagine happens? (e.g. “... turned the thermostat to its minimum temperature”)

**After each post-it note has been through this process, paraphrase using the diagram what you think the participant means, and ask them to confirm/amend, before going onto the next post it note.**

5. When you were thinking or describing how the heating system works – can you think of any other devices that work in the same way? Or did any other things come to mind?  
**Use examples participant has offered already of analogies with other devices (e.g. programmer works like an alarm clock, or boiler works like a kettle), but do not suggest analogies yourself. If they hesitate or look uncomfortable, do not pursue this.**

*“For this last step, I will be asking you to say how confident you are that this diagram reflects how you imagine your home heating system works. I’m going to go through each part of the diagram, and paraphrase what I think you mean. If you are happy this reflects what you imagine/think – I will put a ‘smiley’. If you are unsure about what you think (i.e. if the diagram reflects what you think makes sense, but you are not sure this is correct/what you really believe), then I’ll put a ‘?’. If I have misunderstood something, please let me know, so I can amend the diagram to reflect what you imagine.”*

- **Go through each component and conduit and paraphrase what has been annotated.**
- **Ask “does this reflect what you imagine” and wait for a response.**
- **If they are happy, annotate with a ‘☺’**
- **If they suggest an amendment, make the amendment, then annotate with a ‘☺’**
- **If they are not sure, annotate with a ‘?’**

**CHECK ALL QUESTIONS ANSWERED IN SECTION 4.0**

“Thank you for participating in this study, the interview are now over”

## Appendix 2

### Appendix 2 Part 1 - Output 1 Analysis Table for categorizing behaviour patterns of home heating

<b>1) Control</b> -devices adjusted in a household during a typical week	<b>2) Agents</b> -range and type of agents contributing to behaviour patterns	<b>3) Regularity</b> -of behaviour patterns	<b>4) Frequency</b> -of adjustments	<b>5) Set points</b> -how specific -how variable	<b>6) Synchronicity</b> -of behaviour patterns with other factors	<b>7) Category</b> -Compatible shared theory/ generic theory of device function
Control Device	-Single -User (Manual)	-pattern may be completely irregular -some parts of pattern may be repeated -changes in regularity may be based on range of lifestyle and system factors	-frequent adjustments - exact behaviour pattern not repeated - minimal periods of no adjustment when	-Value may be specified, approximate or general (turn up/turn down) -variable set point value	-Regular and irregular daily activities -occupancy of dwelling -type and level of activity carried out by occupants -changes in additional variables (e.g. external temperature / comfort levels)	Generic Valve (Manual)
e.g. Thermostat	-Single -User (Manual)	-mainly irregular patterns, but some parts may be repeated (entire daily pattern never repeated) -changes in regularity based on range of lifestyle, and system factors	- frequent adjustments of set point when users at home and awake - no adjustments when absent/sleep	-Specific values less important than direction and extent of adjustment (turn up or down, turn right up, or right down) -considerable variations in set point value based on range of lifestyle & system	-Adjustments coincide with regular activities (e.g. turning right down when going to bed, turning up when getting up, turning down when leaving for work or cooking), -Irregular activities	Valve (Kempton, 1986)

				factors - Set point turned right down at night	(e.g. turning up when coming home earlier than usual) -other variables such as external weather(e.g. turning up when it snows outside), or user comfort (e.g.turning down when user hot from exercising)	
Control Device	Single/Multiple User (Manual)	- regular/irregular pattern depending on lifestyle <b>If used as primary control:</b> - patterns may be repeated -occasional variations in patterns -may be inf	-Infrequent adjustments - no adjustment when house unoccupied/ users asleep -multiple users may increase frequency if they have different comfort goals <b>If used as secondary control (e.g. in conjunction with automatic timer):</b> -adjustments may only occur occasionally	-Set points values chosen specifically to activate/deactivate heating <b>If control offers scale:</b> - values may vary(e.g. to 'click' or extreme values) <b>If control offers discrete options:</b> -exact values (corresponding to on/off)	-routine events (if used as primary control) - non-routine events -activity types that affect comfort levels (sedentary activities may encourage user switching on heating, high levels of activity encourage switching off)	Generic Switch
e.g. Thermostat	Single/Multiple User (Manual)	Regularity based on regularity of lifestyle	-Infrequent instances of adjustment - no adjustment when house unoccupied/ users asleep -multiple users may	-Set points values chosen specifically to activate/deactivate heating (e.g. to 'click' when boiler can be heard to 'fire up' or	Adjustments coincide with regular activities (e.g. going to bed, getting up, leaving for work, cooking), -Irregular activities	Switch (inferred from Peffer, 2010)

			increase frequency if they have different comfort goals	extreme increase/ decrease in temperature) -approximate values may be given rather than specific values	(e.g. coming home early, ) -operators own comfort (too hot/ too cold from exercise, sitting still, housework)	
Control Device	-Single/Multiple -User(s) (Manual only) -User + Digital (e.g. Manual set points, -Automated adjustment)	-Regular pattern of adjustment -changes in pattern may occur according to changes in lifestyle (e.g. at weekend) -if automated agent included, adjustments may occur when occupants asleep/ away from the house	-Infrequent adjustments -pattern repeated periodically (e.g. daily)	- Specific values chosen to maintain heating variable (temp, time, boiler activity etc.) - variations in the values chosen match needs of specific regular lifestyle events <b>Note: If two feedback devices are used together (e.g. Home heating Timer and Thermostat), the user may keep static set points if the combined automatic adjustments fulfil their lifestyle requirements</b>	-Regular daily activities -Ad-hoc daily activities (if manually controlled, or if easy to make adjustments to automatic controls)	Generic Feedback – automatic on/off
e.g. Thermostat	Single User (Manual)	-Regular pattern of adjustment based around regularity of lifestyle (e.g. set to 20oC on rising, turned	-Infrequent adjustments (based on frequency of regular activities) -approx. pattern of	-Pre-determined set value for when house is occupied, when unoccupied -Night set point	Adjustments coincide with regular activities (e.g. getting up, leaving for work, coming home, going	Feedback (Kempton, 1986)

		to 18 when leaving the house, turned back to 20 on returning) -intervals between adjustments may vary based on lifestyle, but not comfort levels	adjustment repeated daily	chosen, but not significantly different from daytime set point	to bed), - ad-hoc adjustments rarely made-and only based on changes to activity/occupancy, <i>not</i> comfort	
Control Device	-Single / Dual -User (Manual) -User (Manual +Digital (Automatic)	-Regularity of pattern of adjustment, based on regularity of lifestyle	-Frequency of adjustments depends on the set point chosen by the user (greater set point, greater interval between adjustments, lower frequency) -frequency of pattern of adjustment, dependent on lifestyle / comfort levels	- specific set point values chosen to determine 'automatic off' of heating variable -set point value may vary depending on lifestyle/comfort -may be a 'reset' set point value	-Regular daily activities -Irregular activities -comfort levels	Generic Feedback – automatic off
e.g. Thermostat	single User (Manual on)	-Regularity of pattern of adjustments depends on regularity of lifestyle	- frequency of adjustments depends on set point chosen. If high temp value chosen, not likely to make further adjustments for a while. - frequency of pattern of adjustment dependent on	- Set point values chosen to determine how long heating on – higher set point to ensure heating is on for a longer time -lower set point to ensure heating is on for shorter period of time	-Adjustments coincide with regular activities where heat levels are too low (e.g. getting up, returning from work,) -Irregular activities (e.g. coming home early to cold house ) -operators own	Timer (inferred from Norman, 1986)

			lifestyle/comfort levels		comfort (too cold from sitting still)	
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**Appendix 2 Part 2 - Output 2 Analysis Table for categorizing mental model descriptions of home heating**

<b>1) Control</b> -operated by user to adjust home heating	<b>2) Input Behaviour</b> -afforded by <i>control device</i> for specific user -relates to key/sensed variable -may initiate automatic adjustments	<b>3) Key Variable</b> - related to energy consumption (dependent on research question)	<b>4) Key Element</b> - influences <i>key variable</i> , - linked to control device /sensor (directly or indirectly)	<b>5) Sensor</b> -measures <i>sensed variable</i> -linked to <i>Key Element</i> (directly/indirectly)	<b>6) Sensed variable</b> - measured by <i>sensor</i> - value used to enable automatic adjustment	<b>7) Rule</b> -how variations in <i>Input Behaviour</i> affects the <i>Key Variable</i> , - criteria for automatic adjustments of <i>Key Variable</i> including the role of a <i>sensor, sensed variable and key element (where relevant)</i>	<b>8) Category -</b> generic / shared theory -(Manual/ Automatic)
Control	<i>Control</i> -allows continuous/ interval adjustments that affect the <i>Key Variable</i>	<i>Key Variable</i> -controlled by <i>Key Element</i>	<i>Key Element</i> - may house <i>Control</i>	None	n/a	Variations in <i>Input behaviour</i> of <i>control</i> are <u>linearly</u> related to: variations in <i>Key variable</i>	Generic Valve (Manual)
e.g. Thermostat Knob	<i>Thermostat Knob</i> allows increase / decrease temp. dial to adjust <i>Boiler Intensity</i>	Boiler Intensity	Thermostat	None	n/a	<i>Increasing/decreasing</i> the <i>Thermostat Knob</i> results in increases/decreases in <i>boiler intensity</i>	Valve (Kempton, 1986)

Control	<i>Control</i> -allows discrete modes (e.g. on/off) that affect the <i>Key Variable</i>	<i>Key Variable</i> - controlled by <i>Key Element</i>	<i>Key Element</i> - may house <i>Control</i>	None	n/a	When <i>Control</i> is <u>activated</u> , it <u>enables</u> <i>Key Variable</i> When <i>Control</i> is <u>deactivated</u> , it <u>disables</u> <i>Key Variable</i>	Generic switch (manual)
Eg. Thermostat knob	<i>Thermostat Knob</i> allows Increase / decrease temp. dial to turn on/off <i>Boiler Operation</i>	Boiler Operation	Thermostat	None	n/a	When <i>Thermostat Knob</i> is turned up, it activates <i>Boiler Operation</i> . When the <i>Thermostat Knob</i> is turned down, it deactivates <i>Boiler Operation</i>	Switch (Peffer, XXX)
Control Device	<i>Control device</i> -determines/initiates <u>target</u> value of <i>Sensed Variable</i> -influences <i>Key Variable (Or other variables)</i> -enables automatic maintenance of target value of <i>Sensed Variable</i>	<i>Key Variable</i> -controlled by <i>Key Element</i> -changes result in changes to <i>Sensed Variable</i>	<i>Key Element</i> – influences <i>Key variable</i> - receives input from <i>Sensor</i> (directly or indirectly)	<i>Sensor</i> -detects <i>Sensed Variable</i> and feeds back to <i>Key Element</i> (directly or indirectly)	<i>Sensed Variable</i> -measured by <i>Sensor</i>	<i>Control</i> determines /initiates <u>target</u> value of <i>sensed variable</i>  This value is compared to <u>current</u> value of <i>sensed variable</i> , measured by the <i>sensor</i>  If target value is <u>higher</u> than current value, the <i>key element</i> will <u>enable</u> the <i>key variable</i> . If <u>lower</u> /same, it will <u>disable</u> the <i>key variable</i>	Generic Feedback – (automatic on/off )
e.g. Thermostat knob	<i>Thermostat knob</i> - lets me set my desired <i>room temperature</i>	Boiler operation	Thermostat	Thermometer	Room temp.	<i>Thermostat knob</i> determines the target <i>room temperature</i>	Feedback (Kempton, 1986)

	- it influences when the boiler comes on and off - this room temperature is then automatically maintained					<p><u>Target Room Temp.</u> is compared to <u>current Room Temp.</u> , measured by <i>Thermometer</i></p> <p>If <u>Target Room Temp.</u> Is higher, the <i>Thermostat</i> enables <i>boiler operation</i>. If lower/same, it disables <i>boiler operation</i>.</p>	
Control	<p><i>Control</i></p> <ul style="list-style-type: none"> <li>-activates <i>Key Variable</i></li> <li>-determines/initiates <u>target</u> value of <i>Sensed Variable</i></li> <li>- automatically disables <i>Key variable</i> when target value reached</li> </ul>	<p><i>Key Variable</i></p> <ul style="list-style-type: none"> <li>-controlled by <i>Key Element</i></li> <li>-changes result in changes to <i>Sensed Variable</i></li> </ul>	<p><i>Key Element</i></p> <ul style="list-style-type: none"> <li>- influences <i>Key variable</i></li> <li>- receives input from <i>Sensor</i> (directly or indirectly)</li> </ul>	<p><i>Sensor</i></p> <ul style="list-style-type: none"> <li>-detects <i>Sensed Variable</i> and feeds back to <i>Key Element</i> (directly or indirectly)</li> </ul>	<p>Sensed Variable</p> <ul style="list-style-type: none"> <li>-measured by <i>Sensor</i></li> </ul>	<p><i>Control</i> activates <i>Key Variable</i> AND determines/initiates <u>target</u> value of <i>sensed variable</i></p> <p>This value is compared to <u>current</u> value of <i>sensed variable</i>, measured by the <i>sensor</i></p> <p>When target value is reached, the <i>Key element</i> <u>disables</u> the <i>Key Variable</i>.</p>	Generic Feedback – (Manual on / automatic off )
e.g. Thermostat knob	<p><i>Thermostat knob</i></p> <ul style="list-style-type: none"> <li>- activates <i>Boiler Operation</i></li> <li>- lets me set my desired <i>Time Period of Boiler Operation</i></li> <li>- automatically disables <i>Boiler Operation</i> when this time period is reached.</li> </ul>	Boiler Operation	Thermostat	Timer	Time Period of Boiler Operation	<p><i>Thermostat knob</i> activates <i>Boiler Operation</i> AND determines <u>target</u> value of <i>Time Period of Boiler Operation</i></p> <p>This value is compared to <u>current</u> value of <i>Time Period of Boiler Operation</i> measured by the <i>Timer</i></p>	Timer (Norman, XXX)

						When time period is reached, the <i>Thermostat</i> <u>disables</u> <i>Boiler Operation</i>	
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**Appendix 2 – Part 3: Walk-through questions to guide analysts when categorizing output 1 from QuACk**

<b>Q1) Control</b> What heating controls does the user adjust in a typical week?	<b>Q2) Agents</b> a) How many agents (human or digital) are responsible for creating the pattern depicted? b) Who are the agents? c) When do different agents come into play?	<b>Q3) Regularity</b> a) How regular is the pattern of adjustments? b) When do changes in regularity occur?	<b>Q4) Frequency</b> a) How frequent are the adjustments b) When do changes in frequency occur?	<b>Q5) Set points</b> a) How specific are the set points values? b) How do set point values vary?	<b>Q6) Synchronicity</b> What do the variations in the pattern co-occur with?	<b>Q7) Association</b> a) Can the intention of the user be identified in the behaviour pattern? b) Has the user represented this device in their mental model description?
e.g. -Thermostat -Programmer -TRV -Boiler override -Boiler water temp -Manual on/off switch Etc.	e.g. a) single duel multiple b) --user only -user and housemate -housemate only -user and automatic agent -housemate and automatic agent	e.g. a) --regular daily pattern of adjustment -irregular evening pattern of adjustment -regular daytime pattern of adjustment Etc. b)-Regular pattern	e.g. a) -frequent infrequent b) -frequent during the evening and infrequent otherwise -infrequent during the week and frequent during the weekend -always frequent	e.g. a)-specific values described -approximate values described -general increases/decreases shown b)-Large variations in set point values -static set point	e.g. -Routine events (school times, work times, bedtimes, waking up times) -non-routine events (home early, leaving late, day-trips, household party) Changes in other variables (comfort	e.g. a) -yes (single agent, multiple agents but intention of different agents is clear, multiple agents fulfilling joint intention) - No (multiple agents confusing intention of user)

	<p>c) -user adjusts set values, automatic agent makes adjustments according to set values</p> <p>-user makes adjustments during week, housemate at the weekend</p> <p>-user makes adjustments during day, housemate in the evening Etc.</p>	<p>during week, but irregular at weekend</p> <p>- regular pattern during the day, but irregular pattern in evening</p> <p>-Regular pattern all the time</p> <p>Irregular pattern of use, but regular intervals when adjusted Etc.</p>	<p>-always infrequent Etc.</p> <p>Note: <i>The analyst needs to infer what constitutes 'frequent' or 'infrequent', depending on the type of control</i></p>	<p>values</p> <p>-minor variations ins set point values point values</p> <p>-static set point values during the week, variations at the weekend</p> <p>-static set point values during the day, large variations in the evening Etc.</p>	<p>levels, external temperatures</p> <p>Changes in activity levels (inactive, active)</p> <p>Changes in activity types (cooking, exercising, sleeping, studying, watching TV)</p>	<p>b)-Yes</p> <p>-No – control device absent from output 2</p>
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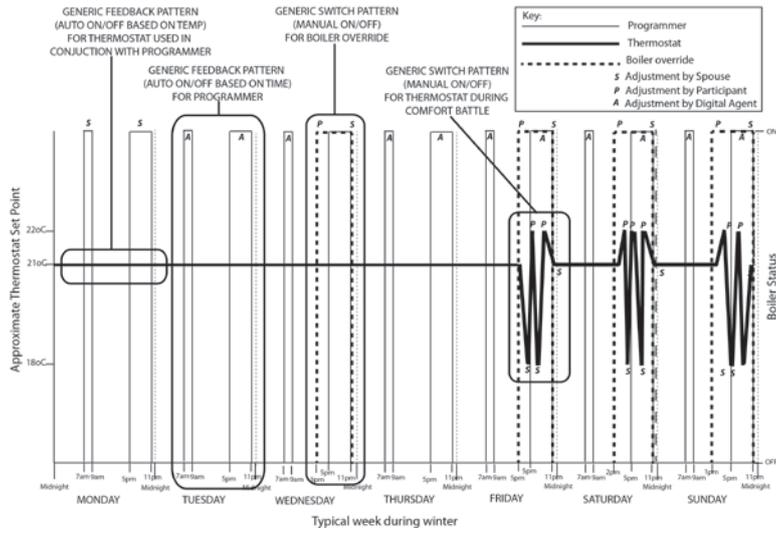
**Appendix 2 – Part 4: Walk-through questions to guide analysts when categorizing output 2 from QuACK**

<p><b>Q1) Control Device</b> What specific element does the user <u>directly</u> interact with?*</p>	<p><b>Q2) Input behaviour</b> a) What adjustment does this specific user do with the <i>control device</i>?* b) What does the user believe they are influencing? c) Does the user describe/imply the system making 'automatic'</p>	<p><b>Q3) Key variable</b> What energy consuming variable is the user trying to influence when they adjust the <i>control device</i>?</p>	<p><b>Q4) Key element</b> Which element does the user believe is responsible for controlling the key variable?</p>	<p><b>Q5) Sensor</b> Does the user describe/ imply a 'sensing' element that measures a variable to enable 'automatic' adjustments? If not, go to Q7</p>	<p><b>Q6) Sensed variable</b> What variable does the user describe /imply as being measured by the sensor?</p>	<p><b>Q7) Rule</b> What rule can be constructed from the users mental model to describe: how the <i>input behaviour</i> affects the <i>key variable</i>, including the role of a <i>sensor</i>, <i>sensed variable</i> and <i>key element</i> (where appropriate)?</p>
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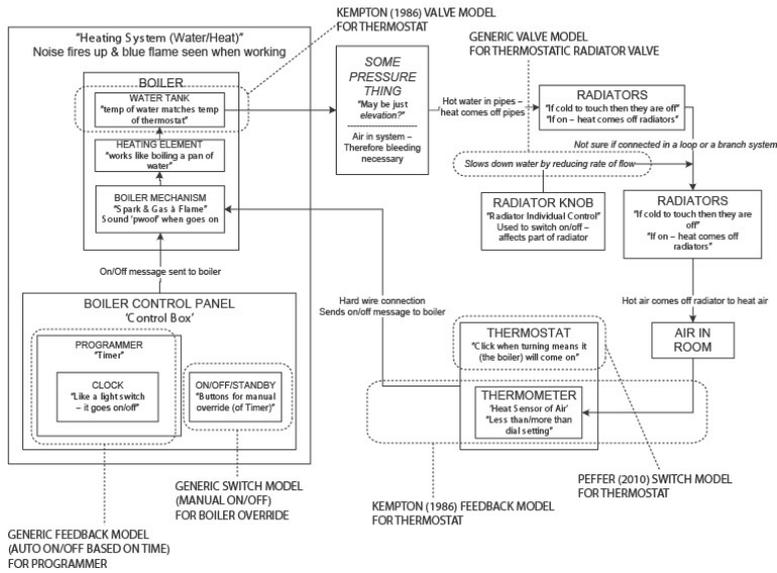
	adjustments?					
e.g. -Thermostat dial -Boiler on/off switch -Programmer schedule -Programmer override -TRV knob -Boiler temperature control Etc.	e.g. a) - setting target or specific value of variable -changing existing value of variable on a scale -selecting on/off etc. b) -temperature (house, room, water, body) -intensity (boiler, water/gas flow) - duration (boiler activation, time periods for activation) etc. c)-'it' turns on/off according to... -'it' turns itself off... -'it' maintains a target value of.. Etc.	e.g. -length of boiler activation periods - length of boiler activation - intensity of boiler - amount of heat transferred to radiators - amount of heat emitted from radiators - amount of water heated - radiator temp -temp of water - speed of water flow Etc.	e.g. -boiler - programmer - thermostat - TRV Etc.	e.g. -clock -thermometer -timer -heat sensor -flow sensor -body temperature sensor Etc.	e.g. -house temperature -room temperature -water/gas temperature -boiler intensity -water flow rate -body temperature -length of time boiler has been operating -length of time Etc.	Compare with examples of generic and shared theories of home heating.

## Appendix 3

### Appendix 3- Part 1: Example Categorization of Output 1 using Updated Analysis Reference Tables



### Appendix 3- Part 1: Example Categorization of Output 1 using Updated Analysis Reference Tables



## Appendix 4

Table to show how system image of the home heating system can effect user mental models that underpin Norman's (1986) 7 stages of Action

Level	Characteristics Of existing UI	Impact of existing UI on UMMs	Effect on Goal 1: Maintain Routine Comfort Needs (numbering relates to Norman's (86) stage of activity)	Effect on Goal 2: Ad-Hoc Heating (numbering relates to Norman's (86) stage of activity)	Effect on Goal 3: - Avoid Wasting Heat (numbering relates to Norman's (86) stage of activity)
				<i>Set long term controls:</i> a) Program schedule b) Thermostat set point c) TRV set point	<i>Override Heating system:</i> a) 1 – Press boost button
System level	Thermodynamics data missing	Thermodynamics missing from UMM	5 – cannot perceive how thermodynamics effect the speed and distribution of heat around the home 6-may interpret comfort levels or temp display before thermodynamic variable has had time to fulfil comfort goals 7-may evaluate that long-term settings do not meet comfort goals and conclude that target temp/ schedule durations need to increase	n/a	2 – cannot form intention to use residual heat 3 –will not specify early end times for schedule 4 – will not program early end times 5 – cannot perceive how residual heat is being used 6- cannot interpret how much residual heat provides benefit to occupants 7 – cannot evaluate if residual heat has been used
	Range of Controls	-Multiple control devices present in UMM -hierarchy of controls may not be evident	3 – may form less appropriate specification if importance of programmer and thermostat not understood 4 – May set up long-term controls with inappropriate set points 5 – May give inappropriate weighting to particular state indicators (e.g. programmer on indicator, rather than boiler on indicator) 6 – May misinterpret state of system (e.g. assume boiler should be active when any control indicator is showing). 7 – may evaluate that system is operating ineffectively when it is responding appropriately	3 – may select an alternate specification to override heating 4 – may override heating with less appropriate execution (e.g. thermostat increase/ boiler on-off button)	3 – may form less appropriate specification to avoid wasting heat (e.g. Adjusting TRVs in used rooms) 4 – may execute controls inappropriately (e.g. frequent adjustment of TRVs) 5 - May give inappropriate weighting to particular state indicators (e.g. TRV set points rather than Schedule end times) 6 – may inappropriately interpret a set point as an indicator of energy being saved (e.g. TRV just after turning down) 7 – May over-estimate the reduction in wasted energy due to less appropriate settings

Lack of visible connection between devices	-Some connections between components missing in UMMs -interdependency of devices not appreciated	3 – inappropriate specification may result if dependency between programmer & thermostat is not understood 4 – user may fail to make adjustments to both schedule and thermostat 5 - may perceive program schedule activation as independent of the thermostat set point for turning on boiler 6 – may interpret programmer as not functioning is thermostat has stopped boiler 7 – may evaluate long term settings have not been made	5 – may perceive boost status, as independent of the to thermostat set point for turning on boiler 6 – may interpret boost as not functioning if thermostat has stopped boiler 7 –may evaluate heating schedule override has not been achieved	3 -missing feedback loops from room temp to TRV may result in inappropriate specification 4 – user may execute TRV controls inappropriately (e.g. frequent adjustment to save energy) 5 – user may focus perception on TRV set point and overlook more important state indicators for saving energy 6 – user may interpret low TRV set points as indication that energy is not being emitted 7 – user may over-estimate energy saved by adjusting TRVs
Variable prominence of devices	Some control devices missing from UMMs	3 – cannot form recommended specification if programmer, thermostat or TRV missing from UMM 4 – cannot set up as recommended 5 – May not perceive state indicators on control displays absent from UMM (e.g. , thermostat calling for heat / programmer on times, set points of TRVs) 6 – May make interpretations from incomplete state indicators (e.g. assume boiler should be on due to schedule, when thermostat has turned off when set temp achieved) 7 – May evaluate incorrectly that heating system is not functioning as it should.	3 - cannot form recommended specification if boost control missing from UMM 4 – may override heating with less appropriate execution (e.g. thermostat increase/ boiler on-off button) 5 – May not perceive state indicators on control displays absent from UMM (e.g. , thermostat calling for heat ) 6 – May make interpretations from incomplete state indicators (e.g. assume boiler should be on due to boost, when thermostat has turned off when set temp achieved) 7 – May evaluate incorrectly that heating system is not functioning as it should.	3 - cannot form recommended specification if programmer, temp display or TRV missing from UMM 4 – cannot set up as recommended 5 – cannot compare comfort to room temp if temp display missing from UMM 6 – may misinterpret feeling cold to heating system rather than low activity 7 – may evaluate heating system should be overridden unnecessarily
Distributed control devices	Metadata associated with UMM components include effort for access/adjustment	3-TRV adjustments not specified as involve physical effort 4-TRVs not adjusted (though default setting may be appropriate)	n/a	3-TRV adjustments not specified as involve physical effort 4-TRVs not adjusted

Device Level - Programmer		Device Level - Thermostat		
Consideration of residual heat on schedule end times not	-thermodynamics variable missing from UMM	n/a	n/a	2 – cannot form intention to use residual heat 3 –will not specify early end times for schedule 4 – will not program early end times
Conditional link to Thermostat not communicated	-conditional rule for boiler operation missing	5 - schedule on indicators may be misperceived as 'boiler on' periods 6 – user may be confused if boiler is off during scheduled periods 7 – user may evaluate that long term settings are not effective		
Temp sample unclear	-UMM assume whole house/comfort sampled	3 – specify thermostat adjustment for outlying rooms/comfort 4 – inappropriate adjustments made to thermostat set point 5 – temp value perceived as whole house/comfort 6 – value that does not match users physical experience in outlying rooms / own comfort may result in confusion 7 – user may evaluate that display is faulty / system is not working properly	n/a	6 – value that does not match users physical experience in outlying rooms / own comfort may result in confusion 7 – user may evaluate that display is faulty / system is not working properly
Feedback function not communicated	-Feedback link missing -function of device considered 'valve'	3- Thermostat not specified as a long-term control 4- adjustments made to the set point to fit routine comfort needs (rather than single setting chosen)	n/a	3 thermostat may be included in energy saving specification inappropriately 4 – unnecessary adjustments made to thermostat

Device Level - TRV	Feedback function not communicated	-Feedback link missing -function of device considered 'valve'	3 -missing feedback loops may result in inappropriate specification 4 – user may execute TRV controls inappropriately (e.g. frequent adjustment to provide comfort) 5 – user may focus perception on TRV set point at expense of schedule times / thermostat set point. 6- user may interpret TRV high setting to indicate higher volume/temp heat is emitted from radiators saved energy 7 – user may over-estimate contribution to comfort levels	n/a	3 -missing feedback loops may result in inappropriate specification 4 – user may execute TRV controls inappropriately (e.g. frequent adjustment to save energy) 5 – user may focus perception on TRV set point at expense of schedule times 6- user may interpret TRV low setting to indicate no heat is emitted from radiators saved energy 7 – user may over-estimate energy saved
	Function of device not communicated	- function misunderstood	n/a	3 – User may specify alternate controls for override 4 – user may execute alternate controls for override	n/a
	Conditional link to Thermostat	-conditional rule for boiler operation not applied to boost	n/a	5 – boost activation perceived to indicate boiler activation 6 – if boiler not active when boost is on, use may be confused 7 – user may evaluate that override was unsuccessful	n/a
	Complicated set up procedure	Metadata associated with UMM components include	3 – programmer omitted from specification 4 – on/off times not scheduled	n/a	3 – programmer omitted from specification 4 – on/off times not scheduled
Device Level - Boost					

Slow response not communicated	-slow response missing from UMM	3 – user may specify frequent adjustments for TRV to fulfill comfort needs 4 – user may execute frequent adjustments of TRVs 5 – users may perceive TRV settings as indicators of volume of heat output 6- user may interpret TRV high setting to indicate heat is emitted at higher temp/rate from radiators	n/a	2 – user may form intention to avoid heating rooms temporarily unused 3 – user may specify frequent adjustments of TRVs to save energy 4 – user may execute frequent adjustments of TRVs 5 – users may perceive TRV settings as indicators of volume of heat output 6- user may interpret TRV low setting to indicate no heat is emitted from radiators saved energy 7 – user may over-estimate energy saved
Mapping between setting and room temperature values	-function of device considered 'valve'	5 – users may perceive TRV settings as indicators of volume of heat output 6- user may interpret TRV high setting to indicate heat is emitted at higher temp/rate from radiators	n/a	5 – users may perceive TRV settings as indicators of volume of heat output 6- user may interpret TRV low setting to indicate no heat is emitted from radiators saved energy
Distribution across house/low level access	Metadata associated with UMM components include effort for access/adjustment	3 – TRV omitted from specification 4 – TRV not adjusted	n/a	3 – TRV omitted from specification 4 – TRV not adjusted

## Appendix 5 – Instructions for Participant

### **18.16. Home heating Simulation - Instructions for Participant version 2.0**

#### **19.17. Background**

We are interested in how people think about home heating, and how they use home heating devices. We think that central heating devices can be difficult to understand, or that it can be difficult to heat your home in the way that you want. We think that these difficulties may result in energy being wasted.

#### **20.18. Home heating Experiment**

This experiment has 3 parts, a computer simulation exercise, a questionnaire and an interview.

##### 1) Computer simulation exercise (25 minutes)

We have created a simulation of a central heating system in a typical family home. You are responsible for operating the home heating controls in the simulation. Two days will be simulated over a period of 20 minutes. Every minute you will be presented with a goal, and it is your task to try to fulfil these goals\*. The goals will be typical of a family with school age children. Please imagine yourself in this scenario, even if it does not reflect your own circumstances. A paper user manual is also available for some of the controls, should you want to refer to them. You will be given 5 minutes to familiarise yourself with the simulation and manuals before starting the exercise. We are interested in understanding how you tackle each goal using the home heating controls available. All the controls function, and when you change a setting, the simulation will make the corresponding changes to how the house is heated.

**\*Please do not worry if you cannot fulfil all the goals. Just do what you think is appropriate.**

##### 2) Questionnaire (5 minutes)

Our study has two different versions of the home heating interface, and you will be presented with one version only. You will be asked to fill in a short 'usability' and 'workload' questionnaire. This will help us to compare the 2 versions of the interface to see how it affects the way people control home heating.

##### 3) Interview (15 minutes)

The final part of the experiment involves an interview with a paper-based activity. We will be asking you questions about how **you** think the heating system from the simulation works\*. Together we will create a diagram to represent this. We are interested to see if this helps explain the way you tackled the goals in the simulation. We will audio record the interview as an aid memoir.

**\*We are not interested in testing if you know how the system actually works – we only want to understand how you 'imagine' it works.**

**21-19. How this data will be used**

Home heating is a complicated subject. We do not expect anyone to know the best way to control heating in their home. Your answers will help the design of heating and energy monitoring devices to make it easier for people to be energy efficient in a way that fits in with their lifestyle.

All your answers will be kept confidential and stored securely.

**Please can you fill in the information on the next page and bring this sheet with you to the study (PTO)**

**22-20. Participant demographic information**

Please fill in the following information – all information will be treated confidentially.

- 13. Gender (please circle) Male/Female
- 14. Age Group (please circle) 20-30 31-40 41-50 51-60 61-70 Over 70
- 15. Occupation.....
- 16. Length of time using central heating with radiators (approx. years).....
- 17. Type of Accommodation (please circle) flat, terrace house, semi-detached house, detached house, other.....
- 18. Number of bedrooms.....
- 19. Do you own the accommodation? (please circle) Yes/No
- 20. Number of people in the house (please state) Adults (over 18)..... Children (under 18) .....
- 21. Do you know if your accommodation has insulation? (please circle) Yes/ No / Not Sure

## Appendix 6 - Example Script for instructions during 'Play' section of Experiment

### Realistic Condition

At the top of the screen you will be presented goals every 2 minutes (which is every 2 hours in the simulation). The goals are your tasks for the experiment and relate to rooms and times that you want to get to a comfortable temperature. The screen will flash yellow each time the goal changes.

Beneath this the day and time is shown. This is the 'simulation time', and is speeded up so that we can cover 2 days in 20 minutes. The digits counting up are 'minutes', not seconds, and you need to be aware of the time to tackle the goals.

These bars are showing you how far through each of the simulation days you are, so you can see how much longer you have to go.

This represents a house - just like in real life, you can only 'be' in one room at a time. There are working controls in each room. To operate them, you need to 'go' to the room and click on the control.

The control will appear to the right of the screen, and you can view the control or change settings in this area.

All the controls that appear here, operate like 'real' devices. When you make changes, this affects how the house is heated. As the rooms change temperature, they will show the level of comfort by changing colour and a description at the top. The goals will ask you to be 'comfortable', which is between 'too cool' and 'too warm'. If you cannot reach the goal, by doing what you think is appropriate, don't worry, just move on to tackling the next goal when it appears.

User manuals for 2 of the devices are provided in case you need them. You may look through this during your practice time if you want.

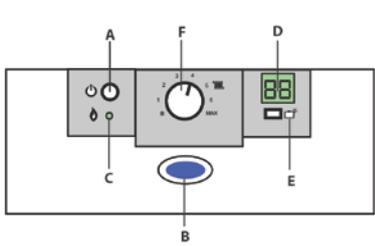


## Appendix 7 – User Guides for Home Heating Simulation

### 9.5.1 Realistic Condition - Boiler user guide

CONTROL APPLIANCE

CONTROLS



A - MASTER SWITCH FOR ON/OFF

B - MAINS ON/OFF INDICATOR

C - BURNER ON INDICATOR LIGHT (GREEN)

D - DISPLAY

E - HOLIDAY BUTTON

F - CENTRAL HEATING TEMPERATURE CONTROL

OPERATING APPLIANCE

**OPERATING THE APPLIANCE**

**SWITCHING THE APPLIANCE ON/OFF**

Switching on

B Switch on the appliance by pressing the master switch.  
The indicator light shows blue

**SETTING THE CENTRAL HEATING TEMPERATURE**

B Turn the central heating temperature control to the desired level, between 40 °C and 90 °C.

B When the burner is lit, the green indicator light underneath the on/off switch is illuminated.

**FROST PROTECTION**

B Leave master switch on.  
B Turn the central heating temperature control to .

If the temperature falls to 5 °C within the boiler it will fire to avoid the possibility of freezing.

**HOLIDAY SETTING**

Activating holiday mode:

B Press the holiday button until it lights up.  
Central heating is switched off; the frost protection remains active.

**CONTROLLING CENTRAL HEATING**

B Set the timer to the correct time.  
B Set room thermostat to the desired room temperature.  
B Set the thermostatic radiator valves to the desired settings.

1

CONTROLS

2

OPERATING

## 9.5.1 Realistic Condition - Programmer user guide

### THE PROGRAMMER

The simple instructions contained in this user guide are designed to help with the programming and operation of the unit.

- 1 SET indicator - RUN in the normal position
- 2 Time of day
- 3 Time period symbol
- 4 SET button
- 5 BOOST or adjust (-) button
- 6 ADVANCE or adjust (+) button
- 7 ENTER button
- 8 SELECT
- 9 System ON indicator
- 10 SET positions
- 11 PROGRAMME positions
- 12 BOOST symbol
- 13 ADVANCE symbol
- 14 AM/PM symbol
- 15 PROGRAMME Indicator

### Manual Overrides

**BOOST FUNCTION- 1 hour Temporary Override**  
 The boost facility will allow the user to boost the system which is currently 'OFF' for 1 hour. To indicate the boost being activated BOOST will be shown on the display for the duration of the boost period. The system ON indicator will also be illuminated.

**ADVANCE FUNCTION - Brings forward the next ON or OFF Operation**  
 The advance facility will allow the user to advance the system to 'ON' when currently 'OFF' or switch the system 'OFF' when currently 'ON'. To indicate the advance feature being activated ADVANCE will be shown on the display until the next programme switching time. The system ON indicator will also be illuminated.

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### Programme Override Facilities

With the Programmer operating in the normal running mode it is possible to alter the functionality of the programme by means of the SELECT button. The options include:

- AUTO- 24hrs - Timeswitch follows all programmed 'ON' and 'OFF' times.
- OFF - Timeswitch will be constantly 'ON'.
- OFF - Timeswitch will be constantly 'OFF'; there is the ability to turn off the heating during the summer without altering the programme times. Boost is still available.

All of the settings above will be permanent, i.e. unaffected by programme times, until alteration by the user.  
 The diagram below illustrates how to alter the setting. It assumes that the programme is in the AUTO mode to begin with.

Timeswitch will be continuously ON.  
 Timeswitch will be continuously OFF.  
 Programme will return to normal ON and OFF times.

### Setting the On and Off Times

To alter these settings please proceed as follows:-

**DEFAULT SETTINGS**

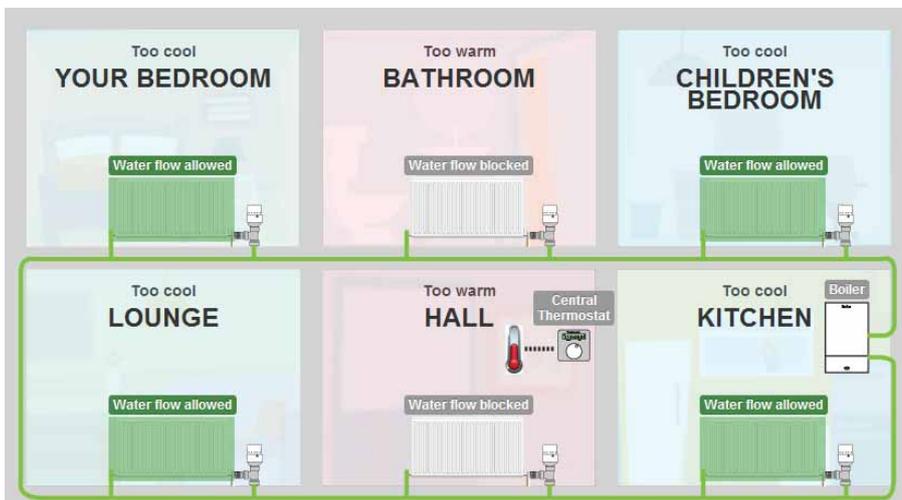
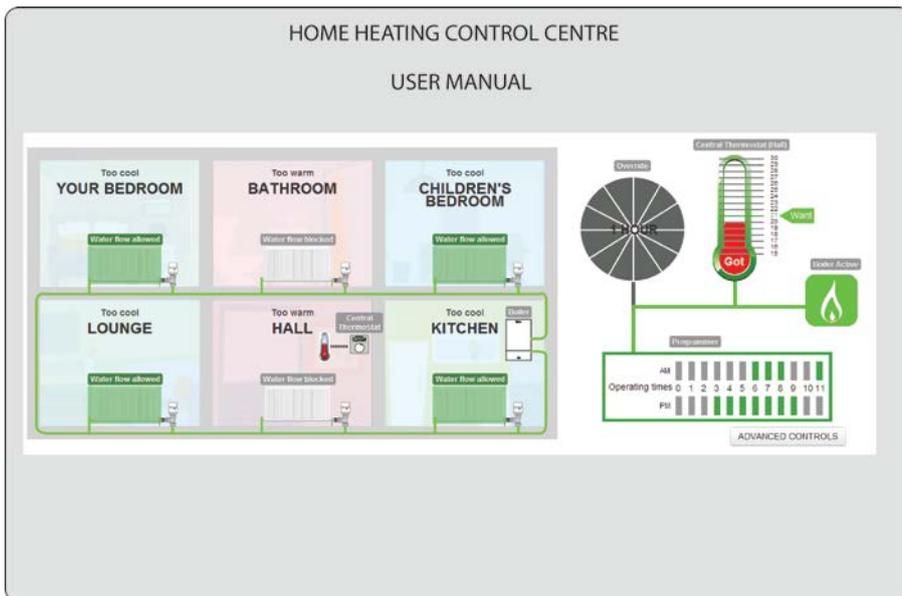
1st ON	1st OFF	2nd ON	2nd OFF	3rd ON	3rd OFF
6.30AM	8.30AM	12.00PM	12.00PM	4.30PM	10.30PM

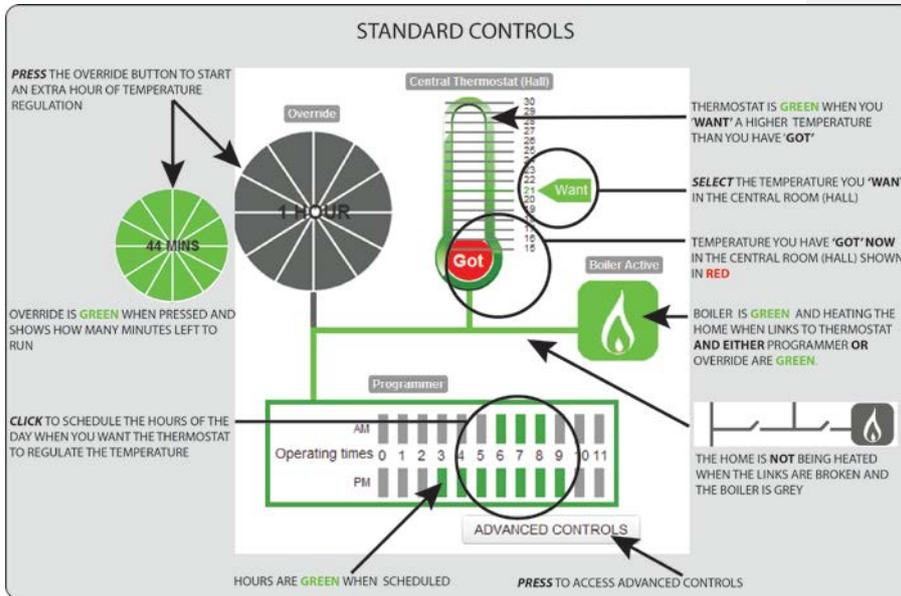
The default time settings shown above are preset at the factory  
 NB. The factory default settings for the 2nd ON/OFF times are both set at 12:00pm (midday) which cancels this 'ON' period giving 2 ON/OFF periods for the day. If a midday 'ON' period is required set the 2nd ON and OFF times accordingly. If not press ENTER twice.

**What is a programmer?**  
 ... an explanation for householders.

Programmers allow you to set 'On' and 'Off' time periods. Set the 'On' and 'Off' time periods to suit your own lifestyle. On some programmers you must also set whether you want the heating to run continuously, run under the chosen On and Off periods, or be permanently off. The heating will not work if the room thermostat has switched the heating off.

### 9.5.1 Design Condition - Control Panel user guide



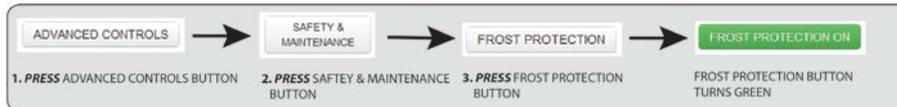


### COMMON REASONS TO USE ADVANCED CONTROLS

TO SAFELY MAINTAIN OR FIX BOILER



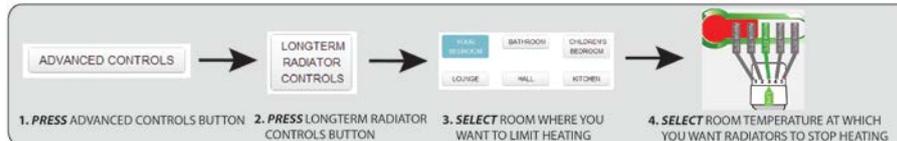
TO PROTECT YOUR BOILER FROM FREEZING IN COLD WEATHER



TO SAVE ENERGY WHEN GOING ON HOLIDAY



TO SAVE ENERGY IN UNUSED ROOM OR ROOMS THAT FREQUENTLY GET TOO WARM



## Appendix 8 - Home Heating Simulation: Goals presented to participants

The Simulation time covers 2 days and a night, ranging from 6am day 1, to 10pm day 2. A 'real time' minute equates to 2 hours simulation time. The participant is presented a goal at the start of the minute, and may use the remaining minute to adjust the settings to tackle their goal.

Real Time (minutes)	Simulation Time	Goal
1	Day 1: 6am	Your family are waking up. You are all in the upstairs bathrooms and bedrooms getting ready for the day. You want to be comfortable there between 6.30 and 7.30.
2	Day 1: 8am	At 8.30, everyone leaves the house for school or work. You plan to return home for lunch at 12.00 for a couple of hours. Before you leave, you want to minimise the amount of energy wasted whilst no-one is in the house.
3	Day 1: 10am	You come home earlier than expected. Feeling cold from being outside in winter, you want to warm up quickly in the living room. At 11am, you worry about wasting energy so you make sure you are not overheating the house.
4	Day 1: 12pm	You have a friend over for lunch in the kitchen. You want to feel comfortable eating there until 1.30pm
5	Day 1: 2pm	You decide to study/work from home in the living room. You want to be comfortable there until 4pm
6	Day 1: 4pm	The children come back home from school and complain of being cold. They are in the kitchen and you want to help them warm up as quickly as possible. They have a snack and start doing their homework in the kitchen. You want them to be comfortable there until 5pm.
7	Day 1: 6pm	You are cooking dinner in the kitchen. Your partner has come home and is running around playing with the children/doing exercise. Everyone is in the kitchen or living room and feeling uncomfortably hot. You want to be comfortable there, until 7.30.
8	Day 1: 8pm	Your children will soon be getting ready for bed, you want them to be comfortable in their bedroom between 8.30 and 9.30
9	Day 1: 10pm	After a long day - you want to be comfortable in the living room between 10 and 11.30 whilst you sit and watch TV with your partner.
10	Day 2: 12am	You are going to your bedroom for the night and plan to get up at 6.30. You want to be comfortable there, but avoid wasting energy.

<b>11</b>	Day 4: 2am	You are all asleep in bed- For the purposes of this study, you can make adjustments to prepare for tomorrow if you wish. Your regular routine is to get up at 6.30am, leaving the house at 8.30. You will return for 2 hours at 12.30 for your lunch then go out, leaving the house unoccupied until 4.00. The children go to bed at 8.30, and you and your partner go to bed at 12
<b>12</b>	Day 2: 4am	You are all asleep in bed- For the purposes of this study, you can make adjustments to prepare for tomorrow if you wish. Your regular routine is to get up at 6am, leaving the house at 8.30. You will return for 2 hours at 12.30 for your lunch then go out, leaving the house unoccupied until 4.00. The children go to bed at 8.30, and you and your partner go to bed at 12
<b>13</b>	Day 2: 6am	Your family are waking up. You are all in the upstairs bathrooms and bedrooms getting ready for the day. You want to be comfortable there between 6.30 and 7.30.
<b>14</b>	Day 2: 8am	At 8.30, everyone leaves the house for school or work. You are returning home for lunch at 12.30. You want to minimise the amount of energy wasted whilst you are out.
<b>15</b>	Day 2: 10am	It is getting very cold outside - the temperature begins to drop below freezing (Although you are not at home - For the purposes of this study, you can make adjustments if you wish).
<b>16</b>	Day 2: 12pm	At 12.30 you get back home for lunch in the kitchen. You want to feel comfortable there until 1.30
<b>17</b>	Day 2: 2pm	You plan to be out between 2.30 and 4pm. You don't want to waste energy whilst the house is empty
<b>18</b>	Day 2: 4pm	You come home with your children feeling very cold as it is starting to snow. You all go to the living room. You want to warm up quickly there and stay comfortable until 5.30
<b>19</b>	Day 2: 6pm	Your partner comes home with a surprise - you are going away for the weekend, leaving at 8pm this evening and returning in two days at 6pm. You want to make sure you don't waste energy/money whilst you are away.
<b>20</b>	Day 2: 8pm	You are worried that the pipes might freeze and burst with the cold weather, when you are away - make any adjustments you think are necessary.

## Appendix 9 – Amended QuACk Interview Script for Simulation

### 23-21. Interview Template for home heating simulation.

#### 24-22. 1.0 Notes for Interviewer

- The interview questions are separated into 3 sections
  1. Background experience in Home heating & discussion of terminology
  2. Device Function – identification of components, their function and relationships between these to produce a schematic of the participants mental model
  3. Verification of content
- Answers from any question may inform different sections and the investigator should follow a participants train of thought even if it is referring to another section.
- Participant answers may contradict models of different sections,. This is expected, and the participant should not be challenged on their inconsistencies as peoples models may not be compatible with each other, and may vary in different contexts.
- Equipment needed:
  1. Template of house and radiators
  2. A3 paper
  3. post it notes
  4. Marker pens (conduits, smileys, question marks, instructions)
- The output of the interview includes:
  - 25-23. a diagram of the participants mental model of home heating function, created with and validated by the participant, showing the components and the relationship between components.
  - 26-24. Answers to questions on background experience and attitudes

#### 27-25. 2.0 Background Experience in Home Heating

Introduction to participant

*“For this first section, I will be asking about your past experience with home heating systems so that I get an idea of what may have influenced your ideas about how heating systems work.”*

22. Do you have any specialist knowledge about heating, energy use or thermodynamics of buildings?
23. What is your previous experience of home heating devices?
  - a. What sort of devices were they - can you describe them, or do you know the make?
  - b. What type of device you are most familiar with? ***If they struggle – suggest a couple to get them going*** (e.g. central heating with radiators, electric fires)
24. Which of the following statements best reflects you attitude to heat energy (you can select more than one).
  - a. I want to save money
  - b. I want to protect the environment
  - c. I want to keep warm

- d. other.....
25. What home heating devices did you recognize from the simulation? We will use these to create the diagram (**ask them to describe what they look like and what they refer to them as. Write names on post-it notes, agree a terminology – thermostat, programmer, timer, switch, receiver, boiler**)
- a. What devices did you use in the simulation? ( go through devices present
    - i. Do you ever use the thermostat control?
    - ii. Did you use the programmer? If so which buttons (boost/advance/24hr/set)?
    - iii. Do you use the controls attached to the radiators?
    - iv. Did you use the boiler control panel buttons? If so, which buttons (holiday, power, temp knob, frost setting) ([Naturalistic](#)[Realistic](#) version only)
    - v. Did you use the main power button?
    - vi. Did you use the boost button? (Design version only)
    - vii. Did you use the advanced options (Design version on) If so, which buttons (TRV's, power, frost, holiday)

### 28.26. 3.0 Mental model of Device Function

Introduction to participant

*“In this section, I will be asking you how you think the home heating system for the simulation works. We are not interested in knowing the ‘correct’ answer. We are looking to understand what you imagine happens, as this is more likely to explain your approach to tackling the goals. Please say what you think, or have a ‘guess’. Afterwards you will be asked how sure you are. Don’t worry if things you say do not match things you have said before, it is normal for people to think differently about how things work, when presented with different questions. As you answer the questions, we will use the stickers/post-it notes, to help build up a picture on this template of the interface.”*

6. How can you tell when the heating is on/off? (what do you see, hear?)
7. What do you think EACH DEVICE is connected to? (**use the following prompts to draw out the different elements of the system and the different conduits and dependencies. Arrange components mentioned and conduits / relationships in a picture paper. Go through each component and conduit and work out dependencies using relevant prompts.**)
  - a. What do you think EACH DEVICE does?
  - b. What do you think happens when you turn up/down/on/off EACH DEVICE?
  - c. Depending on their answers, ask relevant follow-on questions, e.g.
    - i. How does the boiler know when to come on/off?
    - ii. What happens when you override the programmed times?
8. If you turned the VARIABLE DEVICE (e.g. thermostat/BOILER CONTROL/TRV) to its maximum setting – what would happen? Can you explain it using the diagram so far?**(Use the diagram and paraphrase what they are saying, to give them an opportunity to confirm/amend)**
9. If you turned the VARIABLE DEVICE (e.g. thermostat/BOILER CONTROL/TRV) to its minimum setting – what would happen? (Can you explain it using the diagram so

far?*(Use the diagram and paraphrase what they are saying, to give them an opportunity to confirm/amend)*

10. If you turned THE ON/OFF DEVICE (mains power, holiday, boiler control power, boost, advance etc. depending on what is on the diagram), ON– what would happen?
11. If you turned THE ON/OFF DEVICE (mains power, holiday, boiler control power, boost, advance etc. depending on what is on the diagram), OFF– what would happen? (Can you explain it using the diagram so far? (Can you explain it using the diagram so far?*(Use the diagram and paraphrase what they are saying, to give them an opportunity to confirm/amend)*

#### 29-27. 4.0 Verification

I'm now going to go through and check how happy you are that the diagram we have constructed, represents how you imagine the home heating system in the simulation works. I'm going to go through each element, and the links between them and ask you how sure you feel about this. If you feel sure, I will add a 'smiley'. If you are uncertain, I will put a questionmark.

1. Components. Do you feel sure about COMPONENT. *(Go through each component and check notes about the way it functions. Read this back to the participant and say 'how sure are you that the DEVICE functions by \_\_\_\_\_? If they are sure, mark with a 'smiley', if they are uncertain, with a '?'*
2. Links. Do you feel sure about CONDUIT?. *(Go through each conduit and check notes about what this links to and its functions. Read this back to the participant and say 'how sure are you that the THIS DEVICE connects to THAT DEVICE functions? If they are sure, mark with a 'smiley', if they are uncertain, with a '?'*
3. CONDUIT PURPOSE. Do you feel sure about CONDUIT PURPOSE?. *(Go through each conduit and check its purpose. Read this back to the participant and say 'how sure are you that the THIS CONDUIT has THIS PURPOSE? If they are sure, mark with a 'smiley', if they are uncertain, with a '?'*

Thank you for taking part in this experiment. Please sign this form to collect your £10 reimbursement for your time.



## Appendix 10 – Chi-Square Test Results

### 9.5.2 Chi-Square test results comparing appropriate and inappropriate functional models for key controls by condition

Appropriate Model \* Experimental Condition Cross tabulation

		Experimental Condition		Total	
		Design	Realistic		
Appropriate Model	No	Count	14	29	43
		Expected Count	21.5	21.5	43.0
		% within Appropriate Model	32.6%	67.4%	100.0%
		% within Experimental Condition	18.7%	38.7%	28.7%
		% of Total	9.3%	19.3%	28.7%
	Yes	Count	61	46	107
		Expected Count	53.5	53.5	107.0
		% within Appropriate Model	57.0%	43.0%	100.0%
		% within Experimental Condition	81.3%	61.3%	71.3%
		% of Total	40.7%	30.7%	71.3%
Total	Count	75	75	150	
	Expected Count	75.0	75.0	150.0	
	% within Appropriate Model	50.0%	50.0%	100.0%	
	% within Experimental Condition	100.0%	100.0%	100.0%	
	% of Total	50.0%	50.0%	100.0%	

### 9.5.3 Chi-Square cross tabulation comparing presence of Controls in UMMs and Behaviour Strategies

Was CTL present in UMM? * Was CTL used in Sim? * Experimental Condition Crosstabulation					
Experimental Condition			Was CTL used in Sim?		Total
			No	Yes	
Design	Was CTL present in UMM?	Count	36	11	47
		Expected Count	12.8	34.2	47.0
		No % within Was CTL present in UMM?	76.6%	23.4%	100.0%
	Was CTL present in UMM?	% within Was CTL used in Sim?	73.5%	8.4%	26.1%
		% of Total	20.0%	6.1%	26.1%
		Count	13	120	133
	Yes	Expected Count	36.2	96.8	133.0
		% within Was CTL present in UMM?	9.8%	90.2%	100.0%
		% within Was CTL used in Sim?	26.5%	91.6%	73.9%
	Total	% of Total	7.2%	66.7%	73.9%
		Count	49	131	180
		Expected Count	49.0	131.0	180.0
	Total	% within Was CTL present in UMM?	27.2%	72.8%	100.0%
		% within Was CTL used in Sim?	100.0%	100.0%	100.0%
		% of Total	27.2%	72.8%	100.0%
Realistic	Was CTL present in UMM?	Count	52	12	64
		Expected Count	22.8	41.2	64.0
		No % within Was CTL present in UMM?	81.3%	18.8%	100.0%
	Was CTL present in UMM?	% within Was CTL used in Sim?	81.3%	10.3%	35.6%
		% of Total	28.9%	6.7%	35.6%
		Count	12	104	116
	Yes	Expected Count	41.2	74.8	116.0
		% within Was CTL present in UMM?	10.3%	89.7%	100.0%
		% within Was CTL used in Sim?	18.8%	89.7%	64.4%
	Total	% of Total	6.7%	57.8%	64.4%
		Count	64	116	180
		Expected Count	64.0	116.0	180.0
	Total	% within Was CTL present in UMM?	35.6%	64.4%	100.0%
		% within Was CTL used in Sim?	100.0%	100.0%	100.0%
		% of Total	35.6%	64.4%	100.0%
Total	Was CTL present in UMM?	Count	88	23	111
		Expected Count	34.8	76.2	111.0
		No % within Was CTL present in UMM?	79.3%	20.7%	100.0%
	Was CTL present in UMM?	% within Was CTL used in Sim?	77.9%	9.3%	30.8%
		% of Total	24.4%	6.4%	30.8%
		Count	25	224	249
	Yes	Expected Count	78.2	170.8	249.0
		% within Was CTL present in UMM?	10.0%	90.0%	100.0%
		% within Was CTL used in Sim?	22.1%	90.7%	69.2%
	Total	% of Total	6.9%	62.2%	69.2%
		Count	113	247	360
		Expected Count	113.0	247.0	360.0
	Total	% within Was CTL present in UMM?	31.4%	68.6%	100.0%
		% within Was CTL used in Sim?	100.0%	100.0%	100.0%
		% of Total	31.4%	68.6%	100.0%

## Appendix 11 – Goal Achievement Criteria

Goal ID	Sim Day	Presentation Time	Start Time	End Time	Children's Bedroom	Master Bedroom	Bathroom	LivingRoom	Kitchen	Hall	Temperature target	Goal Type	Notice
1	1	06:00	06:30	07:30	yes	yes	yes	no	no	no	19.5-20.5	Comfortable	Plan
2	1	08:00	08:30	09:59	yes	yes	yes	yes	yes	yes	<i>Less than 15.0</i>	save energy	Plan
3	1	10:00	10:00	10:59	no	no	no	yes	no	no	19.5-20.5	comfortable	Adhoc
4	1	10:00	11:00	11:59	yes	yes	yes	yes	yes	yes	18 - 20.6	Avoid overheating	Plan
5	1	12:00	12:00	13:30	no	no	no	no	yes	no	19.5-20.5	comfortable	Adhoc
6	1	14:00	14:00	15:39	no	no	no	yes	no	no	19.5-20.5	comfortable	Adhoc
7	1	16:00	16:00	17:00	no	no	no	no	yes	no	19.5-20.5	comfortable	Adhoc
8	1	18:00	18:00	19:30	no	no	no	no	yes	no	19.5-20.5	comfortable	Adhoc
9	1	20:00	20:30	21:30	yes	no	no	no	no	no	19.5-20.5	comfortable	Plan
10	1	22:00	22:00	23:30	no	no	no	yes	no	no	19.5-20.5	comfortable	Adhoc
11	2	00:00	00:00	06:29	no	yes	no	no	no	no	18 - 20.6	Avoid overheating	Adhoc
13	2	06:00	06:30	07:30	yes	yes	yes	no	no	no	19.5-20.5	Comfortable	Plan
14	2	08:00	08:30	12:29	yes	yes	yes	yes	yes	yes	<i>Less than 15.0</i>	save energy	Plan
16	2	12:00	12:30	13:30	no	no	no	no	yes	no	19.5-20.5	Comfortable	Plan
17	2	14:00	14:30	15:59	yes	yes	yes	yes	yes	yes	<i>Less than 15.0</i>	save energy	Plan
18	2	16:00	16:00	17:30	no	no	no	yes	no	no	19.5-20.5	Comfortable	Adhoc
19	2	18:00	20:00	11:59	yes	yes	yes	yes	yes	yes	<i>Less than 15.0</i>	save energy	Plan
20	2	20:00	20:00	11:59	yes	yes	yes	yes	yes	yes	More than 13	Safety	Adhoc

Nb; Goals 12 and 15 are not represented here as they delivered 'realistic' information during the simulation that may influence actions (e.g. changes in external climate, or expected activities the following day), rather than demand a specific, measurable state of affairs to be achieved.

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## Appendix 12 – Participant Breakdown

Table 20 – Representation of participants in different studies/chapters

Participant	Label given in studies	Chapter(s)
Participant 1	Participant C	Case study of Home heating (Chapter 3)
	Participant 1	Analysis of Gulf of Execution & Evaluation (Chapter 6)
Participant 2	Participant X	Case study of Energy use (Chapter 5)
	Participant 2	Case study of Home heating (Chapter 3)
Participant 3	Participant A	Case study of Home heating (Chapter 3)
	Participant 3	Analysis of Gulf of Execution & Evaluation (6)
Participant 4	Participant Y	Case study of Energy use (Chapter 5)
	Participant 4	Analysis of Gulf of Execution & Evaluation (6)
Participant 5	Participant Z	Case study of Energy use (Chapter 5)
	Participant 5	Analysis of Gulf of Execution & Evaluation (6)
Participant 6	Participant B	Case study of Home heating (Chapter 3)
	Participant 6	Analysis of Gulf of Execution & Evaluation (6)
Expert	Expert	Analysis of Gulf of Execution & Evaluation (6)

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