Mental Model Interface Design – Putting Users in Control of Home Heating

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# Abstract

Occupant behaviour is a key variable affecting the amount of energy used in homes. The understanding, interface and interaction with heating controls holds the potential to influence how heating is operated and, in turn, how much energy is consumed.  A study was undertaken to test a series of hypotheses that the design of the home heating interface can positively influence the achievement of home heating goals, if it is specifically designed to communicate a user mental model (UMM) of how the system functions. This would encourage appropriate inhabitant behaviour. The experiment involved 20 pairs of participants matched by age, gender and home heating experience. The participants were asked to attain a series of home heating goals using an accelerated home heating simulator. The impact of specific design features of a novel interface design was compared to an interface offering a traditional home heating system experience. The evidence confirms that design features contributed to differences in UMMs, intentional behaviour, and goal achievement. A mental model approach to design can be used as a means of putting users ‘in control’ of their heating system to enable them to better fulfil their home heating goals.

# Keywords:

behavioural change; design; energy conservation; heating / space heating; mental models

# Introduction

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 to meet realistic heating goals (Revell & Stanton, 2014). Placing the responsibility on householders to optimally use energy and minimise waste could be considered unfair, when the devices they are expected to operate were not designed to this specification (Sauer, 2009; Revell & Stanton, 2016). Nevertheless, literature on sustainable research in the domestic domain is frequently focused on the user, with occupant behaviour identified as a key variable affecting the amount of energy used in homes (Dalla Rosa & Christensen, 2011; Emery & Kippenham, 2006; Guerra -Santin & Itard, 2010; Lutzenhiser & Bender, 2008; Raaij & Verhallen, 1983). One perspective for explaining householders’ behaviour that has recently received a resurgence in interest, is the work of Kempton (1986). He discovered that variations in the way occupants behaved with their home heating thermostat could be explained by differences in their ‘mental model’ of its function.

Mental models can be thought to be representations of the physical world (Johnson-Laird 1983, Rasmussen 1983, Veldhuyzen and Stassen 1976), constructs that can explain human behaviour (Kempton 1986, Wickens 1984) and internal mechanisms allowing users to understand, explain, operate and predict the states of systems (Craik 1943, Gentner and Stevens 1983, Hanisch et al. 1991 Kieras and Bovair 1984, and Rouse and Morris 1986). There are many definitions of mental models and different perspectives from which to consider them (Revell & Stanton, 2012, Richardson & Ball 2009, Wilson & Rutherford 1989). This paper adopts a combination of the definitions by Norman (1983) and Keiras & Bovair (1984) and refers to a mental model held by a user of a specific device that contains information about the operation and function of that device, and has been accessed and described by an analyst.

Kempton (1986) found that different types of UMMs held by occupants, encouraged different behaviour strategies for saving energy overnight. He estimated that considerable energy savings could result if specific UMMs of thermostat function were promoted to domestic users. Kempton categorized UMMs into what he described as valve and feedback commonly held theories of the home heating thermostat. Users with a valve UMM 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 UMM 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 referred to this latter UMM as an amateur theory of home heating as it reflected a simplistic version of the way the heating system works.

Kempton described how different UMMs might predict different behaviour patterns of thermostat set point adjustment. He discovered that holders of a valve UMM had a unique behaviour characteristic absent in those holding feedback UMM. At night, valve theorists regularly set the thermostat back to below normal comfort levels, which Kempton described as ‘night set back’. Kempton (1986) proposed that despite the valve UMM being less accurate than the feedback UMM, this behaviour characteristic was likely to result in greater energy savings overall.

Since Kempton (1986), additional UMM types of thermostat function have been proposed in the literature such as Timer (Norman, 2002) and Switch (Peffer et al., 2011). Users holding the timer UMM use the thermostat analogous to a kitchen timer. When they want the boiler to operate for an extended continuous period, they select a set point much higher than the current room temperature value. When they want a short period of boiler operation, they select a set point only a little higher than the current room temperature. Those holding the switch UMM are thought to operate the thermostat in the same way as an on/off switch, where a set point above or below the current room temperature is chosen to ensure boiler activation and deactivation, respectively. Like the valve UMM, these additional UMM types assume it is the user that must regulate the boiler to maintain a comfortable house temperature, rather than rely on automated boiler regulation by the programmer and/or thermostat.

Misunderstandings about how to operate home heating controls remains a present day problem (Brown & Cole, 2009; Revell & Stanton, 2014; 2015; 2016, Shipworth et al., 2009). Kempton’s findings were expanded by Revell & Stanton (2014; 2015) to consider functional UMMs of all home heating controls present in the home, as well as their interactions at a system level. They found that incomplete or inappropriate UMMs at a device and system level explained differences in behaviour strategies that either wasted energy or jeopardised comfort goals. This means many users are not, ultimately, in control of their home heating system.

This paper sets out to explore if changes in the design of heating controls can influence the mental model elicited in users, directing their behaviour to influence the achievement of home heating goals. An extended introduction is presented positioning home heating in terms of control theory and complex systems, before describing current design and technology approaches to home heating control. The methodology adopted, including a description of the development of a home heating simulator, is then provided. The initial results of an empirical study investigating the links between interface design, mental models, control strategies and goal achievement follow. Finally, the implications of the results in terms of mental model theory and the relevance and implications to industry and practitioners, are discussed.

## Heating systems from the perspective of control theory

The term ‘control’ is subject to a variety of interpretations. The Oxford English Dictionary provides three definitions that reflect the different senses in which the term is used in this paper: 1) The capacity to control the behaviour of people, machines or events (e.g. “their heating goals were fully within their control”); 2) Control as a form of regulation (e.g. at a high level, “they controlled their energy consumption levels”, or more granular level, “boiler activation was controlled by a thermostat”) and; 3) Controls as objects that can influence devices (e.g. “they used all the key heating controls on the interface”). Control is often considered from an information processing perspective with a large part of human factors literature historically focused on control room operation (e.g. Edwards and Lees, 1974; Kragt, 1994; Stammers & Hallam, 1985). For the domestic domain, however, a functional approach, such as Hollnagel’s (1993) Contextual Control Model (COCOM) is more fitting. Hollnagel emphasises that human performance is determined by situation, with a range of strategies being adopted. Selection among possible actions is driven by the demand characteristics of the situation. Hollnagel (1993) highlights three main concepts in his model of contextual control: 1) Competence (the possible actions a system can apply to a situation according to needs/demands); 2) Control (performance and manifestation of competence, based on 4 control modes), and; 3) Constructs (what is known or assumed about the situation where action takes place). Competence aligns with the the view of control as the capability to direct a cause of events, with the added requirement to link control to needs and wants. Increased regulatory control, such as the adjustment of boiler activation, has little benefit without reference to a higher level capability goal, such as keeping warm, or optimising consumption. Hollnagel’s concept of control relates to regulatory behaviour. He describes four different control modes, each of which correspond differently to performance, presented in order of least efficient to most efficient:

1. ‘Scrambled’ control mode (irrational or random action with minimal reflection, such as ‘trial and error’ or panic strategies).
2. ‘Opportunistic’ control mode (user takes the salient features of the current context to determine the next action and employs heuristics rather than plans due to inadequate constructs resulting in inefficient actions with many useless attempts undertaken).
3. ‘Tactical’ control mode (in situations that allow sufficient time for a limited planning beyond immediate need).
4. ‘Strategic’ control (best performance for achieving higher level goals, requiring sufficient time for both planning and action. Dominant features of the interface are less significant for performance).

This breakdown of the ‘regulatory’ sense of the term control and the clear relationship between time available and the control mode possible, helps frame how the reader can consider increased or decreased control in home heating systems. The first two modes emphasise a poor return on outcomes for actions taken, depicting lower levels of control. The implication is that for modes 3 and 4 there is a better return on outcomes for action, and that the user is in a better position to tackle long term goals (e.g. energy conservation), but only when sufficient time is available for action.

Hollnagel proposes a cyclical model of human action whereby actions depend on the users’ construct (akin to a UMM), which is influenced by the system information and feedback, which themselves are influenced by the actions undertaken. Actions with home heating controls are clearly more involved than simply choosing a set point. The next section emphasises the inherent complexity of the home heating system and offers a simplified model that builds on Hollnagel’s model of human action in the home heating context.

## Home Heating as a Complex System

Sauer (2009) considers the central heating system to be the most complex system in the domestic domain with good cause. Inherent in slow responding systems, cause and effect when interacting with the central heating system is difficult to gauge by observation alone (Crossman & Cook 1974). The user is also faced with multiple distributed controls that vary between households in their location, interface and functionality. Optimal comfort and consumption levels are dependent not only on the compatible adjustment of integrated controls, but also 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). Simplistic strategies to reduce consumption through means such as government recommendations (e.g. turn the thermostat down 1 degree) or smartmeters showing aggregated energy consumption, may not be fit for purpose (Revell & Stanton, 2015). Recognizing the complexity of the domestic domain is important. In complex systems, when operators control processes, they do so whilst accessing their UMMs (Moray, 1990). Strategies to influence or mitigate for human behaviour in complex systems would therefore benefit from an approach that actively considers the role UMMs play.

Figure 1 - Different variables that affect home heating behaviour and their consequences

Figure 1 depicts a simplified relationship between the variables described that have a combined influence on observable user behaviour with home heating systems. It highlights how the consequence of user behaviour (e.g. regulatory control of the heating system) in terms of goal achievement is also subject to variables acting in the broader system (e.g. building structure, infiltration, insulation, external temperature and system dynamics such as the thermodynamics of the house). At the base of the diagram, it hypothesises how device design directly influences user behaviour (e.g. by the actions that are supported), and indirectly influences user behaviour (via the filter of UMMs, by representing feedback from actions and system dynamics).

## Home Heating Interface Design & Technology

Norman (1986) proposes that designers could help users to operate technological systems more appropriately by designing interfaces that encourage a ‘compatible’ UMM of the way the system functions. He proposed that a compatible UMM was necessary to enable users to develop appropriate strategies to successfully interact with a system and emphasises the role played by individual goals in observable user behaviour. Appropriate in this paper is considered applicable to the genuine functioning of a system, but does not take into account that systems may be ‘inappropriately’ designed to sustainably meet an intended goal. Literature investigating domestic energy consuming behaviour lends support to the need to adopt a mental models approach to the design of technology in the home. Sauer et al. (2009) emphasised how a poor mental model of home heating system functioning would prevent an operator from knowing how to interpret the information available on instructional displays. Shipworth et al (2010) echoes this position by stating that using energy consuming 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 (allowing regulatory control) and make it easy to reduce consumption (i.e. are ‘competent’ according to Hollnagel, 1993). Peffer et al. (2011) proposes that user misconceptions that encourage incorrect usage cannot be easily overcome by better interfaces, as usability is essential, but insufficient for correct use. Whilst Lutzenhiser (1993) argues that human behaviour limits the efficiency of technology introduced to reduce consumption, Glad (2012) found that it is often the choice and positioning of technology, as well as usability issues, that impedes discovery and use by householders (Glad, 2012). These same issues were found to contribute to incomplete or incompatible UMMs (Revell & Stanton, 2014; 2015; 2016), further compounding the problem. Revell & Stanton (2016a; 2016b; 2016c) make a strong case that a mental models approach to interface design both at the system and device level could foster the appropriate conceptions necessary for improved performance.

The authors recognize that the face of heating control is changing with the introduction of smart and intelligent heating systems (e.g. Hive, Nest, Netamo, Honeywell Evohome, Tado). These systems vary in their features and capability, beyond the typical heating system setup, but many include suggestions by Hollnagel (1993) who advocated that the design of control surfaces and panels, decision support systems and intelligent predictive systems modelling action outcomes could be adopted to benefit action selection.

Almost all of these intelligent heating systems offer remote heating control via an app or website. Others allow zoning via smart Thermostatic Radiator Valves (TRVs) (e.g. Honeywell Evohome, Heat Genius). Proximity detection is also offered by some, via motion sensors (e.g. Nest) or GPS tracking (e.g. Tado) to intelligently control boiler activation without conscious input by the user. Systems such as Nest also learn user schedules based on adjustment behaviour (as opposed to intentional set up) to determine boiler activation time periods taking into consideration the thermodynamic properties of the house. However, none focus on ‘how’ the heating system works in a way that allows a UMM to be constructed that aids regulatory control.

In the future, if systems get ‘smart enough’, it may not be necessary for users to be actively involved in heating control. However, the complexity of the domestic setting, with varying heating goals by multiple occupants, non-routine schedules, unique thermodynamic considerations and dynamically changing external variables all impacting comfort and energy consumption, it may be some time before the user can be ‘out of the loop’. Until then, a mental model approach to heating system control is recommended.

## The present research

 This paper describes the results of a study investigating if the promotion of a compatible UMM through interface design alone, allows householders to be more ‘in control’ of a heating system, by enabling boiler activation regulation strategies that influence the overall duration of goal achievement. Adopting theoretical and case study approaches, the authors have already extended the work of Kempton to test its present day relevance (Revell & Stanton 2014; 2015; 2016a; 2016b; 2016c). However, the body of literature does not show evidence of empirical testing of association between design, mental models, behaviour and goal achievement.

Studies associating mental models and behaviour often train the users on the intended model and assume a model is held if expected behaviour is observed but do not capture the UMM itself (e.g. Gentner & Stevens, 1983). Work by Sauer et al. (2007, 2009) examining how providing support aids on a home heating interface could help users better plan heating schedules has also shown benefits in goal achievement, but did not explore the link between the design and UMMs. This work also favoured Hollnagels’ (1993) strategic control modes (which relies less on visual prompts) as there was no time limit for planning and action.

The study presented in this paper differs from previous work by being more realistic in the types of goals presented and the time available to interact with the heating system. Training on the intended UMM is not provided nor is the task novel, so the interface design is required not only to impart the intended UMM, but to amend or change existing UMMs of home heating function held by participants. The UMMs held are accessed, described and categorized, rather than assumed based on observed behaviour, to be clear on the mechanism for the behaviour change. This paper will now progress to describe the method and report the results on an experiment designed to improve the users’ construct (their UMM) directly through novel interface design, in order to enhance regulatory control so householders are more ‘in control’ of their heating goals.

# Method

This section covers the experimental design of the empirical study, the development of a home heating simulation, the participants and study procedure as well as the method for analysis of results.

## Experimental Design

A matched-pair, between-subjects design was adopted to test 3 hypotheses:

* Hypothesis 1 states ‘The design of heating devices influences the inclusion and functional appropriateness of UMM descriptions of those devices’.
* Hypothesis 2 states that ‘UMM descriptions of devices influence the pattern of device use for boiler activation’.
* Hypothesis 3 states that ‘Strategies of device use for boiler activation influence the overall duration of goal achievement’.

### Independent Variable

The version of the interface presented to participants (either ‘Realistic’ or ‘Design’) represented the independent variable. The ‘Realistic’ interface was based on the type, presentation and layout of devices typically found in UK homes. The term ‘Realistic’ refers to the interface only, rather than ‘naturalistic’ or ‘actual’ behaviour. Participants presented with the ‘Realistic’ condition made up the control group. The experimental group were those exposed to the ‘Design’ interface. This was designed to promote more appropriate mental models at a device and system level.

The dependent variables to test hypothesis 1 were:

a) Number of appropriate functional UMMs identified of key controls (comprising the Programmer, Boost, Thermostat and TRV);

b) Number of key UMM system elements mentioned.

The dependent variable to test hypothesis 2 was the number of set point adjustments that resulted in a change of state of boiler activation. For hypothesis 3 the dependent variable was specified as the total proportion of time the target rooms were within goal temperature range.

The authors adopted a ‘cascading approach’ to analysis of data. The significant results from hypothesis 1 were used to inform the focus of exploration for hypothesis 2, which in turn defined the relevant focus of hypothesis 3. This was adopted to ensure that data to test all three hypotheses could be collected from each participant in a single sitting, rather than 3 separate studies. Figure 2 shows the link between hypotheses and the focus of exploration.

Figure 2 Diagram to show relationship between the independent variable (IV) and dependent variables (DV) for the 3 hypotheses reported in this paper. A ‘cascading’ experimental design was undertaken with the significant results from hypothesis 1 driving the focus on analysis for hypothesis 2, and the significant results from hypothesis 2 driving the focus of analysis for hypothesis 3.

Whilst a number of different hypotheses were examined during the full study (that will form the content of future papers), this paper focuses on boiler activation as the dependent variable to illustrate the relationship between design, UMMs, behaviour strategies and goal achievement. Boiler activation behaviour has a clear link to both energy consumption and user comfort and, as such, understanding how changes to interface design can promote aspects of UMMs, to influence this behaviour, demands investigation.

## 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 (Mean=38). Pairs in each condition were matched by gender, age category, and the number of years’ experience with central heating (+/-2 years), which was established through a demographics questionnaire prior to the study. Experience was defined as living in an abode with gas central heating (with radiators and thermostat control) and being responsible as a sole user, or one of multiple users, for adjusting controls. Experience ranged from 5 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 websites.

## Designing a home heating interface to promote compatible UMMs

A home heating simulator was developed to allow manipulation of the home heating interface presented, whilst controlling the broader system variables and user goals.

The simulator was based on the prevalent heating system setup found in the UK, with key controls comprising a central thermostat, programmer, boost (or over-ride) button, and Thermostatic Radiator Valves (TRVs). Figure 3 shows a typical design and distribution of visible controls in a UK home. This can be thought of as the ‘interface’ householders have with their heating devices in their home. The simulator followed directly from previous work by the authors, investigating the barriers to the development of compatible UMMs (Revell & Stanton 2014; 2015), the requirements in the form of design specifications for a compatible UMM (Revell & Stanton 2016a), and design solutions based on these specifications (Revell & Stanton, 2016b). Revell & Stanton (2016a) undertook analysis of this traditional interface at both the ‘system’ and ‘device’ level. At the system level, the controls are distributed across the home at different levels of prominence. TRVs are ankle height adjoining radiators in each room. The central thermostat is positioned at eye level in the hall with high levels of exposure to occupants. The programmer and master switch are often below eye level and positioned away from the thermostat, (e.g. in the kitchen). Connections and interdependencies between devices are not explicitly communicated, so lack of awareness of a device, or ambiguous device design can lead to misunderstandings. Evaluation at the ‘device’ level considered the design of the key heating controls (e.g. Thermostat, Programmer, Boost, TRV), as defined by a home heating expert.

Figure 3 – The ‘interface’ (design of components, layout and distribution of devices) that a householder is confronted with within a traditional home heating system comprising gas combi-boiler, central hall thermostat, programmer and TRVs. A boost button is a feature on the programmer device.

The design specification, based on expert recommendations, to promote an appropriate UMM to encourage optimal interaction (Revell & Stanton 2016; 2017) included features relating to:

* Control devices (e.g. their function, responsiveness and integration with other devices)
* Overall system (e.g. comfort being linked to other broader system variables, the hierarchy of controls, room temperature as a slow responding variable linked to the thermodynamics of the house, and the interdependency of devices).

Revell & Stanton (2016b) propose a design solution in response to this design specification to meet key issues identified as hindering the development of a compatible UMM. These are summerised in table 1.

Table 1 - Key home heating elements poorly communicated in a traditional home interface and corresponding design intervention found on novel interface design.

To reflect the experience of a traditional interaction with home heating controls, the interface in figures 3 and 4 was developed. The ‘tunnel vision’ experience was emphasised where users can typically only view and access a heating control when in the same room. Similarly, feedback at a system level of comfort across the house is not supported, so the ability of users to gain an understanding of thermodynamics relating to their house structure, and the resulting differing response times for changing temperature levels in different rooms and at different times of day is hindered. Links between controls and a means of communicating how they work together are absent from the interface.

Figure 4- Example of Realistic home heating interface for simulator – only one room can be accessed at a time to enable awareness and access of heating controls

Figure 5 – Example of Realistic home heating interface for simulator. Feedback relating to comfort levels are shown for each room through changing coloured backgrounds and labelling, mapped to a pre-set temperature range.

The novel interface created to promote a compatible UMM can be seen below in figures 5 and 6. A systems view is supported by providing dynamic feedback on the comfort levels in all rooms to the householder at the same time. Links between key devices are also emphasized in the feedback panel (left) as well as the main control panel (right). A key design feature of the novel interface design was emphasis of the conditional rule, a concept that is poorly supported in traditional heating systems, despite being a key concept relating to boiler activation. The conditional rule refers to the interdependent nature of programmer, thermostat and boost button for boiler interaction, when all three controls are present in a home heating system configuration. The conditional rule requires synchronicity between the thermostat signalling to the boiler that heat is required (i.e. because the thermostat ‘set point’ is above the current room temperature), and the scheduled ‘on’ period from a programmer, (or present activation of the boost button). If the thermostat ‘calls for heat’ during a programmed ‘off’ time and the boost button is not selected, the boiler will not activate. If the programmed ‘on’ time, or the boost button is selected when the thermostat is *not* calling for heat (i.e. because the thermostat ‘set point’ is equal to, or below the sampled room temperature), then the boiler will not activate. The boiler will only activate when both thermostat and timer conditions are met. Figures 6 and 7 show how the conditional rule is emphasised in the control panel of the novel ‘Design’ interface. The flame icon illuminates during boiler activation. Analogous to a circuit diagram, this is only possible when the thermostat control and either the programmer or boost control are also ‘active’. If these conditions are not met, there is a ‘break’ in the circuit and the flame icon remains un-illuminated.

Figure 6 - Novel interface designed to promote a compatible UMM for home heating at both a system and device level

Figure 7 - The main control panel emphasises key inter-connected controls for boiler activation and through a switch analogy communicates the conditional rule.

## Apparatus and Procedure

Individual participants were presented with a version of the home heating simulation, matched to their experimental condition. The simulation was displayed on a Samsung LE40M67BD 40” TV monitor attached to a DELL Latitude E6400 laptop. This was connected to the internet webpage hosting the simulation and controlled with a mouse. The ‘Realistic’ version reflected the design of a typical gas central heating system and the ‘design’ interface was constructed to promote a compatible mental model of the home heating system following recommendations from Revell & Stanton (2016) (see figures 4,5,6 and 7). Both versions of the interface shared the same simplified underlying thermodynamic model to allow dynamic feedback resulting from changes in control set points and external temperatures. A set insulation level limiting heat flow was provided for the outer walls and roof represented in the simulation. Variations in heat flow were modelled such that rooms adjacent to outside walls *and* roof (bedrooms) lost heat at the highest rate, followed by the kitchen, lounge and bathroom, which were adjacent to either an outside wall *or* roof. The hall lost heat at the lowest rate as it was adjacent to other rooms. The upper rooms (bedrooms and bathroom) gained heat from the lower rooms (lounge, kitchen and hall).

Prior to data collection, a consent form, participant information sheet, and participant instructions were provided to each participant. Participants in the ‘Realistic’ condition were asked to imagine they were operating the home heating controls as if they were in their own home. Participants assigned to the ‘Design’ condition were asked to imagine they had been provided with a digital interface to control the existing heating system in their home setting. Participants were then provided with the user manuals for their experimental condition and exposed to a 5 minute practice session with the key elements of the interface indicated by the analyst. The simulation ran for 22 minutes with a home heating goal presented textually at the top of the screen, every minute. The goals represented typical home heating goals as defined by the home heating expert used in Revell & Stanton (2016) for a family with young children and were matched in sequence for each condition. The goals focused on 1) enabling 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 and 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). Example goals are shown in table 2 below:

Table 2 – Sample of ‘naturalistic’ goals presented during the simulation.

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 the new goal. At the end of the experiment, participants were interviewed to access their UMM description. Bias is a key issue when conducting research into UMMs, as internal knowledge constructs cannot be accessed directly (Revell & Stanton, Wilson & Rutherford (1989). A systematic method of access, description and interpretation was adopted to mitigate this risk through the use of the Quick Association Check (QuACk) by Revell & Stanton, 2016c. This was developed using qualitative approaches and is grounded in theory (Kempton, 1986, Payne, 1991) to improve construct validity. It is a structured interview method that includes activities and templates to produce user-verified outputs, ready for analysis without further interpretation by the analyst. The UMM description is created in conjunction with the participant and then systematically categorized using the analysis reference table (see table 4) which includes walk through questions for consistent application. High agreement of categorization (92%) of UMM features using the analysis reference table has been shown in Revell & Stanton (2016a). This method seeks to access ‘device model’ UMM content as this is thought to have a higher association with user behaviour. The output included participant initiated system components (described on post it notes), with links drawn between components. Probes are used to gain insights into cause and effect and rules of operation (e.g. “How does the boiler know when to come on/off?”, “What would happen if you turned the thermostat to its maximum setting?”). QuACk was applied to capture descriptions of UMMs in play during interaction with the simulator. The outputs are likely to be a composite of both existing knowledge triggered by the interface and new knowledge elements amending the interface, in line with the iterative process of mental model formation described by Johnson-Laird (1983). Following the QuACk interview, participants were debriefed and paid £10 for their participation.

## Analysis of UMM Interview Output

To enable statistical analysis, the paper-based diagram outputs from the semi-structured interviews relating to UMM descriptions needed categorisation and quantification. The first dependent variable relating to Hypothesis 1 was the ‘Number of appropriate functional UMMs identified of key controls (comprising the Programmer, Boost, Thermostat and TRV)’;

These key home heating devices and their corresponding appropriate mental model categorisation are shown in Table 3.

Table 3 - Criteria for categorisation as an ‘Appropriate UMM’ for key heating controls, by applying the analysis table (table 4) to UMM descriptions from semi-structured interview output.

The categorisation process used the paper based UMM description diagrams and applied the analysis table (Table 4) derived from Revell & Stanton (2016a). In Table 4 the analyst is prompted to identify key elements of UMMs relating to controls, controlled variables, sensors, sensed variables and rules of operation. Rather than seek out confirming data, the analyst must check the combination of criteria to appropriately categorise the model held. Using the thermostat control as an example, Table 4 demonstrates how each generic model identified, represents different ways that heating devices may be thought to function by a user (only one being functionally appropriate for that device).

Table 4 - Analysis Table for categorizing mental model descriptions of home heating (from Revell & Stanton, 2016)

The second dependent variable relating to hypothesis 1 to be measured was the ‘Number of key UMM system elements mentioned’. For each UMM description, a count of key UMM elements from table 5 was undertaken. This list was derived in conjunction with a home heating expert when creating a compatible UMM in Revell & Stanton (2016a) and considers elements at both a device level (e.g. the inclusion of key controls, features and functions) and a system level (e.g. the integration between controls with the conditional rule, the impact of thermodynamics on comfort, and the link between boiler activation and energy consumption). Data collected for hypothesis 1 was based on an included/excluded criteria, so evidence of the same element multiple times in a single UMM description would not increase the count.

Table 5 - Key components of UMMs of Home Heating (derived from Revell & Stanton, 2016)

## Analysis of Simulation Data

The ‘cascading’ experimental design (see figure 2) used the findings from hypothesis 1b, that occurrence of the conditional rule was significantly higher in the ‘Design’ condition than the ‘Realistic’ condition to further specify the dependent variable measured for Hypothesis 2 (UMMs of devices influence the pattern of device use for boiler activation). That an understanding of the conditional rule has been used to intentionally regulate the boiler can be observed if thermostat set point choices consistently result in a boiler change of state. This can only result when the chosen set point crosses the current (hall) room temperature. To test the statistical significance of this Hypothesis 2, 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, so regulating boiler activation.

Hypothesis 3 stated that ‘strategies of device use for boiler activation influence the overall duration of goal achievement’. In line with the ‘cascading experimental design’ (figure 2), the approach to goal analysis was driven by the focus and significant results from hypothesis 2. This focus on boiler activation drove an analysis based on either comfort or energy consumption. However, the naturalistic goals, which were presented to the participants, related primarily to comfort, with only 4 out of 20 goals focused purely on energy saving. As such, achievement of target temperature values, rather than energy consumption related boiler operation was used in the analysis of ‘duration of goal achievement’. The dependent variable for hypothesis 3 was further specified as “the total proportion of time target rooms were within the goal temperature range”. Table 6 shows the criteria used for goal achievement for each set goal.

Table 6 – Criteria for goal achievement following ‘cascading’ experimental design.

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 and converted into a percentage of overall goal achievement.

# Findings

This section describes data gathered from users’ mental model description, variables relating to their behaviour with heating controls in the simulation, and goal attainment based on room temperatures. The Mann-Whitney U test for non-parametric data was used to determine the significance of differences in the Realistic and Design group for hypotheses 1 and 3, and an independent t-test was used for hypothesis 2. Descriptive charts were used to examine the data further, followed by appropriate tests for statistical significance (e.g. Pearson’s Chi-Square, Fisher’s Exact test).

## Hypothesis 1 –The design of heating devices influences the inclusion and functional appropriateness of UMMs of those devices

#### An increased number of appropriate functional models of key devices will be identified by participants in the Design condition.

Hypothesis 1a) predicted that participants in the Design condition would identify a greater number of appropriate functional models of key devices, than those in the Realistic condition. Figure 8 shows a boxplot illustrating the median, interquartile range and minimum and maximum of appropriate functions described by participants to key controls in their UMM diagrams. The total number of appropriate functional models mentioned in participants’ UMMs in the Design condition was 61, compared to 46 mentioned in the Realistic condition. Results of the Mann Whitney U test found this difference to be statistically significant (U=108.00, Z= -2.617, p < 0.01) supporting hypothesis 2.

Figure 8 - Frequency of appropriate functional models for key controls

Examining these data in more detail in a bar chart, it was found that, regardless of the experimental condition, most participants held an appropriate functional model of key devices linked to boiler activation when considered as separate devices (e.g. the programmer schedule, the boost button and central thermostat control). The differences in functional models at the device (rather than system) level could therefore not be attributed to differences in the design of these devices (see figure 9). It was instead found to be attributable to UMMs of TRV control function, with a statistically significant improvement found in the Design condition (=9.60, d.f.=1, p < 0.01).

Figure 9 – Graph to compare the frequency of appropriate and inappropriate functions assigned to key controls.

####  Improved number of key UMM system elements will be mentioned in UMMs of participants in the Design condition

Hypothesis 1b predicted that participants from the Design condition would describe a greater number of key home heating system elements. Figure 10 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 U 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 1b.

Figure 10 - Number of key system elements present in UMM descriptions.

Exploring the data further in a bar chart (figure 11), the presence of the conditional rule was found to represent a significant difference between conditions (=5.226667, d.f =1, p < 0.05) (along with TRV attributes). This indicates the Design condition was effective at increasing the presence of these elements.

Figure 11 – Frequency of key system element present UMM descriptions.

## Hypothesis 2 – User mental models of devices influence the pattern of device use for boiler activation.

Following the results of hypothesis 1 in this cascading experimental design (see figure 3) , hypothesis 2 predicted that effective boiler control (defined as the proportion of set points adjustments that changed boiler state by crossing the hall temperature value) would occur more often in the Design condition. The graph in figure 12 shows how mean changes in thermostat set point differ considerably between condition. In the ‘Realistic’ condition, mean adjustments in thermostat set point occur below the mean hall temperature. In contrast, the Design condition results show mean adjustments in thermostat set points crossing the mean hall temperature value.

Figure 12 - Graph to demonstrate the interaction between thermostat set point, mean hall temperature and boiler change of state, by experimental condition.

The results of 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, lending support to Hypothesis 2 (see figure 13)

Figure 13 - Percentage of thermostat set point choices leading to boiler state change

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## Hypothesis 3 – Strategies of device use for boiler activation influence overall goal achievement

Following the results of hypothesis 2 in this cascading experimental design (see figure 3), hypothesis 3 predicted that overall goal achievement (defined as the total proportion of time the target rooms were within goal temperature range) would be greater in the Design condition. Figure 14 shows boxplots illustrating the median, interquartile range and minimum and maximum for duration of goal achievement. A Mann Whitney test was undertaken, showing a statistically significant difference in overall goal achievement between conditions (U=125.500, Z=-2.015, p < 0.05). In the Design condition, where significantly more participants used strategies of boiler control where the thermostat set point crossed the hall temperature value (following the results of hypothesis 2), the mean proportion of time the target rooms were within goal temperature range was 27.90% (n=20, SD 30.12). For the Realistic condition (where there was a higher incidence of set-point adjustments that did not result in a change of state of boiler operation) this reduced to a mean of 17.63% (n=20, SD 32.22). This lends support to hypothesis 3 that strategies of device use for boiler activation influence overall goal achievement.

Figure 14 – Total proportion of time within goal temperature range

# Discussion

This paper set out to demonstrate an association between device design, the development of appropriate home heating mental models, resulting behaviour patterns relating to boiler activation, and the overall duration of home heating goal achievement. Figure 15 summarises the link between hypotheses and the statistically significant findings relating to boiler activation, demonstrating evidence for this association. This result is significant as it demonstrates not only that design changes can influence higher level goals, but also provides evidence for both the cognitive and behavioural mechanisms that led to this change.

Figure 15 – Link between Hypotheses and summary of statistically significant findings relating to boiler activation

## More appropriate mental models

That participants from the Design condition were found to have more appropriate functional models of key heating controls, and key system elements (in support of Hypothesis 1) is particularly encouraging, given the lack of formal training provided to promote specific model types. Traditionally studies attempting to manipulate mental models provide extensive training, followed by comprehension and retention tests (e.g. ; Hanish & Moran 1983, Kieras and Bovair 1984). Improvements in the presence of the conditional rule following the associated design feature reflects advice from Keiras and Bovair (1984:p.271) that the most useful information to provide users is “specific items of system topology that relate the controls to the components and possible paths of power flow”. This was realised in the control panel interface with key controls linking both to each other, as well as boiler activation.

Studies linking mental models and behaviour often use novice participants who are not required to overcome an established mental model of the device in question (Gentner and Stevens, 1983). This study, in comparison, comprised of participants with between five and forty years’ experience of home heating controls. This user group will already have existing mental models built up through experience with heating systems. Where inaccuracies, additions or omissions exist, amendment of these mental models will therefore be necessary (Johnson-Laird, 1983). The cognitive processes involved in overriding variations in well established mental models puts a greater onus on the novel interface to disambiguate the system and device functions. An ambiguous design compatible with existing, but inaccurate constructs will fail to amend the UMMs.

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 highlights the success of the interface design in the ‘Design condition’ at disambiguating the inter-connected function of key devices. This has favourable implications for using UMM based design for home heating systems, or any system where inappropriate UMMs have been shown to result in undesirable behaviour and the opportunities for training are limited.

## Greater control of boiler activation

Hypothesis 2 examined differences in boiler activation predicted from significant differences in the presence of the conditional rule 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, the comparison made with sensed temperature to initiate a signal to the boiler to ‘call for heat’, and their dependency on the setting of the programmer and boost for boiler activation. Whilst a static thermostat set point is encouraged in manuals and by expert advice (Revell and Stanton, 2016a), this was not observed in either condition in this study, as all participants made adjustments to the thermostat set point throughout the simulation. However, the appropriate set point choice for a household 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 overly simplistic 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. In addition, the ease of adjustment due to a simulator study may have encouraged more adjustments than in a home setting. The analysts’ expectations for a static thermostat pattern was unreasonable in these circumstances. Results from a t-test supported Hypothesis 2 that participants in the Design condition operated a greater level of intentional control over the boiler. This result supports the findings of Keiras and 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. The results also lend support to Hollnagel’s (1993) modes of control. Participants in the Realistic condition showed evidence of operating under ‘opportunistic’ control. By employing heuristics relating to set point choice through experience with their own home heating system, rather than the system presented in the simulation, they undertook set point choices that could be considered ‘useless actions’. Participants in the Design condition were able to adapt their set point choice to those used in their home setting, to undertake actions that successfully regulated boiler activation, suggesting they were operating in the higher mode of ‘tactical’ control. Hollnagel (1993) believes that humans operate mainly in opportunist and tactical control modes where both feedback and feed forward conditions are present. The authors attribute the move from opportunistic to tactical control to be due primarily to the control panel representation of the conditional rule, which demonstrates an explicit link between set point selection and boiler regulation, as well as the feedback panel that provide a whole house overview of the impact of set point changes on comfort levels. As the majority of participants in the Realistic condition had an appropriate functional UMM for the thermostat device in isolation, their observed behaviour lends additional support to Revell and Stanton (2014)’s position that UMMs of home heating must be considered at the system level if effective behaviour is sought.

## Increased goal achievement

Participants in the Design condition were also significantly more successful at achieving the goals provided, supporting Hypothesis 3. 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 (with a mean of 27.90% in the ‘Design’ condition and 17.63% the ‘Realistic condition) compared to the results of Sauer et al. (2009), who found a range of between 73% and 94% in his participant pool. By distinction, this study limits time to a more realistic amount of engagement (1 minute per ad-hoc goal) with periods for planning for long term goals. Different modes of behaviour are therefore likely to be elicited in this study.

Sauer et al. (2009) tasked participants with choosing set points 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 under time pressure. Hollnagel (1993) emphasizes how time is inextricably entwined with the concept of control. Time is needed to evaluate events, to select action alternatives and to perform the selected action. The time available evidently constrains the duration of these tasks. In the domestic domain, unlike the industrial domain, tasks are more likely to be self-paced than process paced. However, lifestyles and competing goals will nevertheless limit the time available to focus on home heating control. Depending on the goal in operation, the time period for results are likely to vary considerably. Warming up on a cold day will elicit a very short time period for results, compared to energy saving over time, which forms a longer term goal. Greater generalisability of the results to everyday behaviour is therefore possible from the study described in this paper, given the greater realism of the goals set.

The title of this paper describes putting users ‘in control’ of their home heating. The argument is made in this paper that householders often do not have the capability to influence the course of events within their home to genuinely be ‘in control’ of their home heating goals (which may relate to comfort, energy conservation, health, preservation of building structure etc.). The case is also made that the design and layout of the ‘controls’ (e.g. thermostat, programmer, boost button) users interact with when operating the heating system to influence their home heating goals affects the level of ‘effective regulation’ of the system variables (such as boiler activation). The act of operation does not necessarily equate to a genuine act of control. Only with reference to the intended home heating goals can the success of system regulation be meaningfully assessed. It is concluded that the novel interface design enabled a higher incidence of deliberate control (regulation) of boiler activation, as set point changes more often resulted in a ‘change of state’ (e.g. the boiler being turned on or off). A link between this greater level of regulatory control in the Design condition, to the higher incidence of the conditional rule found in participants’ mental model descriptions seems evident. Since the design of the novel interface in the experimental group was intentionally constructed to promote the conditional rule, this higher incidence in the mental model descriptions of the experimental group is attributed to the design decisions made. As the experimental group also demonstrated a longer period of goal achievement (in terms of comfort achieved) it is proposed that manipulation of the design of heating controls can put the user more ‘in control’ of home heating controls.

## Implications for industry and practitioners

The authors hope that through the literature review and considerations in the design of the simulator, that industry and practitioners recognize the complexity of the task for householders, when embarking on strategies to reduce consumption or ensure their comfort goals are achieved. Is is clear from the many variables that affect the achievement of home heating goals, that simplistic, generic advice to householders is limited in its impact and tailored guidance taking into account householders’ lifestyles and the influence of broader values is necessary. Communicating the impact of broader system variables on optimal consumption would also help enhance and amend householders’ UMMs to improve their behaviour strategies when interacting with heating controls. This ‘communication’ may be through interface design feedback and direction, government campaigns or where applicable, user guides and training.

The authors implore industry and practitioners to adopt ‘system level’ strategies for encouraging appropriate home heating consumption. Traditional home heating controls are designed to be modular, to be compatible with a range of control devices from different manufacturers, and to function in a range of different combinations of devices (for example, programmers and thermostats can be the sole control for the boiler, or operate in combination). Whilst this does provide challenges in the ability of manufacturers to use design as a tool to communicate a clear hierarchy of controls or integrated function in a single device, an approach whereby this is communicated by a single interface is wholly possible. Where there are frequently occurring heating device combinations from key manufacturers, partnerships to aid understanding of how these devices interact would be welcomed by householders.

## Limitations of present research

The measure for goal achievement was based on temperature values for rooms rather than energy consumption or deployment of appropriate action sequences with controls. This meant that appropriate choices in behaviour (e.g. programmer settings) were not taken into consideration 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. To test generalizability to energy saving goals, a different focus of set goals, a more sophisticated thermodynamic model for the home heating simulation and a greater ability to reflect typical behaviour strategies (e.g. opening doors to distribute heat) is recommended.

The cascading experimental design was adopted for pragmatism but prevented hypothesis 2 from being tested with an experimental group who all shared the specific mental model of feature of interest (though the majority did). Future studies of this design would benefit form a larger sample to ensure sufficient numbers of participants with specific UMM features throughout the cascading analysis.

# Conclusions

Differences in the design of an interface have been shown to change the content of mental model descriptions. In this simulation, design features from a novel interface improved the number of key system elements, and the appropriateness of the function of key heating controls, present in UMM descriptions. The increased presence of key system elements, such as the conditional rule in participants’ described UMMs exposed to the Design condition, could explain their more effective ‘control’ of boiler activation, which contributed to their greater goal achievement. From this, it is concluded that a mental models approach to design can give householders greater control of their heating system to deliberately, rather than incidentally, realise their home heating goals.

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