PHD

Investigating the influence of in-home display design on energy-consumption behaviour

Chiang, Teresa

Award date:
2015

Awarding institution:
University of Bath

Investigating the influence of in-home display design on energy-consumption behaviour

Teresa S. Chiang

A thesis submitted for the degree of Doctor of Philosophy

University of Bath, UK
Department of Architecture and Civil Engineering

February 2015

Acknowledgements

The research presented in this thesis was funded by the University of Bath under the University Research Scholarships scheme. I am greatly indebted to my research advisers Dr Sukumar Natarajan (primary) of the Department of Architecture and Civil Engineering and Dr Ian Walker (secondary) of the Department of Psychology for their guidance and support. I am most appreciative of Dr Natarajan and a professional programme developer, who wishes to remain anonymous, for the development of the programmes used in the computer-simulated experiments, and Gokhan Mevlevioglu of the Department of Architecture and Civil Engineering (2011-2012) for building the software architecture and sensing framework used in the energy monitoring experiments. This project would not have been possible without the support from the Departments of Estates and Student Accommodation Services and the help from those who participated in the experiments.

I would like to dedicate this work to my family.

Abstract

Research on interventions aimed to promote energy savings has shown support for direct feedback using in-home displays (IHDs) to reduce energy consumption. These displays are electronic devices that provide real-time energy information and are emerging as an effective tool to communicate with people about their energy consumption. How feedback is presented to people and how they understand the meaning of such feedback largely depends on the design of the display, yet there are relatively few studies that investigate the way in which the display can best be designed to present energy information and motivate energy-saving behaviour. Further, even though there is a wide range of variations in the visual presentation of feedback, there is a lack of focus on the process of optimising the IHD design.

This thesis aims to address the need for designing IHDs at the display component level, by examining three types of display design (numerical displays, analogue displays using speedometer dials, and ambient displays using emotional faces) in both laboratory-based computer-simulated experiments and field-based experiments: participants' abilities to detect changes in energy information shown on the computer-simulated displays were measured by means of accuracy rate and response time, and their subjective preferences for display types were assessed against experimental data; live energy data were displayed using the three design types in a student residence at the University of Bath to see how they would influence energy-use behaviour.

Results from the laboratory experiments demonstrated that both accuracy rate and response time for seeing changes in the information displayed were strongly associated with the type of display design. Participants preferred numerical display and were better at detecting changes in information with this display than with the other two. Conversely, the student residence experiments showed that when participants' attention was divided in a household setting,

there was no difference in energy consumption among experimental groups who received information from any of the three display types. However, these experimental groups used significantly less energy compared with control groups, who had no displays installed. It was concluded that 1) the mere presence of a display device could influence people's behaviour, regardless of the type of display design, people's preferences or the level of user engagement with the display, although there was a strong indication that the ambient design worked better than the other two designs at an arbitrary statistical significance level of 0.95, and 2) subjective preferences and computer-simulated studies are poor guides to the actual performance of IHDs in real-world settings.

This work helps establish how IHDs can be designed and the influence that they may have on people's energy-consumption behaviour. It also contributes to the literature of exploring people's perceptibility of energy information. The method used is replicable and can be applied in similar studies on energy display design. Lastly, the improved understanding gained through this work will facilitate the development of effective smart meter display technology that may help people adopt conscious energy behaviour in the long term.

Outputs of research

Parts of this thesis have been published in the following peer-reviewed journals:

Published paper	Chapter in thesis	Times cited (as of 1 Feb. 2015)
Chiang, T., Natarajan, S. and Walker, I., 2012. A laboratory test of the efficacy of energy display interface design. *Energy and Buildings*, 55, pp.471-480.	4	Google Scholar: 15 Scopus: 8 Web of Science: 4
Chiang, T., Mevlevioglu, G., Natarajan, S., Padget, J.A. and Walker, I., 2014. Inducing [sub]conscious energy behaviour through visually displayed energy information: a case study in university accommodation. *Energy and Buildings,* 70, pp.507-515.	5	Google Scholar: 7 Scopus: 3 Web of Science: 1

The author has presented parts of the work at the following conferences:

- The user interface design of energy displays. *In*: T. Chiang and F. Moran, eds. *Proceedings of Buildings don't Use Energy, People Do? Research on Reducing Energy Use and CO_2 Emissions in Existing Dwellings*. 28 June 2011, Bath. EDEn, University of Bath, pp.77-88.
- So, you think you're smart with your energy use? *Postgraduate Scientific Symposium*, 26 November 2011, University of Cardiff.
- Can you see me better this way? User-centred design of energy meter displays. *Proceedings of Knowledge Gaps in Climate Change Research: How Are You Tackling It?* 11-13 April 2012, Norwich. Tyndall Centre for Climate Change Research, University of East Anglia, pp.26-27.
- Presenting energy information: display design and users' preferences. *2^{nd} Asian Conference on Sustainability, Energy and the Environment*, 3-6 May 2012, Osaka.
- Linking energy information and occupants: from visually displayed energy feedback to occupant behaviour. *Book of Abstracts of the 2^{nd} European Conference on Energy Efficiency and Behaviour*, 20-21 September 2012, Helsinki. Finland: Motiva Oy, pp.35-36.

- Laboratory and real-world tests of smart meter (in-home display) design interfaces. *28th International Congress of Applied Psychology*, 8-13 July 2014, Paris.

Parts of the work developed in the thesis have been displayed at the following public exhibitions:

- The challenge of reducing energy use in the home. *Visual Researcher Stories 2011*, University of Bath.
- Visually displayed feedback on domestic energy use. *Images of Research 2011: Collaboration and Partnership – Interdisciplinary*, at various venues in Bath.
- Designing smart meter displays. *Images of Research 2012: Research in Your World*, at various venues in Bath. In *Images of Research book 2009-2012*, University of Bath, p.37. Available at http://viewer.zmags.com/publication/7348916c#/7348916c/1

Table of Contents

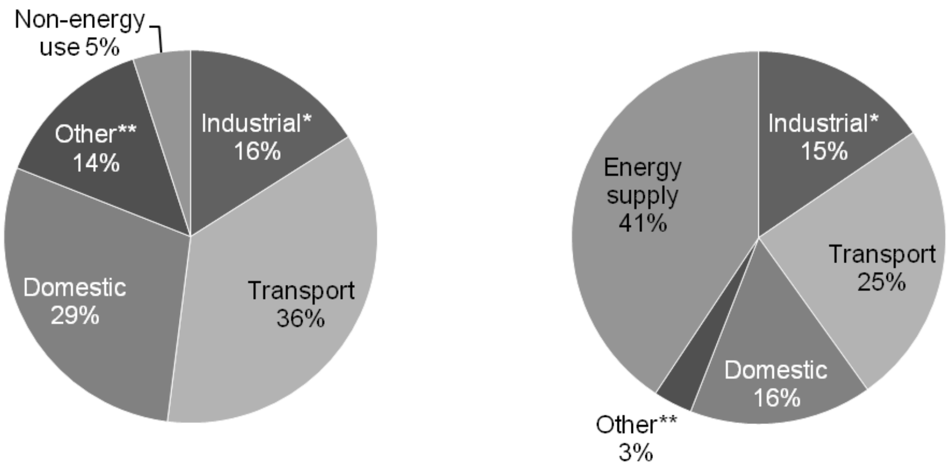
Table of Figures

List of Tables

Chapter 1 Introduction

1.1. Research background

In order to meet the target of cutting the UK's carbon dioxide (CO_2) emissions by 80% below 1990 levels by 2050 (*Climate Change Act 2008*), efforts are required from all sectors of the economy and the government (DTI, 2007). The domestic sector is one of the largest energy consumers and CO_2 producers alongside with transport and industry in the UK (Figure 1.1) (DECC, 2014a, 2014b), hence it represents a potentially significant opportunity for carbon abatement, and is a critical part in the national response to climate change in the policies of energy efficiency (Lomas, 2010).



* Includes industry and business

** includes services and agriculture

a) b)

Figure 1.1. (a) UK energy consumption by sector in 2013 (adapted from DECC, 2014a) and (b) UK carbon emissions by sector in 2012 (adapted from DECC, 2014b)

However, reducing emissions in dwellings may be more difficult to be implemented than it seems. Direct emissions come from electricity and gas consumption, which are the results of individual's everyday decisions and actions; these decisions and actions are shaped by infrastructure through which energy is used, such as the fuel supply technologies, the building in which the fuel is burned, and the appliances that use gas or electricity (Parag and Darby, 2009). Clearly, factors affecting the overall energy use and CO_2 emissions in buildings are interlinked, as illustrated for residential buildings in Figure 1.2. While many more aspects can be added to it, such as physical controls, retrofit adaption measures, social and economic constraints, and personal factors (values, norms, habits), the effect of each factor illustrated still needs to be examined in order to understand better how energy is used in the building, and by proxy how carbon emissions can be reduced. This research focuses on the behavioural aspect of energy use as a result of the interaction between the user and the interventions aimed to promote energy savings.

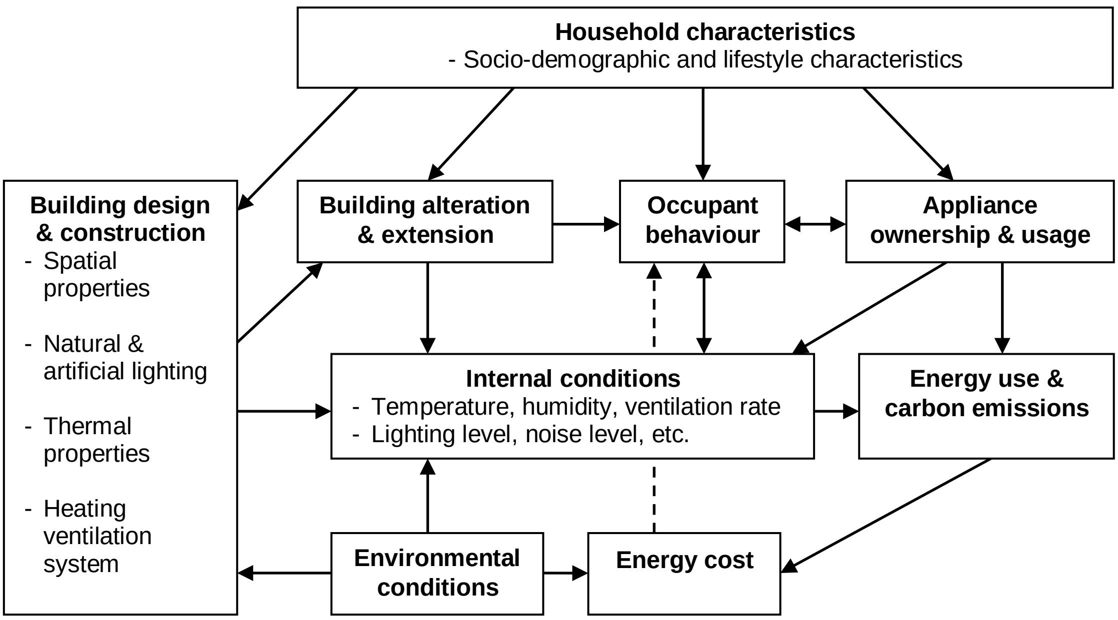


Figure 1.2. Factors affecting domestic energy use (adapted from Summerfield *et al.*, 2009)

If human behaviour is one of the factors related to energy use as shown in Figure 1.2, changing behaviour would help reduce energy use. The UK Governments estimates that actions taken by individuals at home result in over

40% of the UK's energy use and CO_2 emissions, much of which is attributable to heating and travelling, while the rest is caused by other sectors of the economy such as industry, transport, agriculture (Figure 1.3) (DTI, 2007).

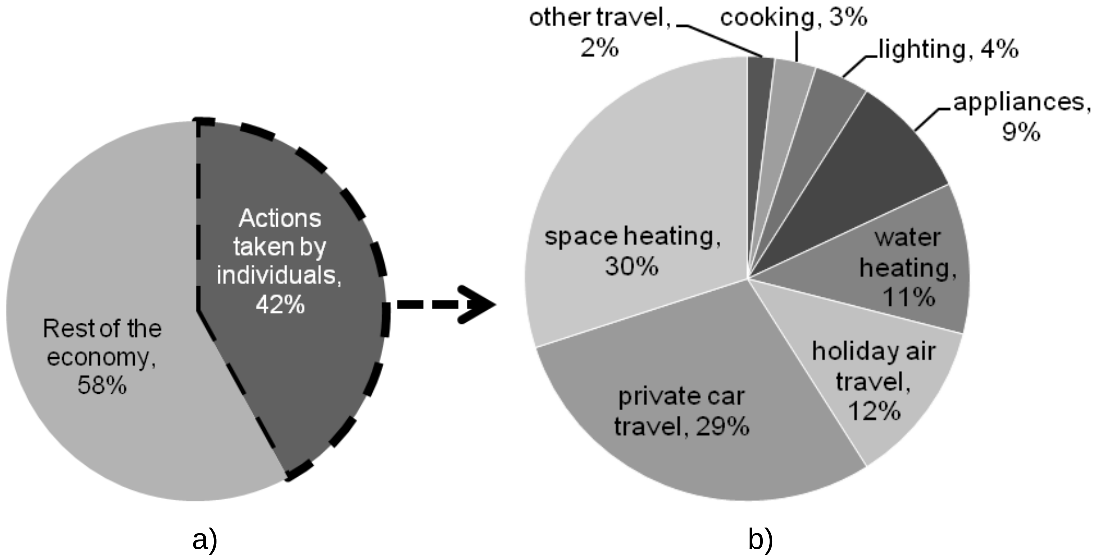


Figure 1.3. (a) Carbon emissions from the UK economy caused by individual actions and (b) Individual annual carbon emissions by end use (both adapted from DTI, 2007)

With the progressive tightening of building regulations and the drive to reduce energy use and improve efficiency, the role of occupant behaviour in reducing energy consumption has come into sharper focus (Darby, 2000; Wood and Newborough, 2003). Research has suggested that behaviour is often guided by habits (energy-related habits are discussed further in Section 2.2.3.2), and that people are more likely to undertake efficient energy behaviours if they can see their energy use and savings (Stern and Aronson, 1984; Kempton *et al*., 1992). Past findings have also suggested that changes in human behaviour can reduce household energy consumption in the range of 5-15%, depending on the quality and type of interventions aimed to motive behavioural change, such as rewards and visual feedback utilised in this research work (motivational interventions are discussed further in Section 2.3) (Abrahamse *et al*., 2005; Darby, 2006). Thus, if energy consumption is the result of individual actions, then people should learn about the link between their everyday behaviour and energy consumption, and change their habits to achieve energy savings (Brandon and Lewis, 1999).

The potential of electronic feedback provided by in-home displays (IHDs) has been recognised for helping to make energy use visible, making the link between actions and their effects more immediate and salient to the occupant than paper-based feedback (Hutton *et al*., 1986; van Houwelingen and van Raaij, 1989; Fischer, 2007; Faruqui *et al*., 2010). Thus, IHDs have the potential to facilitate the learning process, help raise awareness of energy consumption and related habits, and motivate energy savings (using IHDs as a means of feedback is discussed further in Section 2.4).

1.2. Problem

Although using IHDs to give feedback on energy consumption has been found useful for helping occupants learn about their energy consumption and make energy-use reductions at home, the relevance of optimising design arrangements of the user interface for IHDs has been overlooked. Householders may be reluctant to invest time to learn to use a new monitoring device like the IHD due to its unintuitive interface design (Hargreaves *et al*., 2010; Meyers *et al*., 2010; AECOM, 2011). As much of the previous work has centred on the effects of various forms of display rather than exploring the presentation of energy information on the display, there is a lack of systematic comparisons between “pure” display designs (i.e. information is represented in a single format of presentation, e.g. numbers only), and the question of whether different display presentations of information benefit energy users equally is not well investigated. Lastly, there is a need to understand better how IHDs can motivate energy-efficient behaviour and how to maintain this behaviour over various periods of time.

1.3. Aim and objectives

The research aims to address the need for investigating the efficacy of IHD design in communicating with people about their energy use and the effect of IHD design on energy consumption. The objectives have been set as follows to fulfil the aim:

1. To design “pure” IHDs with different display design features, e.g. coloured and non-coloured displays.
2. To measure users’ responses to various IHD designs presenting the same information.
3. To assess the effectiveness of each tested display design in communicating information to the user.
4. To understand the effects of these display designs from the user’s perspective.

1.4. Thesis structure

This thesis consists of six main chapters and appendices. Following this introductory chapter, Chapter 2 establishes the background for the research topic by briefly outlining the current literature on domestic energy use, it then considers the factors associated with forming environment-related behaviours and the constraints preventing people from undertaking pro-environmental actions. This will demonstrate some of the challenges for achieving energy savings through occupant behaviour. Interventions aimed to encourage using less energy are presented, followed by an introduction to the history, development and the current application of direct energy displays, focusing on the literature relevant to the design of IHDs and their effects on communicating energy information to users. Lastly, a review is given of subjective preferences for various IHD designs.

Chapter 3 defines research questions derived from the literature review, and describes the methods adopted in the collection of data and the analysis of results to address the research questions.

Chapter 4 details two computer-simulated laboratory tests (a pilot study and the main laboratory-based experiment) that examined three different types of energy display design and assessed participants' subjective preferences and how easily they could detect changes in information presented in the three display designs when they were looking for these changes.

Building on the laboratory-based test results, Chapter 5 presents two field-based experiments conducted in a university student residence setting, examining the presentation of energy information on live displays and their effects on energy consumption.

Chapter 6 gives an overall discussion of the thesis and the implications of the research project, and concludes with suggestions for possible further work.

Chapter 2 Literature review

2.1. Introduction

Energy consumption in the house depends on varieties of both external and internal factors. From climate conditions to the infrastructure of energy supply, to physical attributes of the building (location, fabric, construction, age, typology, size, orientation, shape, conditions), to the specifications of building systems (e.g. heating, cooling, lighting, ventilation, communications) and appliances, and to the characteristics of building occupants (socio-demographics, socio-economic status, lifestyle, tenure, occupancy time) (Abrahamse *et al.*, 2005; Jackson, 2005; Darby, 2006; BRE, 2005; Sardianou, 2007; Yohanis *et al*., 2008; Guerra Santin *et al*., 2009; Wyatt, 2013), these external factors, in turn, shape internal factors that consist of personal preferences, attitudes, beliefs, as well as opportunities and individuals' abilities (Ölander and Thøgerson, 1995; Abrahamse *et al.*, 2005). Moreover, research in as early as the 1970s estimated that up to a third of energy used in the house is caused by occupant behaviour (Sonderegger, 1978; Verhallen and van Raaij, 1981). Occupants' existing knowledge of energy consumption, habits, personal values, cultural backgrounds (Mansouri *et al*., 1996; Ueno *et al*., 2006) and subjective perception to thermal, visual, acoustical comfort (Alfano and d'Ambrosio, 1991; ASHRAE 55-2013, 2013), coupled with internal factors, have been found to influence individual behaviour and choice to some extent.

Accordingly, energy demand could vary in dwellings with similar physical attributes (Seligman *et al*., 1978; Bahaj and James, 2007) and appliances with similar specifications between most frugal and wasteful households in each hour of the day and night, week, month, season and year (Yohanis *et al*., 2008), as well as within households with similar characteristics (Socolow, 1978; Winett *et al*., 1979). This suggests that influencing occupant behaviour is one of the areas of research likely to lead to significant changes in energy use.

The quantity of literature regarding the external and personal factors of energy use is extensive. This chapter will primarily focus on the area of occupant-related energy use.

2.2. Domestic energy consumption and occupant behaviour

Greenhouse gas (GHG) emissions associated with energy consumption in the UK have generally decreased since the 1990s, and a declining trend of energy consumption from fossil fuels since the 2000s has also been observed[1] (Figure 2.1).

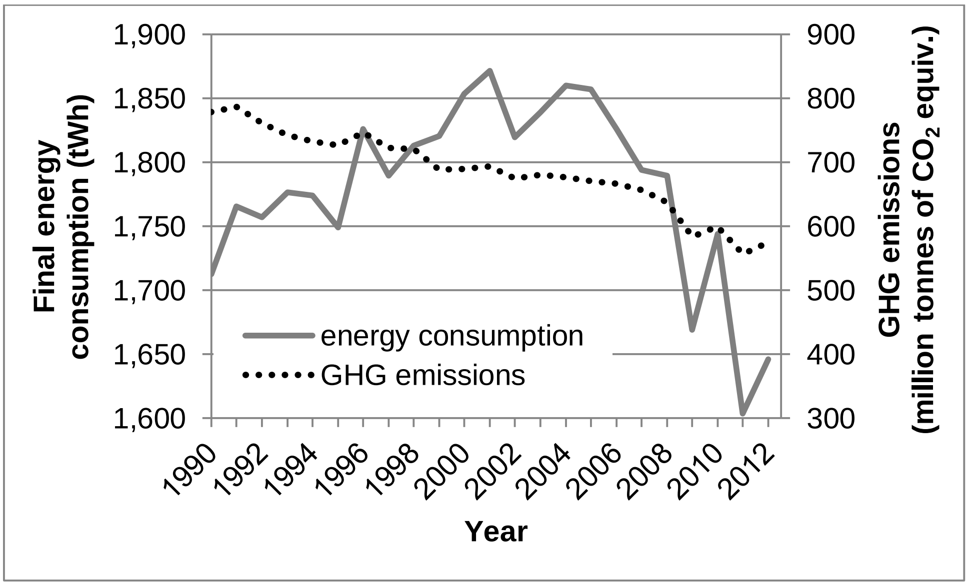


Figure 2.1. UK's energy consumption and GHG emissions between 1990 and 2012 (adapted from DECC, 2014a and DECC, 2014b)[2]

---

[1] It is worth noting in advance that much of the data concerning domestic energy consumption in the UK presented in this section has been sourced from nation statistical publications produced by the Department of Energy and Climate Change (DECC) and the Office for National Statistics (ONS) from the UK Statistics Authority. The methodology background is not revealed in most cases, but is given and reviewed where possible in the footnote.

[2] Energy consumption is measured in million tonnes of oil equivalent (mtoe) in the original sources, this thesis converts the unit into terawatt-hours (tWh): 1 mtoe = 11.36 tWh by using International Energy Agency's Unit Converter found at http://www.iea.org/statistics/resources/unitconverter/.

Domestic energy consumption has shown to be closely related to household income status, which gives households the ability to spend on energy and is generally positively correlated with their consumption (discussed further in Section 2.2.3.3), and environmental conditions such as external air temperatures (ONS, 2014a). Figure 2.2 shows that gross domestic product (GDP) has been declining since 2007 following the economic downturn and started to recover in 2010 when the average air temperature dropped to the lowest since 1990. But in 2012, increases in energy consumption and emissions were observed despite slower growth in GDP, which may be attributed to the colder weather in that year demanding greater fuel consumption for heating (*ibid.*).

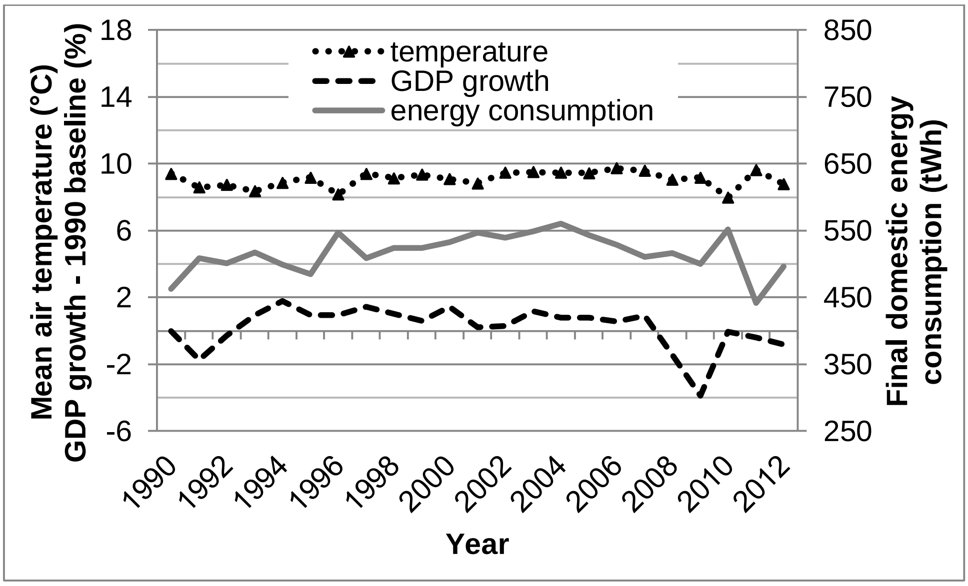


Figure 2.2. UK's domestic energy consumption against external air temperature and GDP growth between 1990 and 2012 (adapted from DECC, 2014c and ONS, 2014a)

The household disposable income between 1990 and 2012 increased by 65% (DECC, 2014c), which enabled householders to change their lifestyle, such as purchasing more appliances (the number of appliances a household owned in 2012 increased by 54% compared with 1990) (*ibid.*). As a result, an 18% increase in the total electricity consumption of domestic appliances was observed during the same period (DECC, 2014c), despite an overall decrease in domestic energy consumption since the 2000s (possibly due to an increase in the development of energy-efficiency measures and technology in the building stock, and changes in energy-related policy and user behaviour (discussed further in Section 2.2.1)) and higher levels of energy efficiency of appliances manufactured in the recent years that may contribute to new appliances consuming 25% less energy than in 1990 (*ibid.*). The increasing trend of energy consumption of appliances is often implicated by the increasing number of home computing and electronic products (e.g. game consoles, DVD players) per household, many of which also come with a standby/sleep mode that could result in more energy being unintentionally wasted (energy-use habits are discussed further in Section 2.2.3.2). Electricity consumption from electronics in 2012 increased by 77% compared with 1990, and was four times greater than in 1990 from computing products (Figure 2.3). It is estimated that the total electricity consumption of new home computing and electronic products increased by 43% and 30%, respectively, in 2012 against 1990 levels (*ibid.*).

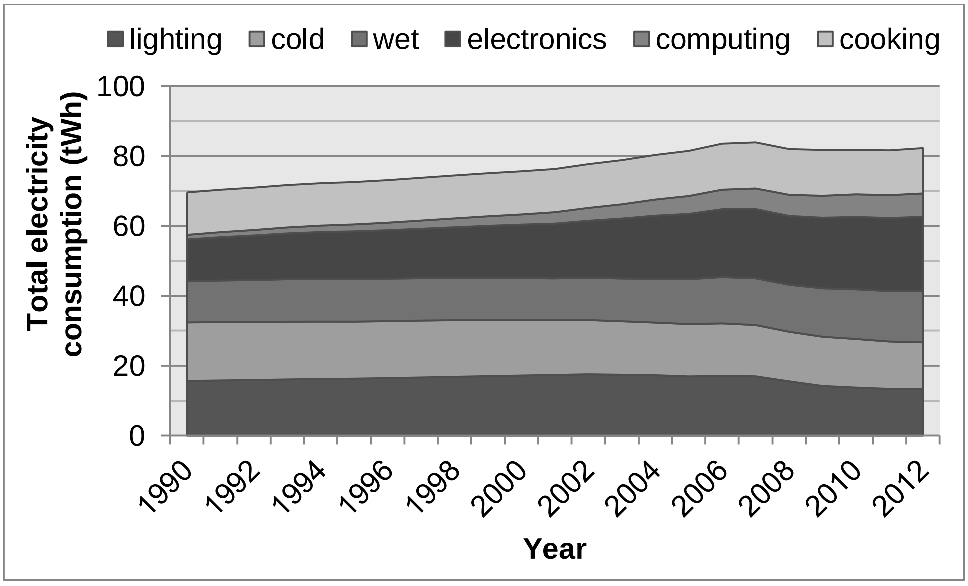


Figure 2.3. UK's domestic electricity consumption by appliance type between 1990 and 2012 (adapted from DECC, 2014c)[3]

[3] While many appliances were included in the data, it was not made clear whether those included were assumed to be the most common domestic appliances owned by households

Contrary to a decrease in the overall domestic energy consumption since the 2000s, the average annual household gas and electricity bills rose by 72% and 11% (inflation corrected), respectively, between 1996 and 2012 (DECC, 2014d). The rises in energy bills and consumption in 2012 may be explained by cooler external temperatures, again, increases in appliance ownership, internal temperatures and heating duration as discussed below, and an increase in fuel prices. In terms of fuel price indices relative to the GDP deflator, the overall domestic electricity prices, including VAT, rose by 26% between 1996 and 2012 (86% and 109%, respectively), while domestic gas prices increased by 97% during the same period (60% in 1996 and 117% in 2012) (DECC, 2014e) (Figure 2.4).

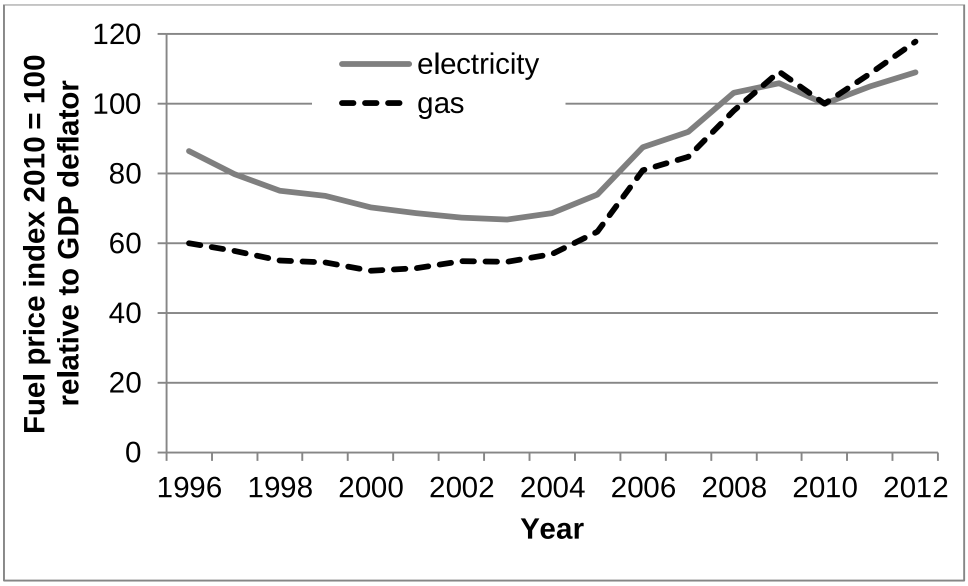


Figure 2.4. Domestic fuel price indices between 1996 and 2012 (adapted from DECC, 2014e)

Figure 2.5 shows that heating has always been the most energy-consuming end use in the house – two thirds of the total energy consumption goes to space heating alone, and one fifth to hot water, making up more than 80% in total. As

---

during the study period (1970-2012), as many other appliances could have also been included, such as portable heater, vacuum cleaner, lawn mower, facsimile machine, etc.

the breakdown of energy by end use was modelled, it is not clear how representative this is, and it is subject to uncertainty from climate data, housing data and building physics assumptions (DECC, 2014c). Despite a fall in energy consumption since the mid-2000s, space heating, lights and appliances still continued to consume more energy in 2012 than in 1990 (it is still early to predict a trend that will persist to rise). The changes observed may largely be due to lower external temperatures and an increased appliance ownership as mentioned before, as well as the improved comfort and satisfaction in the house – the average internal temperature between 1990 and 2012 increased by about 1°C[4] (*ibid.*) – resulting in longer heating duration. On the other hand, energy consumption of hot water and cooking fell slightly, possibly due to a change in lifestyle that involved less cooking at home, switching to showering, and decreasing the frequency and length of bathing time. Householders may also have washed clothes at lower water temperatures.

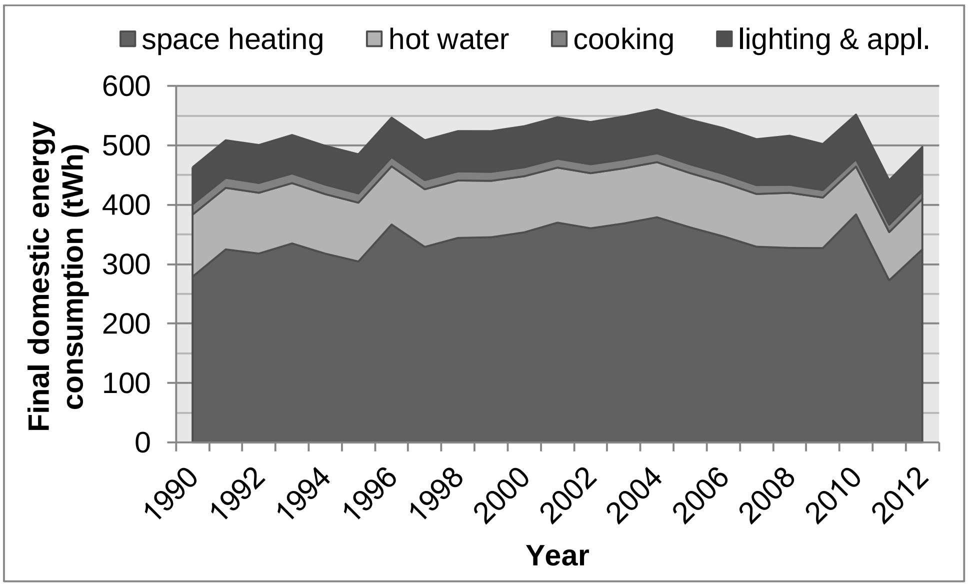


Figure 2.5. UK's domestic energy consumption by end use between 1990 and 2012 (adapted from DECC, 2014c)[5]

---

[4] The average internal temperature includes homes with central heating and non-central heating, but the data do not indicate what the heating period was, as vulnerable households with elderly members, health conditions or low income may have different heating patterns.

[5] Cooking data presented in the graph include gas used for cooking, but not small appliances such as kettles microwave ovens; therefore, small discrepancies are expected.

Gas is primarily used for space and water heating in UK households (other uses include gas stoves for cooking, gas fire places, heated swimming pools, etc.), while electricity is used mainly for lighting and appliances. Figure 2.6 shows that there has been a decline in the consumption of domestic gas and electricity since the mid-2000s. At the same time, energy consumption from renewable and waste sources was notably on the rise, primarily due to an increase in bio-fuel usage in road transport and electricity generated from wind, wave and tidal energy (ONS, 2014a).

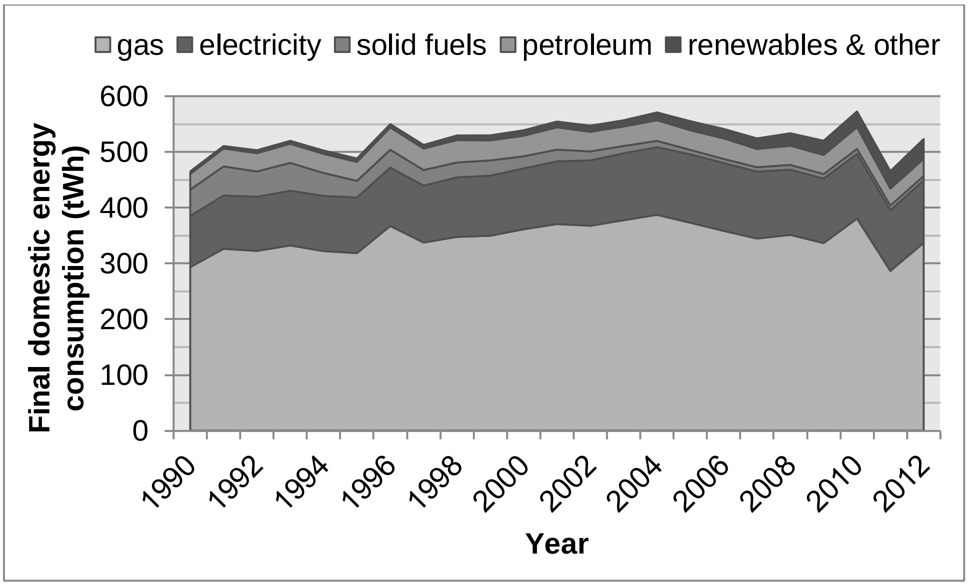


Figure 2.6. UK's domestic energy consumption by fuel between 1990 and 2012 (adapted from DECC, 2014a and ONS, 2014a)

Householders' understanding of their energy consumption may be implicated by their understanding of the power requirement of their appliances. For example, a single lamp of 40 W (Table 2.1) may not seem to use a lot of electricity, but there are on average 27 light fittings per household in 2012[6] (DECC, 2014c). If they are all left on in unused rooms, they would consume about the same amount of electricity as a 1000 W hairdryer. While a hairdryer has a high wattage requirement, it is used much less frequently and for a short period of time per use. It is possible that long-term reductions in energy use cannot be

[6] The data do not indicate whether floor area and occupants were accounted for.

achieved if householders are not aware of their energy consumption, lack in the knowledge of "how much energy is used for what", or misjudge the amount of energy their appliances actually consume (misconceptions about energy use are discussed further in Section 2.2.3.1).

Table 2.1. Power consumption range of common domestic appliances in 2012 (adapted from CSE, 2013)

End use	Appliance	Power consumption range (watt)[2a]
Wet	Electric shower	7,000-10,500
	Tumble dryer	2,000-4,000
	Washing machine	1,200-3,000
	Dishwasher	1,050-1,500
Cooking	Kettle	2,200-3,000
	Electric oven	2,000-2,200
	Electric hob	1,000-2,000
	Microwave oven	800-1,500
	Toaster	800-1,500
Heating	Portable heater	1,200-2,000
	Hairdryer	1,000-1,800
	Iron	1,000-2,000
	Vacuum cleaner	500-1,200
Cold	Fridge-freezer	200-400
Electronics	TV (plasma, LCD)	200-450
	Telephone	40-100
	Home computing (tablet, laptop, desktop computer)	20-150
	Video, DVD or CD player	20-60
	Broadband router	7-10
Lighting	Lights (ceiling, wall, floor, worktop)	40-150

[2a] The range of power demand of an appliance varies depending on the type and its model.

2.2.1. Approaches to reduce energy consumption in the house

To reduce energy use in domestic buildings, and by proxy carbon emissions, there are three general approaches to stimulate the change:

2.2.1.1. Regulations and policy enforcement

Against a backdrop of reducing national GHG emissions bound by the UK's own legal framework (e.g. *Climate Change Act 2008*), the European Union's energy-efficiency policies (e.g. Article 13 of the Energy Services Directive 2006), as well as international agreements (e.g. Kyoto Protocol 1997), the UK Government has recognised the roles of government, industry and the consumer in the challenge of improved energy efficiency (DTI, 2006) by undertaking a number of strategies, including investing in smart meters, introducing financial incentives, and imposing obligations on energy suppliers to make energy-efficiency interventions, such as installations of cavity wall and loft insulation, available to their customers. Energy suppliers are also to provide informative bills containing information on past energy consumption in the same period of the previous year, preferably in a graphical form, supported by information on energy efficiency (DTI, 2007), while the consumer is to know their rights to complain about inadequate energy services, switch energy suppliers to compare energy prices, and be given energy-saving advice and information on efficiency and renewable energy (Parag and Darby, 2009).

The UK's building regulations have undergone a number of amendments, raising the standards of energy performance for both new and refurbished homes, and increasing the use of renewable and low carbon sources of energy (DEFRA, 2007; DTI, 2007). There are also other measures introduced to focus on improving energy efficiency in dwellings, such as the Code for Sustainable Homes that has star ratings of energy and water efficiency performance, the Standard Assessment Procedure (SAP) on a rating system for both new and existing buildings, and Energy Performance Certificate (EPC) that indicates energy efficiency for both homeowners and buyers.

Despite the well-meant intentions behind all the new measures and policies, the current main obstacles of realising the full potential of energy-efficiency measures in the housing stock are lack of information about benefits and costs of such measures, lack of motivation, awareness or interest among householders, and lack of access to capital and incentives (Stern, 2007). Without proper implementation strategies, such as consulting the public on new legislation and in developing options on improved billing, this regulation-based approach may not become successful.

2.2.1.2. Physical improvements

Energy performance of domestic buildings can be boosted by renovating the existing housing stock, building new low- and zero-carbon dwellings designed primarily to minimise heating and cooling loads, and developing energy-efficient appliances, lighting and monitoring equipment (Wood and Newborough, 2003).

Research has shown that energy-efficiency interventions in buildings, such as energy-saving lighting, improved boiler efficiency and integrated renewable energy technologies, can bring significant reductions in CO_2 emissions (Lomas, 2010), especially in the task of refurbishing older houses (Boardman, 2007), but they can also lead to changes in behaviour, such as higher indoor heated temperature, longer heating duration (Lomas, 2010).

Despite the increasing development of energy-efficiency interventions and low-carbon technologies, this is a one-off, investment-based approach (energy-related behaviours are discussed further in Section 2.2.2), relying on the advancement of technology, as well as building construction and material innovations, which may not be economically viable for many householders.

2.2.1.3. Occupant behavioural change

Domestic energy use can be reduced by encouraging people to change their energy-use practices in the house. Like with improving technological innovations in building design and construction, the UK Government has also recognised the importance of understanding how individuals affect energy use (DTI, 2006) – while physical measures and upgrades can increase energy efficiency, inefficient consumption behaviours adopted by occupants can have an impact on the building's energy consumption (Jain *et al.*, 2013). Unlike physical improvements, behaviour-based efficiency measures require no expenses to be made (Allcott, 2010) and have little impact on household well-being (Dietz *et al*., 2009). Engaging occupants in repetitive energy-efficiency behaviours (discussed further in Section 2.2.2) will help to ensure that energy savings made from existing and new buildings are not offset by occupants' changing energy demand over time during the life of the building, thus achieving sustained reductions in energy consumption. Therefore, occupant behaviour is an important factor in the challenge of reducing energy use.

Although this approach has shown to result in reductions in energy use, changing behaviour involves many internal factors, perceptual and emotional characteristics, as well as personality traits and demographic factors, of the individuals, which are complex and impossible to control (Kluger and DeNisi, 1996). Further, learning to change a habit or forming a new behaviour will need longer-lasting strategies, such as constant motivations and feedback, to persist (van Houwelingen and van Raaij, 1989; Darby, 2006; Fischer, 2008) (interventions to motivate behavioural change are discussed further in Section 2.3).

2.2.2. Environment-related behaviours

Occupant-related energy consumption is the result of a behaviour with environmental impact. The impact of such energy-related behaviour is not only on the wider natural environment, but also on the home environment where the behaviour takes place. Making efficient use of energy requires conscious efforts, and it is a form of environment-related behaviour. People exhibit pro-environmental behaviour[7] for a number of reasons. Identifying the underlying variables that influence behaviour gives an insight into why people behave the way they do, and highlights the complexities of environment-related behaviour. This section does not intend to be a comprehensive review on the theoretical

[7] Pro-environmental behaviour is a behaviour that consciously and actively seeks to minimise the negative impact of one's actions on the natural and built environment (Kollmuss and Agyeman, 2002), such as decrease energy consumption in a building through careful design, use recycled building materials in new and refurbished buildings.

models of human behaviour in environmental psychology. It will focus on those models that can be extended to the research, and take a broad approach to review those that explain how environment-conscious decisions are generally made.

As mentioned in the previous sections, behaviours related to efficient energy use can be one-off or repetitive (Gardner and Stern, 2002). One-off behaviours are investment-based, relying on technological advancement or physical improvement of the building's energy efficiency, such as substituting an old refrigerator with an energy-efficient one with an A+ class, and fitting double glazing to the window. They are perceived to be effective in obtaining actual energy savings. Their effects usually last for long periods of time, but may be counteracted by psychological effects such as the rebound effect, a reaction to lower energy use or expenses saved by reducing energy use on energy-intensive products, thereby possibly increasing overall energy use (Abrahamse *et al*., 2005). On the other hand, repetitive behaviours rely on continuous efforts, such as turning lights off and adjusting thermostat settings. Although their impact on energy savings may be generally lower than that of one-off behaviours, they are effective in initiating actual behavioural changes, do not require changes in the home environment (Haakana *et al*., 1997; Bonino *et al*, 2012), and could be sustained for the long term (Geller, 2002).

According to rational choice models, people choose actions that are utilitarian-based and most beneficial (e.g. time, efforts, comfort) or cost effective to themselves (Mansourie *et al*., 1996; Martiskaïnen, 2007; Frankish, 2009). If people rationalised their decisions based on the outcome of the act, they are likely to benefit from energy-saving interventions that provide accurate information on benefit and cost relations, and the net benefits of desired behaviours (Frankish, 2009). However, it is possible that decisions are often made on intuitive judgements, and individual preferences are not well defined or consistent (*ibid.*); therefore, the effect of providing information may be weak.

According to attitude models (Ajzen and Fishbein, 1970), people may perform environmental behaviours if they have a fair amount of knowledge about the environment. This assumption is based on a linear progression from knowledge to concern, to pro-environmental behaviour, suggesting the potential of providing information about the impact of energy use on the environment for increasing the knowledge and the possibility of saving energy. However, this assumption, like rational choice models, does not take account of other factors which may influence behaviour, such as habits, emotions, social norms[8] (Jackson, 2005); therefore, the relationship between attitudes and subsequent actions is not always strong. This may explain the attitude-behaviour gap that makes the transition from information to action difficult (Costanzo *et al.*, 1986) (discussed further in Section 2.2.3.3).

Another reason for people to make environmentally conscious decision on their consumption of natural resources is related to personal norms, which are personal ideas about how one should act and are experienced as feelings of moral obligation, that lead to altruistic behaviour by giving up personal benefits for the collective's interests. This is known as norm activation model (Schwartz, 1977). This is a pro-social orientated behaviour which can be stimulated if a person behaves in accordance with personal norms and feels a sense of pride, and if a person is aware of the negative consequences of their behaviour for others and ascribes responsibility for taking improved actions (*ibid.*).

In accordance with predictions from social identity models, attitudes and behaviours are influenced by families, friends, colleagues and/or neighbours, whom people use as a "reference group" to identify their sense of who they are and where they stand in society (Tajfel and Turner, 1979). A number of studies have supported this theory in the application of energy consumption and suggested that people are likely to adopt efficient energy behaviours if those around them change or are mindful of their behaviours (e.g. Hori *et al*., 2013).

[8] Social norms are ideas about which norms others might hold (Fischer, 2008).

This section shows that interventions aiming to change behaviour should be in sync with people's needs to target the underlying behavioural variables. For example, a design based on rational choice models should stress the cost savings of an A-rated high-efficiency condensing boiler, whereas a design based on social identity models should focus on the average energy consumption values of others in the neighbourhood.

2.2.3. Factors hindering efficient use of energy in the house

2.2.3.1. "Lost in translation"

A common problem encountered by households attempting to reduce their energy consumption is the invisibility of energy. For householders to learn about the link between their behaviour and energy consumption, unambiguous and effective feedback about energy use is required. The information that people receive should be readily comprehensible and, ideally, should prompt appropriate action to reduce consumption without requiring too much analysis and interpretation.

In the UK, the most accessible feedback about energy consumption is, typically, provided through quarterly energy bills, the way in which information is presented, however, makes bills difficult to understand for some consumers (Roberts *et al*., 2004). For example, energy units are often used in the bills to indicate energy consumption, but there may not be sufficient information supplemented to explain to the consumer what they mean (feedback information is discussed further in Section 2.4.1). Another example is the payment system for energy bills which show estimated usage and an invoiced sum four times a year, then the consumers receives a bill at the end of the year showing the cost of actual consumption for them to pay or claim the difference. Another source of feedback for households is energy meters, which are generally installed outside the dwelling hidden away from sight. This arrangement potentially makes householders less aware of their energy use, who may also have a limited understanding of their energy consumption

(Roberts and Baker, 2003), or little knowledge about their energy bills (Brounen *et al*., 2013) and their appliances' energy-efficiency rating (Yohanis, 2012).This is exacerbated by infrequent meter reading, which means billed usage is often estimated rather than measured, resulting in a lack of knowledge, awareness, motivation and engagement for energy-use reduction. Moreover, householders who pay by regular automated payment (Direct Debit), which is encouraged by most energy suppliers, are particularly unlikely to receive any feedback on their consumption, as they pay automatically without having to open their bills. Quarterly credit payers have limited engagement due to poor on-bill feedback, while pre-payment meter users have strong engagement but feedback is still limited (Roberts and Baker, 2003; Roberts *et al*., 2004). As a consequence, these payment methods are potentially counter-productive to the development of energy-conscious practices (Wood and Newborough, 2003). Clearly, as the sources of energy use are not well identified, the lack of clear feedback information on consumption could hinder even those with a good understanding of the impact of their behaviour on energy use from using energy more efficiently (Darby, 2000).

Apart from the intangible flow of energy used in the house, the misconception of energy use can be a barrier preventing householders from taking better control of their energy use. Research conducted between the 1990s and 2000s found that people were aware of environmental issues and were concerned about climate change, but failed to make a link between their everyday actions and emissions, and ultimately climate change (DTI, 2007; Martiskaïnen, 2007). People perceived the issues of climate change to be complicated and were disempowered or underestimated their role in changing the situation (Moser and Dilling, 2004). Many might be knowledgeable about how to save energy, but they perceived implementing energy-efficiency measures to be expensive, and concerns for being efficient with energy use often had a low priority in their daily lives (Roberts *et al.*, 2004).

Electricity and gas consumption in the UK are measured in kWh and are absolute in terms of consumption, but they are not always well understood due to their abstract units (see Section 2.4.1.1 for alternative units to relate energy consumption to common objects for comparability); whereas cost units in pounds and pence are commonly used to accompany kWh to represent the amount of energy consumed and are useful motivators for reducing consumption (Fischer, 2008; Anderson and White, 2009), but they can be misleading due to changes in energy prices (Hayes and Cone, 1981), which happen in some countries, such as the USA, where electricity prices in summer are higher than in winter due to the increased use of air conditioning.

Another issue is the mismatched understanding of how much energy each appliance in the house actually consumes. Previous research has looked at householders' understanding of energy use compared with their estimation of actual usage (e.g. Mettler-Meibom and Wichmann, 1982 in Froehlich, 2009; Costanzo *et al*., 1986; van den Broek and Walker, in prep). Results suggested that householders frequently underestimated their heating, leading to unintended increase in energy consumption, while energy used for appliances, lighting and cooking was overestimated.

2.2.3.2. Energy-use habits

As mentioned previously in Section 1.1, individual actions have been found to contribute to much of the UK's energy use and CO_2 emissions as results of undertaking habitual behaviours, suggesting that a proportion of daily energy is consumed out of habit, which is not a fully conscious behaviour and is performed without putting much effort into thinking about it first, rather than out of necessity (Barr *et al*., 2005; Fischer, 2008; Maréchal, 2010).

Indeed, leaving appliances on standby was found to be one of the habits frequently overlooked by householders in a self-reporting survey conducted in five Western European countries (France, Germany, Italy, Spain and UK) (EST, 2006). A more recent study that collected more than 9,000 responses using web-based questionnaires on electricity consumption in nine Organisation for Economic Cooperation and Development (OECD) countries similarly supported the finding that householders tend to forget to switch off appliances in standby mode more often than enacting other curtailment behaviours, such as switching off lights in unused rooms and fully loading dishwashers (Urban and Ščasný, 2012). This might be due to the increasing number of appliances with a standby/sleep mode that results in invisible energy use and wastage. While it was not clear why those five countries were selected and how the participants were chosen, the Western European survey examined how some 5,000 Europeans used energy through the everyday actions they undertook, and found that Italians fared the worst when it comes to the standby mode, with 80% of them leaving an average of six appliances on standby on a regular basis. In contrast, the OECD study found that Italy was one of the countries that most frequently switched off appliances or appliances on standby (others were Canada, France and the Netherlands). Nevertheless, putting appliances on standby tops the UK's energy-wasting habits list (see below), with 71% claiming to do this and 65% leaving chargers plugged in and switched on. In another study that compiled 21 surveys on standby power consumption conducted in over 1,000 homes in 12 OECD countries and China, electronic appliances put in standby/sleep mode were found to continue to consume some amount of current known as leakage current (Bertoldi *et al*., 2002; Meyers *et al*., 2010). Although the study pointed out that the survey results were not entirely comparable due to differences in the way in which standby power was measured in each country, it is noteworthy that many studies on energy-use behaviour similarly raised the issue of leaving appliances on standby. Thus, the proportion of standby power consumption against the totality is clearly illustrated, and it is not a country-specific issue.

It was not clear in the studies reviewed whether standby consumption was due to individual habits or thoughtless design. The user may have a habit of forgetting to switch off the power when they have finished using an appliance, whether the standby feature is incorporated into the design or not. Further, while appliances on standby run on a low power mode, which is intended for saving energy consumption compared with leaving the appliances full on and for reducing the waiting time when the working mode is resumed, they can be mistaken for being powered-off and thus energy is wasted unintentionally.

The list below shows the inefficient energy habits in the UK and the proportion of householders who admit to habitually carrying out these actions on a weekly basis (EST, 2006):

- 71% leave appliances on standby
- 67% boil more water than needed in the kettle
- 65% leave electrical chargers plugged in
- 63% leave lights on in unoccupied rooms
- 48% use the car for short journeys
- 44% wash clothes at 60 degrees
- 32% leave the engine running while the car is stationary
- 32% use the tumble dryer when the washing line could be used
- 28% leave the heating on while the house is unoccupied
- 27% over-rev the car engine
- 22% turn up the thermostat instead of reaching for a jumper
- 15% wash clothes at 90 degrees

However, a large proportion of householders recognise that many of the habits listed above are important to break. Figure 2.7 shows that “leaving appliances on” tops the list of habits to change (25%), which may be due to the large percentage of householders surveyed admitting to doing it (71%) and thus wishing to change. On the other hand, only 1% said to wish to change the habit of washing clothes at 90 degrees, but the list does not account for those who do not do it, i.e. the value is low because very few surveyed householders do it (15%).

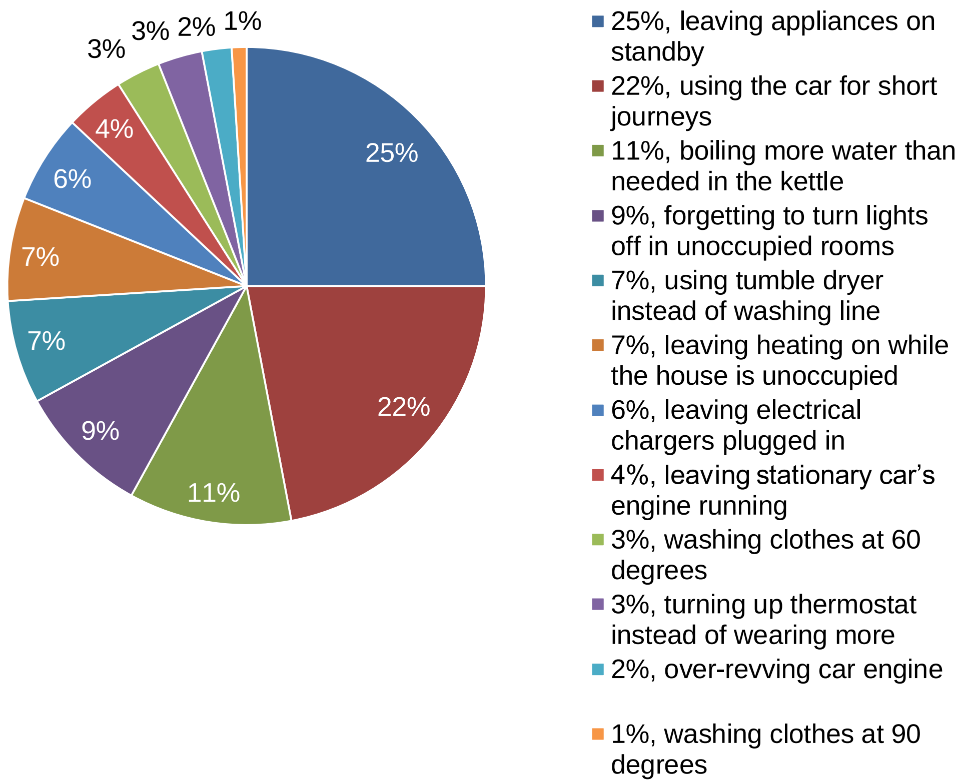


Figure 2.7. Habits that UK householders believe are most important to break (adapted from EST, 2006)

These habits may seem to be harmless, but the consequences add up (e.g. energy bills). Take leaving appliances on standby for example. The UK Government estimates that powering appliances left in standby mode accounts for an average of 200-591 kWh per household per year, about 5-16% of an average electricity consumption of 3800 kWh a year (EST, 2012; DECC, 2014f), or 5-16% of an average electricity bill of £530 a year (DECC, 2014d) using an average electricity price (2014) of £0.14 per kWh (DECC, 2014g). In broader terms, it is estimated that there would be enough electricity saved to power 2.7 million homes for a year if everyone in the UK switched off appliances and avoided using standby; enough energy would be saved to heat 1.7 million homes for a year if the thermostat was turned down by one degree; and enough money would be saved to pay around 75,000 family fuel bills for a year if everyone replaced one ordinary light bulb with an energy-saving one (EST, 2006).

Although habits are repetitive behaviours that require continuous efforts, it is possible to unlearn “bad” energy habits and form “good” ones. Motivational interventions, such as the provision of information on the negative financial or environmental consequences that certain habits will have and the benefits of other habits will bring, should well help to stimulate behavioural changes and energy savings (EST, 2006) (motivational interventions are discussed further in Section 2.3).

2.2.3.3. Household characteristics

The Western European survey reported that in the UK, 42% surveyed identified laziness as one of the reasons for their careless energy wastage, 18% surveyed recognised their lack of awareness of their inefficient energy habits, and13% surveyed admitted to a lack of consideration for the environmental impact of their habits (*ibid.*). While the survey did not reveal how it was conducted or analysed, it illustrated the point that habits can have an impact on how efficiently or inefficiently energy is used in the house. However, a household’s ability to make efficient use of energy may also be affected by many external, social and personal factors as discussed so far in this chapter. It is particularly important to consider these factors as they may become extraneous variables that influence the outcome of research. This section focuses on household characteristics, which are contextual and may shape households’ opportunities and affect energy use.

It is worth noting in advance that research investigating the effects of socio-demographic and -economic variables on energy use has yet to come to an agreement, largely due to cross-country differences and the multifaceted drive that leads individuals to undertaking efficient energy-use behaviours. Nevertheless, age, gender, household size and composition, income, and personal views on energy-efficiency interventions and environmentally-friendly activities have been associated, to some extent, with household energy consumption.

Age seems to be a factor influencing energy use with mixed findings. The web-based survey mentioned in Section 2.2.3.2 that collected over 9,000 responses in nine OECD countries on electricity consumption and environmental concern reported that older people appeared to have a higher level of environmental concern, as well as an increased probability of performing energy-saving curtailments, than younger people (Urban and Ščasný, 2012), echoing findings of some earlier studies (e.g. Mansouri *et al.*, 1996). In contrast, age was suggested to have a weak link to energy-saving behaviours by several other studies (e.g. Straughan and Roberts, 1999; Hori *et al*., 2013), and negative correlations between age and retrofitting energy-efficiency interventions, and between age and energy-conservation knowledge were found, even if households with elderly members placed greater importance of energy savings for financial reasons rather than environmental concern (e.g. Mills and Schleich, 2012). This may be argued that a shorter expected remaining lifetime results in a lower level of willingness to pay for energy efficiency, despite the fact that the elderly understand the relationship between energy efficiency and financial savings in the long run. Households with younger heads, particularly with young children, appear to be related to investing energy-efficiency improvements and adopting conservation behaviours (Dupont, 2004) possible due to parents being concerned about environmental effects influencing current and future wellbeing of their children (Mills and Schleich, 2012).

Males are generally less concerned about the environment (Urban and Ščasný, 2012), while females seem to make more energy-conscious efforts and are more interested in receiving energy-related information (Mansouri *et al.*, 1996). Although females may consider more about energy efficiency, males are more likely to focus on technological innovations, accessories and functions; therefore, it is more probable to successfully persuade males to consider energy efficiency if emphasis is placed on the association of quality and economic aspects (Gaspar and Antunes, 2011).

Household size and composition appear to be positively correlated with energy consumption and energy-efficiency investment. The more adults in a household, the more energy is consumed (Wyatt, 2013), but, like the effect that the presence of children has, a greater possibility of installing energy-efficiency interventions and adopting energy-conservation practices for energy-saving and thermal comfort reasons (Mills and Schleich, 2012; Urban and Ščasný, 2012). In terms of per capita energy consumption, on average it is more efficient in energy use in a household with more people sharing (Druckman and Jackson, 2008).

As discussed previously in Section 2.2, household income status can affect energy consumption. Being financially disadvantaged can be a barrier and may be in conflict with personal interest in becoming more efficient with energy use. Expenditure associated with the installation of energy-efficiency interventions and with the purchase of appliances with higher energy-efficiency rating is often cited as the main reason for households holding back from making energy-efficiency investment (Yohanis, 2012). Less well-off households may heat less and adopt reduction strategies, because they already spend larger portions of their incomes on energy bills (Druckman and Jackson, 2008; Cayla *et al*., 2011), while households with higher incomes tend to have higher energy consumption (Poortinga *et al*., 2004; Sardianou, 2007; Summerfield *et al*., 2007), sometimes regardless of age (Brounen *et al*., 2013).

Although affluent households are often related to higher energy consumption, they appear to show higher levels of interest in receiving information related to energy consumption and the environment (Mansouri *et al.*, 1996) and willingness to invest in energy-efficient interventions and appliances, which have been argued as fast, convenient, relatively cheap ways to reduce significant energy use (Urban and Ščasný, 2012; Yohanis, 2012; Wyatt, 2013). Even so, it is not clear if high-income households are more likely to curb their energy use by undertaking fuel-saving activities (e.g. Mansouri *et al.*, 1996; Urban and Ščasný, 2012).

Dwelling type and tenure have also been found to be associated with affluence and energy consumption. Wealthier households are more likely to own the property they live in, and the dwelling type is like to be detached town or country houses which have larger floor areas and more exposed external walls compared with semi-detached and end-of-terrace properties, as well as purpose-built and privately rented properties. As a result, households living in owner-occupied properties tend to consume more energy, per dwelling (Wyatt, 2013). It is unclear whether high-income households living in small owner-occupied properties use more or less energy than households living in larger rented properties. In comparison, social rented properties tend to be smaller than privately rented properties. Wyatt found that council housing and housing association homes have the lowest energy consumption, possibly due to smaller floor areas and lower household incomes that limit households' ability to spend on energy.

The links between education and undertaking energy-saving activities, and between education and adopting energy-efficient interventions, are mixed, particularly in cross-country surveys (e.g. Urban and Ščasný, 2012). Nonetheless, education generally has a positive effect on environmental and energy-use knowledge, and on making more rational decisions on making energy-efficiency investments (Mills and Schleich, 2012; Brounen *et al*., 2013).

There are mixed observations regarding the effects of environmental awareness and concern for saving energy, and they have been suggested to be independent motivations from cost and convenience factors. Concern for the environment and the impacts of global warming may motivate performing energy-saving curtailments and investing in energy-efficiency retrofits (Urban and Ščasný, 2012), but may be less so in countries with abundant natural resources (Hori *et al*., 2013). On the other hand, much of past findings suggests that the claimed environmental consciousness and energy-use literacy do not always lead to making associated efficiency investments, undertaking conservation behaviour, or an actual understanding of home energy conservation (Geller, 1981; Costanzo *et al*, 1986; Egan, 1999; Abrahamse *et al.*, 2005; Anderson and White, 2009; Yohanis, 2012; Brounen *et al*., 2013). This phenomenon is largely reflected in the UK (Witherspoon, 1994), but households do show willingness to change their behaviour in order to reduce energy consumption and environmental damage (Mansouri *et al.* 1996), provided that regular feedback on energy consumption is given (Hargreaves *et al.*, 2010).

Lastly, subjective views on energy-saving interventions and related curtailment behaviours can potentially influence energy use in the house. Studies have found that not every member of the household is equally interested in adopting more efficient behaviours – some may not see energy efficiency in terms of benefit, but rather as sacrifice to comfort (Anderson and White, 2009; Hargreaves *et al*., 2010, 2013). Studies have also suggested that subjective views on the design of energy monitor displays can influence the effect of feedback shown on the display on energy use and how householders interact with these monitoring devices (discussed further in Section 2.5).

2.3. Interventions to motivate behavioural change

The previous sections have demonstrated that differences in human behaviour, individual characteristics and context can significantly affect energy use. This is probably why many studies have supported deploying interventions in combination rather than separately for greater effectiveness (e.g. van Houwelingen and van Raaij, 1989; McCalley and Midden, 2002; Abrahamse *et al.*, 2005), although steps need to be taken to exclude possible confounding effects when using multiple interventions. A way of reducing the possible confounding variation is to use a repeated-measures design (see experimental approach using repeated-measures design in Section 3.4.4). In addition to testing each intervention on the same group of study subjects, each intervention should be tested systematically with and without the presence of the other interventions, so that the effect of each intervention can be studied and interaction effects can be found.

Whether people address their energy-use behaviour for personal reasons or as a result of social influence, they are more likely to change their habits or maintain efficient energy behaviours with the provision of constant motivation and the support of skills or resources if needed (Mansouri *et al.*, 1996, McMakin *et al.*, 2002, Darby, 2006). To date, interventions to promote sustainable behaviours have achieved energy savings with varying degrees of success (Abrahamse *et al.*, 2005). This section focuses on the interventions that were used in the research work.

2.3.1. Antecedent interventions

Antecedent interventions are used to influence underlying behavioural determinants (e.g. attitudes) prior to the performance of behaviour. They include the provision of information, setting a goal to achieve within a timeframe and staying committed to it, and offering incentives. Information and goal-setting were not used in this research in order to minimise pre-study effort from participants, which might be seen as undesirable, but giving financial incentives was suitable in this case to stimulate interest in participation (incentives used in the research studies are discussed further in Section 3.5.2).

2.3.1.1. Incentives

Incentives are often used as an antecedent motivation by the government and energy suppliers to encourage people to save energy in the longer term through behavioural change (Darby, 2000, 2006, 2008; Roberts *et al.*, 2004; Ofgem, 2010). They are given in the form of associated status and convenience, and financial benefits, such as tax credits, rebates, free energy-efficiency devices (Martiskaïnen, 2007; Froehlich *et al.*, 2010; Zhao *et al.*, 2012). Incentives have been shown to support sustained interaction and reductions in energy consumption during the study period (e.g. Jain *et al.*, 2012 (6 weeks)), but their aftereffects may be short-lived (Darby, 2000; Martiskaïnen, 2007; Froehlich, 2009), as new habits and interest may fade away when the incentive is taken away. While some studies did not find financial incentives provide sufficient motivation for people to adopt more efficient energy behaviours (e.g. Pierce *et al*., 2008; Dietz *et al*., 2009), others have introduced non-financial incentives. For example, Petersen *et al*. (2007) used ice-cream party as a prize to stimulate resource conservation in college student residences, and Gustafsson and Bång (2008) used pervasive games connected to the player's own energy consumption to encourage reductions, both found their approaches to be effective in motivating behavioural change.

2.3.2. Consequence interventions

Consequence interventions are given to influence behavioural determinants after an event or action. This research primarily investigates the implications of consequence interventions using feedback, comparisons and rewards for energy consumption in the field-based study (Chapter 5).

2.3.2.1. Feedback

The terms "information" and "feedback" are often used interchangeably in the literature, both with the aim of changing behaviour. However, "information" can be more formally defined as an antecedent measure. It provides general information about certain energy-related problems, and/or possible solutions, such as energy-saving tips, and serves to increase individuals' awareness of the problems and their knowledge about possibilities to reduce these problems (Abrahamse *et al.*, 2005). This is based on an assumption that people would act in more environmentally beneficial ways if they had better information that influences their knowledge, which in turn influences their behaviour (Froehlich *et al.*, 2010).

On the other hand, "feedback" provides a consequence that is contingent on the outcome of the behaviour (Abrahmase *et al.*, 2005). Feedback presents opportunities to people for checking their knowledge against reality, modifying and building their knowledge of the world (Darby, 2000). Therefore, feedback fosters learning (Hutton *et al*., 1986; van Houwelingen and van Raaij, 1989). Instead of telling people how to save energy, it teaches them how to manage energy use by showing how much energy they are already using (Darby, 2009), and by giving them an opportunity to learn from their action, as saving energy is a form of conscious, environment-related behaviour as discussed previously in Section 2.2.2. Thus, providing an environment of constant feedback may help to link people's daily lives and specific needs to their general sense of the environment (e.g. home). Further, a new habit is likely to form if it is supported by continuous, long-term feedback for a durable effect (van Houwelingen and van Raaij, 1989; Darby, 2006; Fischer, 2008).

Research has found that feedback is probably best given through immediacy and accessibility to enhance opportunities for improved understanding and/or behavioural change (Roberts and Baker, 2003). Therefore, it might be reasonable to assume that providing useful energy information (kWh, cost, suggestions on how to avoid waste etc.) instantaneously, or near instantaneously, with as little manual or physical operation required as possible, will raise householders' awareness and, hopefully, prompt behavioural changes. The idea here is that through giving feedback information, householders learn what consequences their current energy-consumption behaviours will have, they will then put what they learn into practice and eventually develop a routine that leads to lower energy use (van Houwelingen and van Raaij, 1989). It might be reasonable to hypothesise that feedback will be more effective than information as it more concretely links a person's behaviour to its consequences, rather than operating on an abstract level and leaving it to the end-user to form links between behaviours and their consequences.

Research has shown that feedback can indeed have an influence on energy savings, if it is given promptly, frequently (van Raaij and Verhallen, 1983, Darby, 2000), over a long period (Henryson *et al.*, 2000), and depending on the type: direct feedback, indirect feedback and inadvertent feedback (after Darby, 2000).

Direct feedback gives immediate consumption data either from meter-reading (e.g. Winett *et al*., 1979) or electronically displayed feedback. The process of learning might be facilitated by providing regular feedback rapidly and constantly, which can be delivered by energy monitoring devices with perceptible outputs from free-standing displays (e.g. Hutton *et al.*, 1986). Accordingly, in the UK, Brandon and Lewis (1999) found that computerised feedback which immediately made fuel use more visible resulted in the largest energy savings compared with five forms of printed information. A range of other studies (e.g. Darby, 2000; McCalley and Midden, 2002; Fischer, 2008) conducted after Brandon and Lewis' work similarly supported the idea that immediate, visible feedback is effective in reducing energy use (energy displays as a means of direct feedback are reviewed further in Section 2.4). This demonstrates that information can be made available on demand; therefore, learning is made possible by looking (Darby, 2000).

Indirect feedback includes improved billing with data that have been processed before reaching the energy user (*ibid.*). In an informative billing study in Norway, households received frequent electricity bills (frequency increased from typically once a year to six times a year) based on actual meter readings rather than estimates, and comparative feedback for showing consumption trend in the same time of the previous year in addition to total consumption and cost, plus a guide explaining breakdown between end uses and which were the highest energy consumers. As a result, householders started to read their bills more frequently with a better understanding (Wilhite and Ling, 1995). This shows that indirect feedback makes learning possible by reading and reflecting (Darby, 2000).

Darby (*ibid.*) refers inadvertent feedback to learning by association. For example, homeowners may associate their homes as sites for generation and consumption of power by observing energy use and achieving savings from micro-generation (e.g. the installation of photovoltaic panels). Another example is the development of community projects on energy conservation that involves social learning (e.g. Nye and Burgess, 2008; Staats *et al*., 2004). This kind of feedback may present an opportunity for a shift in thinking and may have longer-term effects. Consequently, it is not as immediate as direct and indirect feedback.

While each feedback measure can result in energy savings, a greater effect might be achieved when they are combined and then provided continuously (Darby, 2006). For example, the European Union requires that energy bills be based on actual use, historical and benchmark comparisons of energy use and current energy cost, and be provided ‘‘frequently enough to enable customers to regulate their own energy consumption’’ (ESD, 2006). While the optimal level of billing frequency is not explicitly defined, in-home energy displays can provide continuous and real-time feedback on energy consumption to consumers to fulfil the regulated obligation on European utilities (Faruqui *et al*., 2010).

Whilst past research has indicated that providing households with feedback is an effective intervention for reducing energy consumption (Abrahamse *et al.*, 2005; Fischer, 2008), the desired effect of feedback can be affected by the way in which feedback is delivered, hence the type of feedback, and the quality of information provided (discussed below), making the resulting range of savings subjected to the context (Darby, 2006). Moreover, existing knowledge of energy conservation (e.g. Hutton *et al*., 1986), misconceptions of energy use (discussed in Section 2.2.3.1), characteristics of feedback, including the provision of a time-, room- or application-specific breakdown and contents of feedback information (discussed further in Section 2.4.1), and personal preferences for the presentation of feedback (discussed further in Section 2.5) may also influence the effect of feedback.

As demonstrated earlier in the Norwegian study on improved billing, the quality of feedback could be enhanced by increasing the frequency of feedback provision. Accordingly, after reviewing 23 studies incorporating the feedback intervention, Abrahamse *et al*. (2005) suggested that the more frequently feedback is given, the more effective it is – households receiving monthly feedback (Hayes and Cones, 1981) or continuous feedback provided by display devices (McClelland and Cook, 1979) used less energy than the control group, and those who received daily feedback used less energy than those who learnt to self-read meters (Winett *et al*., 1979). This implies that frequent feedback increases people's trust in the accuracy of their energy consumption data, which can potentially stimulate interest and act as a regular reminder to householders of saving energy and maintaining their efforts to achieve a goal.

Providing feedback alone may sometimes not be sufficient for savings and raising awareness, nor effective enough to prompt desired behavioural changes (Darby, 2000; Abrahamse *et al.*, 2005), as householders may initially respond to the feedback provided due to novelty or enthusiasm, then lose their interest over time (Faruqui *et al*., 2010). Although results from many studies have been mixed (Fischer, 2008), there is evidence that feedback information might work better when used in combination with other motivational interventions than on its own (Midden *et al*., 1983; McCalley and Midden, 2002; Fischer, 2008), as different interventions may address different barriers that prevent households from taking action. For example, households that are financially disadvantaged may find feedback given in conjunction with monetary rewards more attractive than feedback combined with emotional rewards (further discussion on rewards in Section 2.3.2.3). In other words, setting goals for reducing household expenses on energy may be more motivating for them than invoking a sense of social commendation.

Despite the positive view on feedback being a catalyst for initiating energy awareness, bridging concern and action, and motivating behavioural change (Darby, 2008a; Faruqui *et al.*, 2010), there are instances where exceptions exist and feedback is likely to be completely ignored. Certain activities and aspects of lifestyle practices are seen by some householders as non-negotiable, such as medical conditions and the pursuit of comfort, who are thus unable to change their behaviour still further or at all (Hargreaves *et al.*, 2010). They either see these activities and the associated usage of appliances as necessities that they have very little control over, no matter how energy consuming they are, or accept that there is only so much they should be expected to do and still have a reasonably comfortable home environment, unless significant financial incentives are on the offer. This aspect of energy use should be considered when assessing the efficacy of feedback, as it will have an impact on people's willingness to implement changes in their energy-consumption behaviours.

2.3.2.2. Comparisons

Comparisons can be self-relative (a person's current behaviour is compared with their past behaviour) or other-relative (a person's behaviour is contextualised with other people's behaviour). Research has suggested that information that allows comparisons to take place will be particularly effective in facilitating behavioural change (Wood and Newborough, 2007a). According to social learning theory, behaviour is learnt from the environment through the process of observational learning (Bandura, 1977). Accordingly, internal factors (attitudes, beliefs, preferences) are influenced by learning from past experiences (trials, errors) and other people's (families, friends, colleagues, neighbours) behaviour and their responses (Jackson, 2005). It is possible that providing information about one's historical consumption and other people's consumption can help one learn about energy use and devise energy-saving tactics. Such comparative feedback helps people evaluate their energy consumption against their own or against other people's, and the effects of self- and other-relative feedback are suggested to be subject to the setting and situation (Roberts and Baker, 2003). In short, an effective comparison works by having meaningful points of reference (further discussions on comparisons in Section 2.3.2.2 and on user's response to comparative feedback in Section 2.5.3).

Self-relative feedback, or historical feedback, enables householders to learn about their energy consumption from comparing between appliances, time periods (past, current, projected), rooms and activities (Wood and Newborough, 2007a), alter their behaviour and adjust appliances' operating periods. This kind of feedback is most disaggregated (Roberts and Baker, 2003) (disaggregation is discussed further in Section 2.4.1.2). Although self-relative feedback with historical data has successfully been correlated with reductions in energy consumption (e.g. Jain *et al*., 2012), currently little research has been done to explore which types of comparison are most effective in influencing behaviour.

Other-relative feedback, or normative feedback, is given in conjunction with self-relative feedback by contextualising self-historical consumption in relation to others (*ibid.*). A number of previous studies have found that high and medium energy users are more likely to reduce their energy use when given other-relative feedback, while low energy users are likely to increase it (Bittle *et al*., 1979–1980; Brandon and Lewis, 1999; Fischer, 2008), possibly due to the rebound effect. Research has also shown that low-income groups are less likely to make further reductions in energy use in the presence of comparative feedback, and so are those who consider themselves frugal (e.g. Mansouri *et al*., 1996; Brandon and Lewis, 1999). The latter's situation may be explained by users' knowledge about energy-saving possibilities that already exists. For both groups, without motivation to save additional energy, comparative feedback on how well one performs will be useless (Fischer, 2008).

Although self-relative feedback is commonly used in comparative studies and may be a useful tool to achieve energy savings (*ibid.*), other-relative feedback involves social norms that can be a powerful motivator for behavioural change (Froehlich, 2009). A study investigating the effectiveness of social normative influence found that hotel guests who were given descriptive normative information, which informs individuals of how most people behave in a given situation, about towel reuse activity of other hotel guests increased their towel reuse rate by 44% compared with those who were not given the information (Goldstein *et al*., 2008). This suggests that hotel guests were persuaded to conform to social norms by modifying their behaviour to match the towel reuse activity of their fellow hotel guests. Peer comparisons can also stimulate a sense of competition, which may provide considerable motivation for curbing energy use comparable to others. For example, a number of studies examining comparative feedback found that participants who were given feedback on both their energy-use behaviour and their peers' used less energy than those who only received feedback on their own performance (e.g. Peschiera *et al*. (2010) on energy use in university student residences), the effect continued even after half a year after the intervention, and the behaviour was altered with hardly any changes in attitudes or intentions (e.g. Siero *et al*. (1996) on industrial energy use). Another feedback study involving monitoring resource consumption and a competition between college student residences achieved a substantial 32% reduction in electricity use compared with the baseline consumption (Petersen *et al*., 2007), suggesting the power of competition. This research intends to extend on this type of study design in a university student residence setting to see how other-relative comparisons work in the design of energy displays (see Chapter 5).

One of the problems with this type of intervention is that although people are interested in seeing comparisons, they do not necessarily make savings when shown to them (e.g. Haakana *et al.*, 1997; Egan, 1999). This may be due to the information deficit, as mentioned in Section 2.2.1.1, that attributes scepticism towards the accuracy of the information provided on comparisons, resulting from a lack of knowledge about the relevant subjects. Providing more information on the subject may not necessarily overcome the problem, instead, an opposite effect might happen where the information overload causes a loss of interest.

Another complexity of using comparisons is that when a performance plateau is eventually reached, any further emphasis on improving an individual's performance or the performance of others may not be effective (Froehlich *et al*., 2010), which points to the need to devise ways to motivate additional energy savings over and above those that have already been achieved.

2.3.2.3. Rewards

Rewards are known to motivate behavioural change. They are usually offered after a behaviour and can take various forms. Emotional rewards, such as enhanced self-esteem, could prompt people to carry out actions for the good of society (EST, 2006; Wood and Newborough, 2007a), even in the absence of financial incentives (McMakin *et al*., 2002). Monetary rewards are in the forms of either direct payments to save energy, or financial savings accrued from reducing energy use. Comfort is another form of reward for people to undertake efficient energy-use behaviours, (Mansouri *et al.*, 1996). It is possible that people choose to put comfort above financial savings gained from energy-saving measures like the installation of wall insulation or draught-proofing (Becker *et al.*, 1981).

Sometimes rewards might be outweighed by incentives. For instance, people may choose to purchase cheaper but less energy-efficient appliances in order to gain cost-saving benefits, even if they have a high level of environmental concern or knowledge of how to save energy (Roberts *et al.*, 2004). Financial incentives in this instance have direct and immediate effects at the time of the event, which make them more attractive than rewards. Moreover, even though emotional rewards could entice people to act in more environmentally responsible ways, there is little evidence that being a “good environmentalist” would lead to reductions in energy consumption, thus it may not be easy to change behaviour by simply presenting positive social approval to people in any mode of feedback presentation, such as through IHDs (Wood and Newborough, 2007a).

Like incentives, the effect of rewards may not be long-term (McClelland and Cook, 1980; Slavin *et al*., 1981, Dwyer *et al*., 1993; Geller, 2002). Consequently, some studies incorporating rewards in their design to encourage efficient behaviours also included penalties to discourage wasteful behaviours (e.g. Holland and Mansur, 2008). Indeed, the use of both positive and negative feedback is likely to yield gains in performance (Kluger and DeNisi, 1996); therefore, it is reasonable to assume that combining interventions is an effective approach to achieving behavioural change.

Nonetheless, it appears that there is still a need for further research on sharing energy information with building occupants to reduce energy use without financial incentives or rewards, as this is often the case in institutional, hospitality and many commercial buildings (Peschiera *et al*., 2010).

Successful interventions that users are motivated to implement or include in their daily lives require clear and specific information and advice without adversely affecting lifestyle or financials, and preferably come from a trustworthy source (Mansouri *et al*., 1996; Roberts *et al*., 2004; Martiskaïnen, 2007). While making energy use visible is one step closer to making energy savings, people also need to understand the feedback information provided, be able to interpret it and be willing to take actions based on informed decisions. Without feedback, it is impossible to learn effectively (Darby, 2006). Therefore, the research looks at how to provide feedback and how it stimulates energy savings.

2.4. In-home displays as a means of direct feedback

Generally, the effectiveness of feedback is enhanced when it is given immediately after an action has taken place (van Houwelingen and van Raaij, 1989; Abrahamse *et al*., 2007). Accordingly, the literature is indicative of the potential of presenting electronic feedback information in the form of energy monitoring devices with direct digital displays at the time of use for achieving greater energy savings compared with paper-based feedback (e.g. Darby, 2000; Wood and Newborough, 2003; Fischer, 2008; Faruqui *et al*., 2010). Unlike paper-based feedback that tends to create a dislocated linkage[9] between specific activities and energy consumed (Brandon and Lewis, 1999), electronic monitoring devices have the ability to quickly process and feedback actual consumption data, and direct displays help people see live energy use and evaluate changes of their own progress against continuous real-time data by identifying specific uses of energy and modifying related behaviour. This way, electronically displayed feedback is provided immediately and continuously during an energy-using event, and could help to raise people's awareness and motivate energy-related behaviour. One of the downsides of such electronic feedback, though, is that it may be difficult to access for users who are not familiar with electronic media. Another drawback is that interactive tools require higher user involvement (Fischer, 2008), which may not be appreciated by some users.

All homes have an electricity meter and a gas meter indicating energy consumption. The meters are not traditionally designed as displays to encourage householders to monitor their energy use, and their displays are relatively crude (Wood and Newborough, 2003). The advancement of information technology and sensor systems has led to the development of computerised feedback systems that allow for cost effective and less intrusive acquisition of energy consumption data (Jain *et al*., 2013).

The display technology grew from the "first generation" of basic digital electricity displays that show electricity consumption instantaneously, to the "second generation" of displays that give historical usage, to the "third generation" of displays that are either integrated with smart metering systems linked to an energy supplier to deliver usage data, or provided as part of off-the-shelf energy monitors that usually consist of a transmitter to clip around the cable on the electricity meter and a wireless screen device to display electricity use (Darby,

[9] Researchers often use analogies to illustrate the blindness in consumption, e.g. when shopping in a store, customers do not know the prices of individual products at the time of purchasing, but only receive a total non-itemised bill at the end of the month (e.g. Stern and Aronson, 1984; Faruqui *et al.*, 2010).

2008a, 2008b, 2010). Direct displays are part the computerised feedback system and are a supplement to the energy meter. They generally have the option of expressing energy consumption in kW, cost or CO_2 emissions, and other functions such as displaying time, temperature, historical consumption for various periods, and alarms (AECOM, 2011). It is worth noting that currently displays are not usually integrated with the smart metering system outside the UK and Ireland.

Experiments on continuous feedback provided by an electronic monitoring device were first conducted in the 1970s and had positive results in conserving energy and increasing knowledge (e.g. Kohlenberg *et al*., 1976; McClelland and Cook, 1979; Allen and Janda, 2006). In comparison with previous research employing antecedent measures, the success of these experiments could be attributed to the ability of such devices that enabled the study to be implemented on a large scale without human intervention, in a less disruptive and more responsive manner, and in a variety of experimental settings (van Houwelingen and van Raaij, 1989).

Between the 1980s and 1990s, personal computers were used to display continuous energy information. For example, Brandon and Lewis (1999) found that among various feedback mechanisms they trialled, the installation of a computer served as a clear, visible reminder of energy consumption, which helped to reduce consumption most markedly and was highly appreciated by their study participants.

The availability of IHDs on the market in the 2000s means a step forward from the traditional sources of feedback on energy consumption, in terms of immediacy and interactivity (Darby, 2010). For example, Ueno *et al.* (2006) developed an interactive tool to provide daily feedback on energy use and price via personal computers, televisions and web-based portals. As a result, knowledge of energy-saving behaviours was increased and consumption of energy was decreased. In contrast to van Houwelingen and van Raaij's (1989) findings, the test group was interested in receiving energy information more frequently. However, the study yielded savings less than McClelland and Cook's (1979) basic electricity monitors did. This suggests that the advancement of display technology does not necessarily stimulate additional energy savings. Nevertheless, direct feedback like this evidently has an impact on behavioural change and the overall energy consumption.

Studies implementing direct real-time feedback reported electricity savings between 5% and 20% (Darby, 2000, 2006; Erhardt-Martinez *et al*., 2010; Foster and Mazur-Stommen, 2012). However, it is notable that studies reporting larger savings typically had small sample sizes. For example, Ueno *et al*. (2006) trialled nine Japanese households in their study and achieved a 9% reduction in electricity consumption. Similarly, Wood and Newborough (2003) trialled 10 UK households with a display directly attached to electric stoves to provide disaggregated feedback, seven of which achieved energy savings of greater than 10%. Darby (2010) reviewed 13 studies involving clip-on monitors (sample sizes varied from 10 to about 50,000) with seven of them (sample sizes varied between 10 and about 100) achieving between 12% and 18% savings against controls. In contrast, the remaining six studies reported savings of between 2% and 6% with a larger sample size (about 20 to about 50,000), echoing findings from the recent Energy Demand Research Project (EDRP, 2007-2010).

The EDRP study was one of the early trials conducted in the UK before the Government announced its plan in 2009 to roll out smart metering with free-standing visual displays showing real-time information on electricity consumption and cost to all households by 2019. It focused on trialling a range of methods[10] for providing feedback on energy consumption in over 60,000 households. The EDRP findings generally supported the literature that providing a real-time display brings about a 2-3% reduction in energy consumption, where

[10] The methods (deployed both standalone and in combination) included smart meters, real-time displays, informative billing, written information on energy saving tips, community engagement, incentives to reduce or shift consumption, alarm and "traffic light" messages, meter reading and heating controller.

effects on electricity consumption were clearer than gas consumption when combined with smart meters. The customer survey also showed that householders paid more attention to the display of electricity than to gas information, possibly due to the design of the push buttons to access the information, and that the presence of a display tended to result in more positive perception of the smart meter (AECOM, 2011). This suggests that advanced metering can stimulate energy savings and offer an opportunity to facilitate feedback, which can be improved if deployed with real-time displays (Darby, 2008b).

One reason the EDRP found such small changes in energy use might well be that the design of the energy display was not communicating information effectively to householders. This research, therefore, aims to refine the findings on direct displays by optimising their design, and examines the effectiveness of different types of display for making changes in energy use easily visible to users. This is done by systematically comparing different display designs and measuring the speed and accuracy with which people could spot changes in the information provided. Users' subjective feedback on the different designs is also assessed (see Chapter 4).

2.4.1. Feedback information

As discussed in Section 2.2.3.1, the primary sources of feedback for households on their energy consumption are their energy meters and bills, which only provide a very limited amount of information. Given that computerised feedback systems are able to display more information options than energy meters and bills can, Roberts and Baker (2003) categorised the types of potential information as follows:

- Real-time consumption information that provides immediate feedback for householders to monitor their consumption on an ongoing basis.
- Comparative consumption information that provides either self-relative feedback on a household's historical consumption or other-relative

feedback on a household's consumption compared with other households that have similar characteristics.

- Disaggregated consumption information that provides feedback on consumption in relation to different end uses in the house.
- Tariff, load-management, or time-of-day cost information that enables householders to identify when they could save money by reducing consumption.

Wood and Newborough (2007a) suggested a broader range of additional information, and design aspects, that could improve feedback, as illustrated in Figure 2.8.

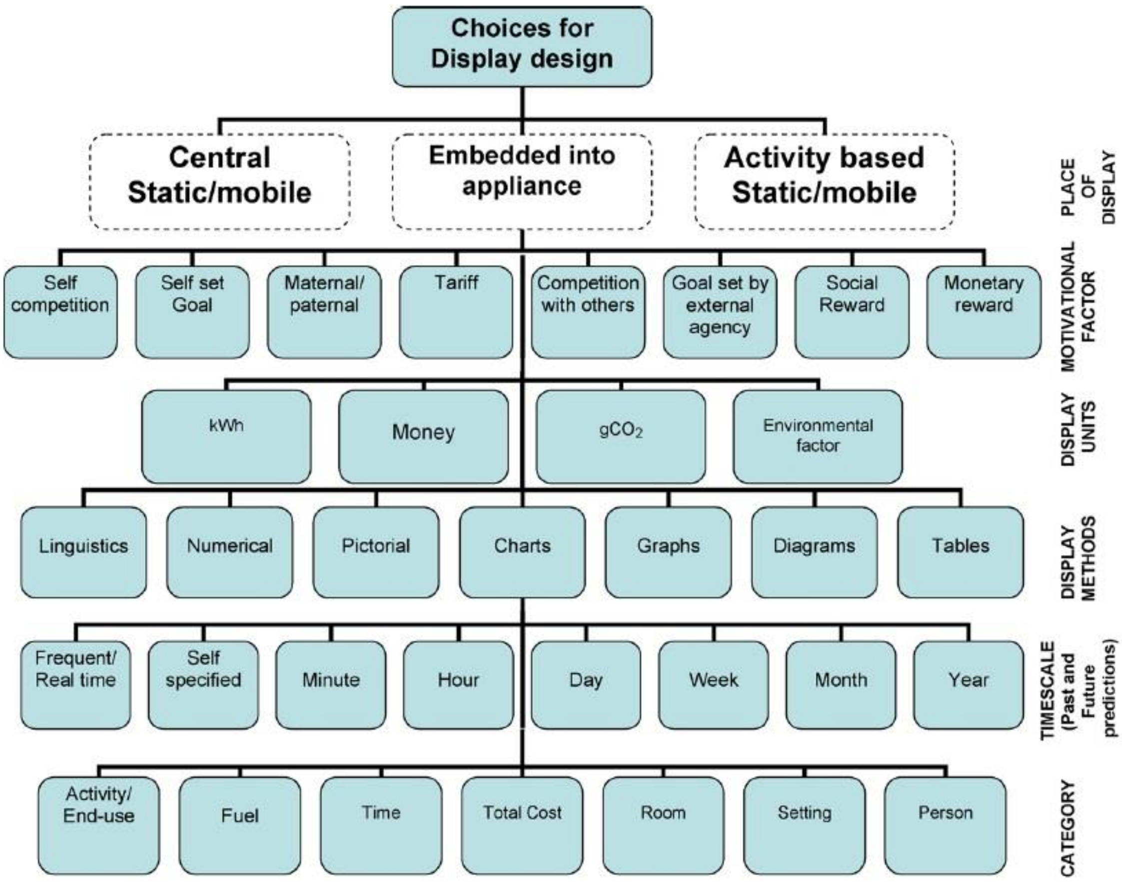


Figure 2.8. Factors influencing the IHD design (Wood and Newborough, 2007a)

Although there are a large number of studies in the literature on feedback and display design, it is difficult to compare directly and identify which types of information have the most motivating impact on household energy consumption. Numerous reviews also faced the same problem (e.g. Roberts and Baker, 2003; Fischer, 2008) that many of the studies are heterogeneous in terms of study design, information type, trial period, baseline, treatment and control, intervention and presentation technique, instead of testing one approach at a time to isolate the effect.

2.4.1.1. Representative unit

Following on from the previous paragraph, there are no clear answers yet to what the most appropriate, effective representative units are for driving actual reductions in energy consumption. As representative units may dictate the comprehension, importance and relevance of energy use to various terms, such as the associated environmental and financial costs (Wood and Newborough, 2007a), different units potentially activate different motives, as well as personal and social norms, although it remains an open question to find which motives and norms would be the strongest in which population groups in society (Fischer, 2008).

Gaining both financial and comfort benefits is often the main motivation for households. Providing feedback on this might help convey the message that it is possible to save energy and money without compromising comfort (Martiskaïnen, 2007). While Anderson and White's (2009) finding of "Everybody understands money" essentially sums up the impact and effectiveness that cost-related information has on energy use, consumption presented in cost units can be misleading as discussed in Section 2.2.3.1, and there are instances where load-shifting, rather than energy savings, is stimulated. In a study conducted by Sexton *et al*. (1987), real-time electricity-use monitors providing projected bills and continuous feedback on a tariff structure where consumption costs differed vastly during peak and off-peak demand periods led to a significant shift of activities to off-peak hours (typically between 9 p.m. and

7 a.m. (DECC, 2014i), thus cancelling out the savings made in peak hours. Time-varying tariffs have been shown to improve demand response and provide for smoother load profiles and greater electricity grid stability (Faruqui *et al*., 2010), and are especially important for households whose goal is to reduce energy costs. However, many consumers in the UK are on unrestricted flat-rate tariffs. Even if saving money is the primary motivator, the financial savings associated with individual energy-saving actions will be small in relation to household income and other household costs, which could carry the risk of perceiving energy use as trivial and inconsequential; therefore, monetary units may be unhelpful to motivate householders to maintain efficient use of energy (Wood and Newborough, 2007a; Krishnamurti *et al*., 2013).

On the other hand, not everyone is particularly energy literate with a good understanding of the energy and power units in relation to energy-use activities (Mansouri *et al*., 1996; Karjalainen, 2011; Bonino *et al*., 2012), and householders may not have direct control over the energy consumption of an appliance or task, such as during a cooking event (Wood and Newborough, 2003). Householders may be familiar with their energy bills showing kWh for their electricity and gas consumption, they still need a better understanding of energy units, so that when feedback indicates consumption in kWh for example, it may bring in a sense of trust in the data due to its scientific basis (Wood and Newborough, 2007a).

The level of familiarity with the environmental consequences of GHG emissions associated with energy consumption is probably even lower than with energy units for most people. Without a good amount of knowledge about the environmental impact of energy consumption, units like gCO_2 or $kgCO_2e$ are likely to be seen as difficult to understand (Fitzpatrick and Smith, 2009; Vassileva *et al*., 2012). Therefore, units representing the environmental effect should best be accompanied with other comparative, representative units to give an idea of relative impact levels. A few studies have attempted to increase comprehension of environmental units by representing energy consumption in terms of the "number of trees" needed to mitigate the associated CO_2 emissions as an alternative. For example, a decrease in consumption was reported when environmental units were presented in equivalent number of trees, compared with an increase in consumption when feedback was given in kWh (Jain *et al*., 2013). The results corroborated similar findings by other recent studies (e.g. Holmes, 2007; Petkov *et al*., 2011) that also supported the potential of the alternative metric of trees for reducing energy consumption. These studies may help inform the results of earlier research which did not find any clear evidence to answer the question of whether it makes a difference to give feedback in terms of monetary units and/or energy units rather than environmental problems (e.g. Bittle *et al*., 1979-1980; Brandon and Lewis, 1999), and suggest that relating energy use to commonly known objects is a helpful way for people to visualise energy consumption better than relying on what energy cost or the abstract scientific units of kWh or CO_2 might mean to people. More research is still needed to investigate whether environmental information alone is as effective as other types of information.

Currently, it is difficult to estimate environmental effects and to display their contributions to global warming accurately. For example, CO_2 emissions associated with fossil fuel burning of electricity vary with geographical location due to the design and efficiencies of electricity plants and networks, and vary with time of day due to their higher intensities during peak demand periods than during off-peak periods. One option for overcoming this, suggested by Wood and Newborough (2007a), is to utilise nationally agreed carbon-intensity factors for electricity and gas. Despite these difficulties, Wood and Newborough (2003) optimistically pointed out that these units have an educational value, particularly when people become more "carbon aware" and for those who are interested in assessing the effect of their activities on the environment. Thus, these units should not be excluded from the display, and new, more effective means of presenting them should be explored.

2.4.1.2. Disaggregation

While energy meters and energy bills can only show a household's total consumption, advanced meters can show disaggregated feedback that breaks down energy use to end-use-, appliance-, time- and room-specific levels for comparisons, providing useful information on when and where most energy is used by what appliance, so that householders can modify related behaviour. The credibility of disaggregated feedback relies on the educational effect of raising awareness of the relative demand from different appliances (Darby, 2006), that can help people understand the relevance of individual actions so that they can learn to make informed decisions about their energy consumption (Karjalainen, 2011). With the advancement of smart metering technology, it should be technically viable and financially feasible in the near future to provide disaggregated feedback by end use at the electricity meter on a large scale. Currently, simple portable plug-in monitors (e.g. Figure 2.9) can serve the same function of providing detailed electricity consumption of an appliance at a time.

Figure 2.9. Portable plug-in energy device

More advanced monitors also work at a localised level like the plug-in ones, but have the additional ability to connect to other monitoring units and allow for remote access via internet (e.g. The Ploggs, see Figure 7.3). A number of studies achieved disaggregation by installing individual sensors on appliances (e.g. Jacucci *et al*., 2009; Grønhøj and Thøgersen, 2011), but the common problem was the logistical difficulty in installing and maintaining individual sensors in residential settings (Jain *et al*., 2012). There have been incongruent findings regarding the disaggregation of feedback, with some studies showing a good indication of the potential usefulness of detailed, appliance-specific data for achieving energy savings (e.g. McCalley and Midden, 2002; Ueno *et al*., 2005; Fischer, 2008) and some remaining in doubt (e.g. Jain *et al*., 2012; Krishnamurti *et al*., 2013). While there still lacks sufficient evidence to date to support for the effectiveness of disaggregated feedback in engendering persistent reductions in energy consumption, a recent study showed that appliance-specific information was strongly appreciated (Karjalainen, 2011). This might well be attributed to the sense of control people would like to have and the direct link that could be made of between changes in behaviour and the outcome.

2.4.1.3. Duration

There is no clear evidence that providing long-term feedback will result in larger energy savings than short-tem feedback. However, in a study reviewed by Fischer (2008), electricity consumers received a one-time supplement to their annual bills that provided comparative feedback and energy-saving advice, it was seen as not prominent enough to attract attention and too weak to link to concrete actions to help enhance consumers' control over their consumption (Dünnhoff and Duscha, 2008 in Fischer, 2008). On the other hand, the Norwegian study mentioned earlier in Section 2.3.2.1 that tested the effect of frequent informative billing on electricity consumption achieved an average of 10% savings relative to the control group, and the savings held steady over the three-year course of the study (Wilhite and Ling, 1995). Therefore, it might be reasonable to assume that when feedback is given over a prolonged period, new energy-conscious habits could be formed during that time, and so savings are more likely to be made.

2.4.2. Display design

Although there is a lack of findings to indicate what representative unit is most effective in driving reductions in energy consumption and whether feedback information on real-time energy display is better presented in numerical, graphical or textual format, design principles can be drawn from general human-computer interaction guidelines. For example, Smith and Mosier (1986) created a set of guidelines for designing user interface software. Those that are relevant to the design of energy displays are summarised as follows:

- Display data in a directly usable form; do not make users convert displayed data.
- Display data consistently with standards and conventions familiar to users.
- For displayed data and labels, choose words carefully and then use them consistently.
- Provide a clear visual definition of data fields, so that the data are distinct from labels and other display features.
- When information handling requires a detailed comparison of ordered sets of data, adopt a tabular format for data display.
- Consider graphics rather than text description or tabulation, to display data showing relations in space or time (for example, trends).

Research studying the layout of energy bills can also offer some insight into feedback design that has been found to operate best in an understandable and appealing way. For example, Roberts and Baker (2003) found that simplicity in display design is important in the sense that the presentation can be simple but not simplistic to avoid people becoming distrustful of the information, and that a combination of text, diagrams and tables are more effective than single-format presentations. Fischer (2008) pointed out that overly complex tools requiring much of the user’s understanding, initiative action and time may not be ideal for users with low levels of literacy and technical interest and a busy lifestyle. Anderson and White (2009) added that details such as the representative units used, the number of features on the layout and the extent of information shown overall may also contribute to their “Keep it simple” approach in design. They also echoed some of the design guidelines proposed by Smith and Mosier (1986) for displaying computer data, who supported the effectiveness of graphical displays over numerical displays in better serving changing values over time.

The location of energy consumption feedback can be local, central or independent (e.g. web-based bills). Currently, local displays are either built into the appliance, or part of the monitoring device, showing individual sources of energy use. Central displays show energy consumption of all the relevant appliances and the relative rates of energy use. They are either fixed in position, or mobile to be hand-held. Portability was one of the key design issues raised in a study conducted by Anderson and White (2009) whose focus groups appreciated the display's mobility but only for a limited period of time. On the other hand, fixed displays should be placed in a well-frequented communal space of the house (e.g. living room, kitchen, hallway), so that they can be easily glanced at and be used as a point of reference.

Wood and Newborough (2007b) analysed how best to display consumption feedback at the points of use to observe the interaction between the user and the appliance, and the appropriate display location for different end uses. Ideally, feedback information should correspond with the appliance type and the associated activities. An appliance-specific display is best for appliances with controls in close proximity to the end use, so that the user can see all the energy-consuming sources with a quick glance. An activity-based display is best placed near an end-use activity to allow for comparisons between different appliances and to enable the user to adopt inter-appliance behaviours that consume the least amount of energy to complete the activity, such as washing hands with cold water instead of hot water. In order to avoid an overwhelming amount of information about energy consumption of many appliances being displayed at the same time, Wood and Newborough recommended having a dedicated display for each end use: heating, hot water, lighting and cooking. This method would, however, be expensive for most households to have several feedback devices. One solution is to have a permanent display, fixed or portable (e.g. a digital picture frame), of energy information with optional settings to switch interfaces between end uses.

For displaying the type of feedback information, Wood and Newborough (2007a) concluded that monetary units are more effective on central displays, as financial rewards for applying for an energy-saving behaviour would be too small to distinguish on local displays. Central displays with an overview of energy and cost data can be represented in a graphical form to show consumption and expenditure trends. Line graphs are most suited to show changes over time, while bar and pie charts effectively show values for different entities, such as appliances, for comparison (see analogue displays in Section 2.4.3). On the other hand, disaggregated numerical information is better for local displays to show even the smallest changes in information by end use. Further, information on local displays requires to be updated more frequently than central displays for constant inspection during an energy-using event.

Anderson and White (2009) proposed a minimum specification for IHDs that an indicator of current rate of consumption in power units and a rate of spend in a numerical monetary unit per day be included, as well as daily cumulative spend in a numerical monetary unit. If the display is designed to offer additional options of functionality toggled with dedicated button(s), it should include the historical rate of spend by day, week, month, and so forth, and the ability to switch between units, such as from pounds per day to kWh and vice versa.

Lastly, the UK Government's first Smart Metering Equipment Technical Specifications (SMETS 1) also attempted to address the question of how to present energy-use feedback more explicitly by including specifications for real-time displays intended for this purpose[11] (DECC, 2012a). The guidelines proposed that information about cumulative energy consumption and money

[11] The specifications document is currently in consultation stage for the development of its second version (SMETS 2). A draft version of these specifications was notified to the European Commission on 31 July 2014 (current draft version 1.58 dated 28 November 2014), so it remains to be seen how effective these will be after the smart meter rollout is complete in 2019.

related to tariff price and payment be provided in numerical form for both gas and electricity, and that the level of active power import be provided in ambient form to indicate the level as low, medium or high. Other information such as communications signal quality, historical energy consumption, local time and payment mode was not restricted to any visual format.

Essentially, a key requirement for IHDs is that the information they carry must be both easily and rapidly understood by householders who are usually actively engaged in other domestic tasks. This can be achieved either directly by virtue of the visual design of the display components (items that contain different categories of data on the display, e.g. a graph showing daily cumulative consumption values), or by contextualising the information by specifically encoding deviations from the norm and highlighting these as important changes that require attention (e.g. a display turns red when consumption is above a threshold and green when below) (discussed further in Section 2.4.4). This thesis aims to develop this idea further to provide useful data on the impact of different display designs carrying the same information on users' ability to detect changes in information shown on the display, and to examine the addition of context to speed and accuracy of comprehension.

2.4.3. "Pure" display design types

Many commercial energy displays employ hybrid user interface designs, and many studies reviewed so far examined the effectiveness of direct energy displays by simply comparing the presence of a display with no display or with other interventions. What the literature lacks is empirical research on testing different types of "pure" interface design against one another to establish the effect of each design separately. This research examines presenting energy information in three design types using Darby's (2009) classification of feedback presentation categories: numerical, analogue and ambient.

Numerical displays (e.g. Figure 2.10a for an Onzo display (Onzo, 2010)) provide detailed and quantitative information, which in principle allows for quick and clear readings to be made (Froehlich, 2009). Numbers are commonly used in commercial energy monitoring displays, and users may find them easy to comprehend due to the constant exposure in a number of activities both at home (e.g. kitchen timer, alarm clock, TV) and work (e.g. security systems, vending machines).

a) Numerical design b) Analogue design c) Ambient design

Figure 2.10. Examples of display design

Analogue displays (e.g. Figure 2.10b for a GEO display (GEO, 2010)) illustrate the scale of consumption usually without numbers, using line graphs, bar charts, pie charts and dials. Compared with numerical displays, these are often considered easier to read and interpret, especially when making temporal comparisons, such as between current and target values (Frankish, 2009). Analogue displays can be effective in checking readings, evaluating future states and conveying quantitative and qualitative information simultaneously in a direct and intuitive manner (*ibid.*). Anderson and White (2009) found through working with focus groups that the design of a speedometer dial was particularly preferred for its qualities of eye-catching movement, intuitive scale and direction of change, and ease of making comparisons. Arvola *et al*. (1993) found that households paid more attention to bar and pie charts than to kWh values, prices and saving tips shown on their feedback letters. Further, Smith and Mosier (1986) and Roberts and Baker (2003) recommended adding labels to the charts to assist understanding. Both bar charts and pie charts are useful for displaying data that are proportional parts of a whole, but bar charts allow for more accurate interpretation and comparisons for such applications than pie charts (Smith and Mosier, 1986; Roberts and Baker, 2003). Therefore, pie charts should only be considered in special cases, and the number of segments should be limited to a maximum of five to avoid information overload (Preece and Keller, 1990).

Ambient displays (e.g. Figure 2.10c for an Energy Orb (AmbientDevices, 2010)) provide an overall indication of a situation, sometimes make use of peripheral vision, and do not require users' detailed attention (Darby, 2006, 2009). No text or numbers are shown; instead, pictures, sounds or flashing lights are used to convey information. For example, an early feedback study involved the installation of a light that blinked to signify that the outside air temperature had dropped to the point where the indoor air conditioner could be turned off (Becker and Seligman, 1978), electricity consumption was reduced by more than 15% from this simple device. Similarly, a recent study found that the use of coloured lighting was more effective in reducing energy consumption than the use of numbers in a thermostat setting task (Ham *et al*., 2009). Nonetheless, there is limited published evidence on the use of ambient signal with IHDs. The present research attempts to introduce the inclusion of pictures of human faces in the design of user interface prototypes. Human faces are known to have the capacity to attract attention, even when reduced to cartoon form (Theeuwes and van der Stigchel, 2006; Langton *et al*., 2008). Presumably thanks to their social and biological significance, human faces seem to be processed differently by the human brain – changes in faces are detected faster and more accurately than in other objects (e.g. Ro *et al*., 2001).

The research intends to find out if analogue dials and bars are also preferred over numbers, and if the face's attention-capturing property makes it a useful cue in the design of energy displays. Specifically, the research looks at two-dimensional emoticon-like faces.

2.4.4. Design features

Real-time energy displays using computerised systems require the development of a user interface to serve as a connection between building occupants and their consumption data (Jain *et al*., 2012.). The impact of energy displays on energy use and the associated behavioural changes therefore relies on the design of the interface (Jacucci *et al*., 2009), and a systematic analysis of what specific design features drive these changes is needed to develop interfaces that can help achieve energy efficiency in buildings (Jain *et al*., 2012).

A likely characteristic of effective feedback is the ability to capture people's attention (Fischer, 2008). For IHDs, the visibility of the changing information that requires the householder's attention can greatly be improved with the use of visually conspicuous features[12] to give sufficient information needed to modify behaviour. Many studies on web page design and display screen design (e.g. Smith and Thomas, 1964; Carrasco *et al*., 1998; Pearson and van Schaik, 2003) have shown that comprehension, distraction and attention are heavily influenced by the colour, size, location, orientation, shape and motion of targets when people search or read displays (e.g. Ling and van Schaik, 2002; Ojanpää and Näsänen, 2003; Wood and Newborough, 2003; Lin, 2005). Colour, in particular, has been found to have the capacity to attract attention to target stimuli due to its highlighting and association effects, and to separate potential target stimuli from non-target stimuli (Boynton and Kambe, 1980). It might also help to shorten search time more than shapes or numbers (Barmack and Sinaiko, 1966, Gummerman, 1975 in Wood and Newborough, 2003). As colour is a basic element in visual perception, the processing of a colour overlaid directly on a set of alphanumeric characters and symbols does not require large amounts of cognitive capacities (Treisman, 1986). Accordingly, colour makes a good auxiliary code for multicolour displays, permitting rapid scanning and detection of patterns and relationships amongst several dispersed data items (Smith and Mosier, 1986).

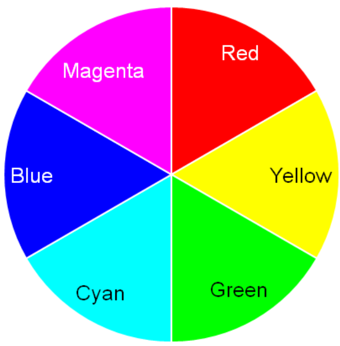
---

[12] Visual conspicuity is defined as a combination of an object's properties, relative to its background, which attracts attention and is therefore seen (Ling and van Schaik, 2002).

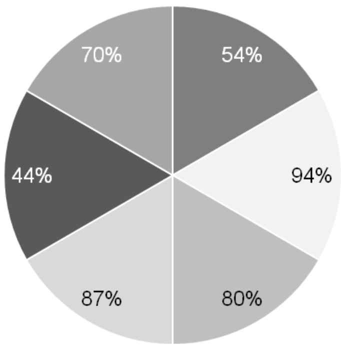
This research intends to study static displays that contain numerical and graphical information, thus dynamic displays (something on the display moves or flashes) and target orientation are not applicable in this kind of presentation, and shape is more suitable as an ambient subject. For these reasons, the main experiments of this research primarily investigate the effectiveness of coloured (i.e. non-black-on-white[13]) display designs against black-on-white display designs in capturing attention to the changing information.

2.4.5. Colour

In the digital world, devices such as computer monitors that release light produce additive colours and typically apply the RGB colour model, in which **r**ed, **g**reen and **b**lue are added to a dark background to create a range of colours. Figure 2.11a shows the three primary colours and their secondary colours.



a) RGB colour model



b) Greyscale conversion

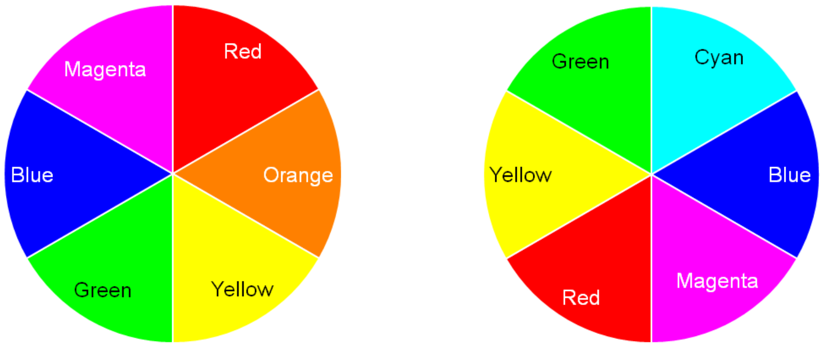
Figure 2.11. Luminance of hue in greyscale conversion (adapted from WorkWithColor, 2013c)

Mixing any two primary colours of equal amounts yields a secondary colour. Mixing equal proportions of the three primaries together results in white. The classification of the primary colours is related to the physiological response of the eye to light. The retina of the human eye has two types of photoreceptor

[13] Previous research has shown that dark text on a light-colour background (positive polarity) resulted in better performance compared with light text on a dark-colour background (negative polarity) (e.g. Humar *et al*., 2014), though further work is required to see if it still remains true in the context of displaying energy consumption data on liquid-crystal displays (LCDs), as the case in this research.

cells called rods and cones. Rods work at low light levels to help night vision; cones work in daylight and consist of three types of cells that respond to light of long (red), medium (green) and short (blue) wavelengths, respectively (Colour blindness awareness, 2010a). As visible light corresponds to a spectrum of various colour wavelengths, and the cone cells in the eye sense roughly three colour ranges, when shining red and green lights at the eye, for example, the eye interprets as yellow light.

On the other hand, artists or painters normally use the set of **r**ed, **y**ellow and **b**lue in the RYB colour model to make up the primary colours on their colour wheels (Figure 2.12a), while the CMYK colour model used in the printing industry to reproduce an array of colours in colour printing uses **c**yan, **m**agenta, **y**ellow and **k**ey (black) (Figure 2.12b). Mixing equal amounts of RYB together yields brown, and mixing CMY together creates blackish brown or grey. Black serves to produce darker colours and perfect black and to reduce consumption of the other three inks (WorkWithColor, 2013a). The set of primary colours being different to what media that emit lights use has to do with certain wavelengths of light being absorbed by pigments or dyes in a light-colour background. Those that are not absorbed create subtractive colours and are reflected back to the eye.



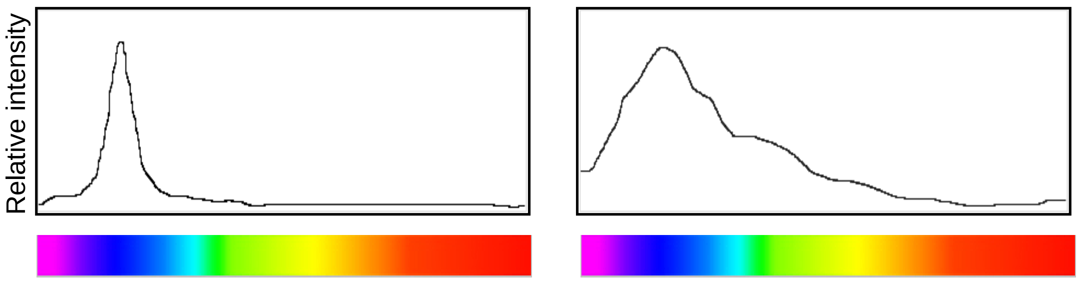
a) RYB colour model for painting b) CMYK colour model for printing

Figure 2.12. Colour-mixing methods for painting and printing showing the three primary colours between the secondary colours they produce

In computers, the colour in the RGB colour model can be numerically specified as an RGB triplet (*x*, *y*, *z*), and each component has an integer value that ranges from 0 to 255. This makes 255 x 255 x 255 = 16,581,375 colours. A colour's RGB value indicates the intensity of its red (*x*), green (*y*) and blue (*z*) element. If all component values are set to 0, the result is black; if all values are set to 255, the result is white.

Any given colour in projected lights is defined by the following dimensions (Wu and Yuan, 2003; WorkWithColor, 2013b):

- Hue describes the colour that is differentiated by the most dominant wavelength in the spectrum without black and white added.
- Saturation is the measure of a colour's purity, i.e. intense versus dull. Saturation is determined by the intensity of a given light and its distribution across the wavelength spectrum. The more saturated a colour the more intense and vivid it appears because it has a narrower range of wavelengths than a similar but less saturated colour (Cambridge in Colour, 2014) (see Figure 2.13 for illustration).
- Each colour has an individual luminance value, which is the measure of the perceived brightness of a colour. A colour's luminance is dependent on its hue and saturation. Figure 2.11 illustrates luminance and shows that by converting the hues on a colour wheel with a constant saturation level to greyscale, blue has the same luminance level as dark grey and yellow is almost as bright as white (100%) (WorkWithColor, 2013c).



a) Highly saturated blue   b) Less saturated blue

Figure 2.13. Saturation levels of a shade of blue in the wavelength spectrum (adapted from Cambridge in Colour, 2014)

Black, white and grey are achromatic colours, meaning there is no colour element in them. They are measured on different levels of luminance – the lightest is white, the darkest is black, and between them is grey in various degrees. Without hue, they change saturation and brightness of colours added to them.

As the human eye is not equally sensitive to all colours, certain colours may appear dimmer than others, such as blue. Further, the lighting condition under which the display is viewed will influence how a colour looks in daylight and at night. Colours can be made more distinguishable by altering their saturation and luminance levels, even for people with defective colour vision (discussed later in this section). Tinker and Paterson (1928-1963, in Humar *et al*., 2014) spent over 30 years undertaking a series of tests to examine colour combinations of text and background, and found that reading speed did not depend on colour, but on brightness and saturation differences, suggesting that high contrasts lead to better legibility. Similar conclusions were made by many readability studies conducted after their work (e.g. Ling and van Schaik, 2002; Ojanpää and Näsänen, 2003; Huang, 2008; Humar *et al.*, 2008). Consequently, Smith and Mosier (1986) proposed using a colour with a higher luminance level, such as cyan in lieu of blue, or using more saturated colours to make the displayed data look clearer. When selecting colours for encoding data, Smith and Mosier recommended red, dark yellow, green, blue and black on a light-colour background (positive polarity); and white, saturated yellow and somewhat de-saturated red, green and blue on a dark-colour background (negative polarity). A recent study investigating the legibility of text on liquid-crystal displays (LCDs) proposed a similar list of contrastive colour combinations and highlighted that positive polarity appeared to enhance the performance of colour combinations better than negative polarity (Humar *et al*., 2014).

Colour has been known to attract attention by making colour coded information more salient, and provides a useful cue for memory retrieval (Hanna and

Remington, 1996; Keller *et al*., 2006). Colour has also been shown able to influence decision-making (Kliger and Gilad, 2012). Further, coloured images, including thermal images in infrared blue-red, have been found to activate a more positive emotional response than greyscale images do (e.g. Giacomin and Bertola, 2012). Research has suggested that colour coding facilitates knowledge acquisition (Keller *et al*., 2006) and produces better performance in identification tasks than achromatic or monochromatic coding when the colour is strongly associated with an object's identity. For example, yellow may be related to bananas, but red is not usually related to hammers (Tanaka and Bunosky, 1993 in Hanna and Remington, 1996). Thus when used for coding, Smith and Mosier (1986) proposed assigning colours based on conventional associations that users are familiar with. For example, red connotes warning in human society and triggers mental awareness to danger, thus it might be used for alarm conditions. Yellow is associated with caution, which is an appropriate colour for alerting messages or to signify changed data. Green might be used for routine data display because it denotes normal "go ahead" conditions. White is considered as a neutral colour, and might be used for general data display purposes.

One major concern for designing colour displays is to make them accessible to all users by taking account of those with colour vision deficiency. Colour vision deficiency happens when one, or more, of the light-sensitive cone cells in the eye is missing (anopia) or is not functioning normally (anomaly) to perceive red, green or blue light, thus it reduces the ability to see some colours clearly and accurately. The condition in which people have problems seeing the red element in objects is called protanopia or protanomaly; the condition in which people are less sensitive to green light is called deuteranopia or deuteranomaly; and the condition in which people are unable to see blue colours is called tritanopia or tritanomaly. Protanomaly and deuteranomaly are collectively known as red-green colour deficiencies. People with these deficiencies are unlikely to make a clear distinction between colours with blue and purple hues, and may have problems identifying the difference between red, green, yellow, and brown. For people with tritanomaly, it may be difficult to distinguish between blue and green, blue and yellow, and violet and red (Colour blindness awareness, 2010c). Red-green colour deficiencies are most common and affect approximately one in 12 men (8%) and one in 200 women (0.5%) of European origin. The prevalence of each colour deficiency condition varies in different population origins (c.f. Chia *et al*., 2008).

A suggestion from Okabe and Ito (2002), who both are protanopes, for designing for those with defective colour vision is to apply redundant coding, which uses colours and a combination of symbols, thick/thin lines, dotted lines, texture/hatching and labelling. They also proposed a set of colours that is unambiguous and strong to both people with normal and deficient colour vision (Figure 2.14). For instance, use vermillion instead of red; use bluish green (emerald) for green; avoid combining violet and blue that appear the same for some, use reddish purple instead; and vary between warm and cool colours (i.e. colours that contain red and blue elements, respectively) when combining colours from the palette. Another way cited in past research is to increase levels of brightness and luminance (e.g. replace greyish blue with sky blue), as human's ability to perceive colours decreases if the light is poor, even for people with normal colour vision.

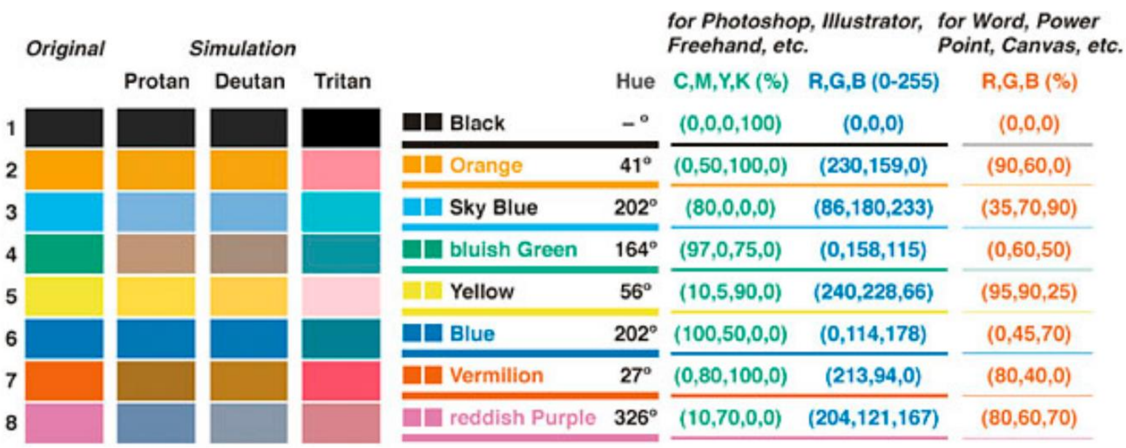


Figure 2.14. Colour-blind barrier-free colour palette (Okabe and Ito, 2002)

2.5. Subjective preferences for in-home display design

2.5.1. The value of user feedback

A sound body of social research has shown that direct feedback provided by IHDs promotes awareness and energy conservation, it has also illustrated the variability in observed savings. Apart from the factors related to the design of IHDs as identified in the previous sections, users' interactions with displays could also influence the effect of feedback on energy-saving behaviour. While the design of IHDs must address questions regarding what information the user needs and what goal the user wishes to achieve, how displays present feedback information is based on how the designer believes the user will respond. Therefore, it is sensible to consider users' perspectives in the design process to optimise for their understanding and motivation, and what behaviour a design is hoping to motivate (Froehlich *et al.*, 2010). The premise is that well designed displays that are "in tune" with the user's goal, needs and expectations will be more effective in saving energy for the maximum number of households (Wood and Newborough, 2007a).

Unsurprisingly, research investigating user feedback has garnered an array of personal preferences for interpreting information (e.g. Roberts *et al*., 2004), different views on energy-efficiency interventions (e.g. Scott *et al*., 2014) and on feedback mechanisms for the IHD design (e.g. Bonino *et al*, 2012). Kaufmann *et al.* (2013) identified four types of customer value perception for smart metering, and recommended incorporating them in energy policy and management, and developing suitable marketing strategies in line with each type of value perception. Several studies have indicated that gathering feedback based on actual experience may be more powerful and useful for designing presentation of information than simply gathering user's opinion on perceived preferences and views. For example, Anderson and White's (2009) focus groups changed their ideal display designs after spending a week using energy monitors. Similarly, households in a small-scale study changed their preferred metric units and comparative feedback type after a week's trial (Fitzpatrick and Smith, 2009).

By examining how households actually use energy displays, and how information is translated into action, research on user feedback could not only assist to identify users' motivations, the need for devising ways to keep them motivated in the long term, and improve the designer's understanding of how the user may react to and interpret energy information, it could also help raise not-so-well-investigated issues on, for example, what happens after energy displays have been installed, after the "honeymoon" period when interest and enthusiasm to newness diminish, and when learning about household energy consumption and usage patterns has been achieved (e.g. Hargreaves *et al*., 2010, 2013), thus contributing to the existing knowledge of how best to optimise the IHD design.

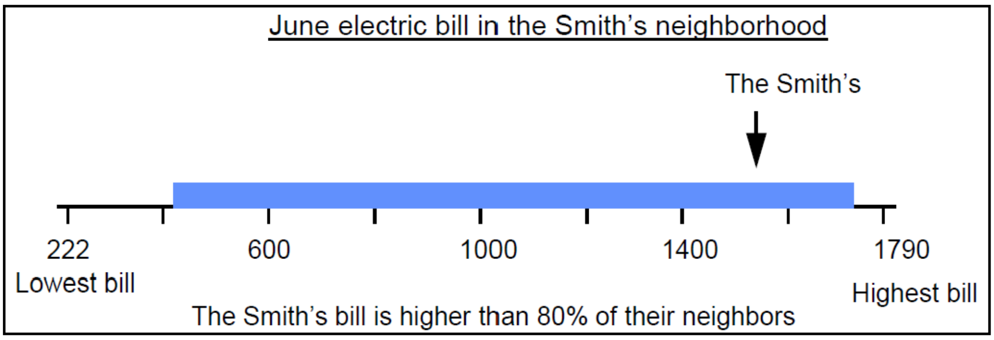
2.5.2. Feedback information and display design

Fischer (2008) summarised from 26 papers the qualities of an effective feedback design valued by households, including that such feedback information be supplemented by graphical representations, clearly labelled and explained, provided frequently and for a long period of time, based on actual consumption, and incorporate comparisons with previous periods, detailed appliance-specific breakdown of usage and what the energy price comprises of. People also seem to appreciate seeing feedback with an interactive element and multiple options for them to choose from on a display. Analogue traffic light indicator on displays was found welcomed in the EDRP trials (AECOM, 2011), while pictorial representation was poorly received in studies conducted in countries such as Norway (e.g. Wilhite *et al*., 1999) and the UK (e.g. Roberts *et al*., 2004), as were attention-seeking alarms and flickering lights. The designer should therefore give careful thoughts to how the user will assimilate graphical information (e.g. Fitzpatrick and Smith, 2009; AECOM, 2011). Further, the attractiveness of the IHD design and how well it fits into lifestyle and home settings have also been found to be important for some users (Fitzpatrick and Smith, 2009; Hargreaves *et al.*, 2010; Bonino *et al*, 2012).

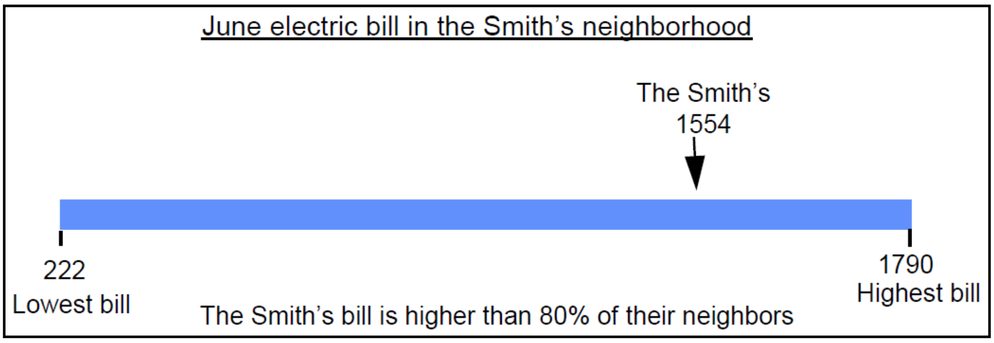
Fischer's review paper, however, did not reveal what was the preferred type of information, as research has shown mixed findings on what information and which type of display design people prefer to receive and what actually could help to serve presenting information better. As discussed in the previous sections, the type of display design and information provided can affect the user's attention and interaction with the display. For example, many study participants considered energy information presented in cost more meaningful than kWh or tonnes of carbon (e.g. AECOM, 2011; Karjalainen, 2011). Their interest in the information and the display, in turn, might influence the amount of energy savings achieved by the presence of IHDs – those who are highly motivated to save energy show a higher level of interaction with the device; those not so motivated are likely to ignore the display completely (Oltra *et al*., 2013). This raises the question of whether IHDs designed to users' liking will result in a greater effect on reducing energy consumption. Krishnamurti *et al*. (2013) investigated this by comparing participants' preferences against experimental evidence. They found that although cost-related (monetary unit) and appliance-specific information was considered more persuasive to participants than energy units, results from their computer-based simulation showed that such preferences would not be as effective as kWh for learning about energy use in the real life. More evidence for these findings is needed, which have yet to be validated through observations.

2.5.3. Comparative feedback

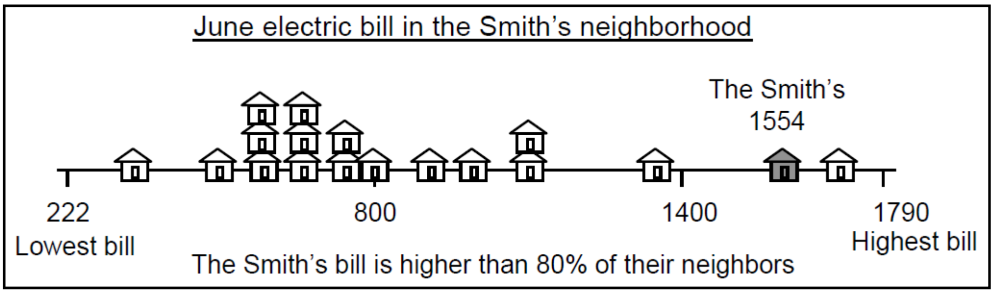
Design preferences have been found to vary between countries and, probably, cultures, suggesting that care should be taken when considering research in different countries. A notable example is a comparison between Egan (1999) and Wilhite *et al*. (1999), who explored consumer reaction to similar graphical designs of other-relative feedback information in the USA and Norway, respectively. Researchers in the USA designed two types of graphical representation to show energy consumption: bar graphs (Figure 2.15a and Figure 2.15b) and distribution graphs (Figure 2.15c and Figure 2.15d). Egan (1999) reported that the level of comprehension for the distribution graphs was markedly higher than the bar graphs. Although the distribution graph in Figure 2.15d was ranked least preferred and most difficult to understand, the bar graph in Figure 2.15b had the lowest rate of interpreting the information correctly. The distribution graph in Figure 2.15c that displayed little houses in a neighbourhood mapped on an *x* axis according to their energy consumption was ranked most preferred to receive and easiest to understand, while the same design concept presented in Norway (Wilhite *et al*., 1999) was judged as "childish" and difficult to interpret. Wilhite *et al*. went on to test two design concepts similar to the graphs shown in Figure 2.15a and Figure 2.15d, and only found marginal differences in interest and comprehension levels for both. Still, they cautioned against the possibility of losing user's understanding in a trade-off with the accuracy of data in simple designs like those illustrated here.



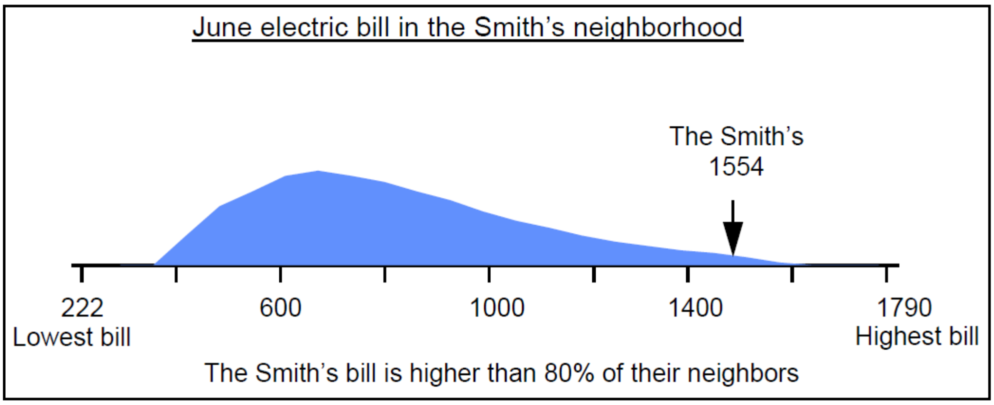
a) Bar graph with a scale



b) Bar graph with no scale



c) Distribution graph with house icons



d) Distribution graph with a curve

Figure 2.15. Graphical designs for presenting other-relative comparative feedback (Egan (1999) adapted from Roberts and Baker, 2003)

Iyer *et al*. (2006) in the USA looked further into methods of clustering households into comparable groups and of choosing suitable graphical designs (bar and distribution graphs in their study). They pointed out that the distribution of household consumption was typically skewed, causing misleading results on bar graphs; therefore, a distribution graph might be more appropriate. Their views coincided with Egan's (1999) findings on users' preferences for graphical designs. They also reported that grouping households within the same meter-reader's route covered in one day, using street name and a combination of house physical characteristics (e.g. construction date, floor area, fuel type) resulted in higher quality comparison groups than dividing households based on entire meter-reading cycle or single house characteristics.

Like the USA and Norway, households in Finland (e.g. Haakana *et al*., 1997) and Japan (e.g. Ueno *et al*., 2005) responded positively to receiving other-relative feedback, mostly for the reason of the inducement of competitive spirit among fellow households. Nevertheless, self-relative comparisons have been well-received in other places such as Sweden and the UK (e.g. Sernhed *et al*., 2003; Roberts *et al*., 2004; Wood and Newborough, 2005 in Wood2007a). Simple bar charts and historical consumption feedback were preferred for comparing a household's energy use in the most recent month, or quarter, of the year with either the same month, or quarter, of last year or the whole of last year. A strong dislike was expressed for receiving statistical information about comparable households' use, whether these homes are in the neighbourhood or not, due to scepticism to the ability of energy suppliers to provide accurate readings and comparisons, and the perceived uselessness of comparing a household's use with an average to estimate if excessive amounts of energy have been used.

The studies reviewed in this section demonstrate that users can interpret different types of presentation if they are well designed (Karjalainen, 2011), but their reactions depend on the choice of wording, labels and chart type, which can range from completely meaningless to highly motivating (Fischer, 2008). It is worth noting that many design principles and user preferences are overlapped, indicating that design principles are the product of trials and errors, as well as of user feedback. However, research has also shown that user preference does not always lead to better task performance (Ling and van Schaik, 2002; Humar *et al*., 2008), irrespective of cultural backgrounds (Noiwan and Norcio, 2006; Cyr *et al*., 2010). After all, the purpose of gathering users' views is not to present information in an aesthetically pleasing way, but to provide sufficient and relevant information to the user to promote engagement (Roberts and Baker, 2003), to properly test for user's understanding of the information presented, to contextualise test results for the researcher, and to incorporate them into future IHD design guidelines.

2.6. Chapter conclusion

This chapter identified factors that can influence domestic energy consumption: the building design that responds to the built environment determines the amount of energy required for the building to function and, although the amount is fixed, can be made more energy efficient (e.g. with retrofitting); whereas the building occupant's energy-use behaviour is variable and can be changed. Challenges for occupants to achieve energy savings include the invisibility of energy, occupants' misconceptions about energy consumption and energy efficiency, occupants being unaware of the link between their behaviour and energy use, and their characteristics, such as age, gender, household size, income and subjective views on energy-efficiency interventions, that may be associated with how energy is used in the building.

Interventions aimed to promote awareness and energy conservation were also reviewed within this chapter. The key issue is to examine which behavioural factors should be targeted by which motivational interventions, i.e. different types of energy use and energy savings are related to different sets of determinants (Abrahamse and Steg, 2009), so that appropriate interventions to persuade building occupants to undertake efficient energy behaviours can be adopted and developed for optimal results.

Past research has shown the possibility of motivating this behaviour through the provision of direct feedback by means of IHDs. For the display to support the information that it carries, an understanding of what part of the display design steers those reductions in energy demand is needed. However, the literature in the areas of feedback and display design lacks evidence to indicate how such feedback can be presented intelligibly on such a display device, and whether user-centred IHD design can enhance the display's performance in the real world.

The review has been presented to support this research to study the design of IHDs that provide visual presentation of feedback information on energy consumption to building occupants, in the hope to improve their understanding and awareness of their energy use, and to induce behavioural change.

A number of goals for this work are summarised as follows:

a) Adopt and develop existing methods to measure the effects of IHDs on subjects' responses and behaviour.
b) Design and empirically test the effectiveness of various display design options. Design should consider appropriate and replicable features.
c) Test on subjects in a controlled environment before trialling in the field.
d) Assess whether subjects' feedback corresponds to the observed effects of the various display design options.
e) Provide evidence that facilitates the future development of IHD design.

Chapter 3 Methodology

3.1. Introduction

To study the role of in-home display design in influencing energy use, the research involved human participants to learn about their responses to the display. This suggested a mixed-research approach to measure the effects of IHDs on participants' behaviour and to gain an understanding of such behaviour through their feedback.

Therefore, the research utilised quantitative and qualitative approaches in experiment-based studies to collect both objective and subjective data, as human nature is a complex subject to study. Descriptions of the general research methodologies are given in this chapter. Experimental methodologies relevant to the specific experiments are presented in detail in Chapter 4 and Chapter 5.

3.2. Research questions

Reviewing the literature on the design of IHDs leads to the following questions that may be drivers for the research project:

- Do different types of "pure" display design presenting the same energy information communicate equally well to people? If not, how do they differ from one another?
- Which design feature(s) is more likely to attract people' attention to the information it carries?
- Can the type of information shown on the display influence people's energy-use behaviour?
- Can user preference help to inform better decision-making in IHD design?

3.3. Research strategies

The research was concerned with quantitative research, qualitative research and their data. Quantitative research collects data, which focus on numbers and frequencies, through methods such as questionnaires and experimental approach, and can be analysed using inferential statistical tests. Qualitative research collates data, which are descriptive in nature (Holah, 2006a), using methods such as interviews and focus groups. Methods of collecting and analysing data pertaining to the research are discussed in Sections 3.6 and 3.7, respectively.

3.3.1. Combining quantitative and qualitative research

The focus of the research was on investigating how different IHD designs affect energy use; therefore, priority was given to the quantitative approach in data collection and data analysis. In addition to objective measures, the research looked at subjective data. Qualitative research aims at gaining a deeper meaning, perspective and understanding of human behaviour in social settings; therefore, it was accepted that the scope of this research work would benefit from gathering participants' feedback on their experiences of engaging with energy displays.

The mixed-methods strategy has successfully been applied in a number of display design and energy feedback studies, illustrating the usefulness of mixed-methods rather than using either method alone. For example, in a longitudinal study conducted by Brandon and Lewis (1999), households provided quantitative information in questionnaires and took part in focus groups after the final meter readings had been taken, and received feedback on their energy consumption in various forms, including post and computerised feedback. Krishnamurti *et al*. (2013) compared their participants' preferences for display designs against experimental data in a laboratory study, and found a gap between stated and actual preferences.

In this research, both data collected in the laboratory-based experiments measuring task performance in accuracy rate and response time and the actual energy consumption data collected in the field-based experiments were used to construct graphs and tables for comparisons, and underwent statistical analyses for making inferences about display designs. Information about participants' subjective preferences for display designs was collected by means of questionnaires and semi-structured interviews, and was reduced to numerical form for analysis. This was facilitated by asking closed questions and sorting responses into categories.

To give contextualised meanings to the results and ask the question "why", methods associated with qualitative research were incorporated to capture participants' experiences and opinions that were not revealed in the quantitative data. This way, the qualitative information assisted to develop an explanation of unexpected findings generated from the quantitative data, and created ideas for further studies. Therefore, in addition to the set questions, participants were encouraged to describe how they felt about and the ways in which they reacted to the experimental treatment, in this case, the display. The information obtained from the expanded responses in the interview was useful in the study with a view to supplementing the quantitative data, by analysing from participants' viewpoints, clarifying some of the underlying reasons, and providing some insight into the extent of influence that subjective views might have on the test results.

In summary, it was necessary to combine multiple research methods to address the research questions on different levels and which would give a broader perspective, making the research more comprehensive.

3.3.2. Evaluation of research methodology

Within this section, three general criteria are adapted primarily, but not exclusively, from Bryman's (2012) work on social research methods to evaluate the quantitative and qualitative research strategies used in this research.

Assessment of the laboratory- and field-based studies is discussed separately in the relevant subsequent sections.

1. Reliability is often a concern in quantitative research. Reliability refers to the extent to which a measure is consistent (Bryman, 2012). For example, accuracy rate and response time were used as the measures of task performance in the computer-simulated experiments of this research project. If similar results were produced using the same measures under the same conditions of the experiment, the measures would be seen as reliable (Holah, 2006b).

   As the practice of qualitative research is not the same as quantitative research, Lincoln and Guba (1985) proposed an alternative term that parallels reliability: dependability, which, in a similar vein, puts an emphasis on whether the findings are consistent, and whether they could be repeated or applied at other times (Bryman, 2012). The merits of qualitative research could be established by adopting an auditing approach (Lincoln and Guba, 1985). Qualitative research has a problem with reliability, however. Due to the close distance between researchers and their participants, objectivity may be compromised. For example, participants' responses may be affected by the characteristics of the researcher; the interpretation of data is subject to the researcher's leanings or predisposition to what is important to focus on (Bryman, 2012). While it has been recognised that complete objectivity is not possible in social research, the researcher will nonetheless endeavour to refrain from allowing their personal opinions or values to get involved in the research (*ibid.*).

2. Replication refers to the extent to which the results of a study can be reproduced by repeating the same procedures (*ibid.*). This is another methodological concern in qualitative research. As each qualitative study is unique, such as in focus groups, it cannot be re-created; therefore, it lacks the ability for other researchers to replicate the study (*ibid.*). On the other

hand, quantitative research using postal questionnaires, for example, is capable of replication to address the potential problem of lack of neutrality or the effects of researcher's characteristics on the results.

3. Validity is concerned with the strength of the conclusions. In the sense of measurement validity, it refers to the degree to which a study measures what it is supposed to measure (Bryman, 2012). Validity is closely related to reliability, and both are concerned with the adequacy of measures. If a measure of a study is reliable, it is a valid measure to reflect the concept it is supposed to be denoting (*ibid.*). There are three ways to consider the validity of a study method:
    - Internal validity refers to the issue of causality. It is concerned with the soundness of a finding from a causal relationship between two or more variables (*ibid.*). From a qualitative research perspective, credibility is in preference to internal validity; it refers to whether the results are believable (*ibid.*). Because the results are obtained from the viewpoint of the participant, it relies on the richness of the information gathered by the researcher to give evidence of the credibility of the research (Trochim, 2006).
    - External validity relates to the generalizability of findings beyond the present study, as quantitative research is mainly concerned with the representativeness of research subjects (Bryman, 2012). Transferability in qualitative research refers to the extent to which the results can be applied to other contexts (Lincoln and Guba, 1985). It, too, depends on the thoroughness of the description of the context, so that comparisons can be made with a similar situation (Shenton, 2004)
    - If the findings of a study are applicable to people's everyday natural social settings, they are said to be ecologically valid, because they represent the real-world experiences (Bryman, 2012). In this research, findings derived from the studies using experiments and interviews might be externally valid because they could be generalized to other samples faced by the same tasks or questions, but the interventions

in an unnatural environment were likely to make the findings ecologically invalid (Bryman, 2012).

3.4. Experiment-based studies

This research adopted the design of experimental research for collecting quantitative data. Unlike descriptive research which observes the subjects without intervening, experimental research allows cause and effect to be studied rigorously by systematically manipulating one of the variables (independent variable), while keeping other variables constant, to see what effect it has on the other variables (dependent variables) (Dancey and Reidy, 2011). A defining feature of the classic experimental research is the random assignment of subjects to experimental conditions to avoid the issue of subject variables, which can decrease the internal validity of findings (*ibid.*).

This research work was built on a laboratory- and a field-based study, both of which were conducted in a controlled, indoor setting. The laboratory-based study consisted of a pilot study (Section 3.4.1) and a main experiment (Section 3.4.2) in which computer-simulated experiments were undertaken. The field-based study (Section 3.4.3) consisted of two experiments carried out in a university student residence.

3.4.1. Pilot study

Before the main experiments were carried out, a pilot study was designed to determine if the proposed work could be accomplished (see Section 4.2). Piloting was an important part of the planning process in this research for two reasons. Firstly, it enabled the author to develop techniques of designing experiments. Secondly, it was instrumental in identifying methodological errors to help improve the overall quality of the implementation of the main experiments.

The pilot study encouraged planning the budget, checking reliability of measures, and deciding on what aspects should and should not be covered in the main experiments later, and what recruitment methods and materials were suitable to the study. The piloting process presented an opportunity to run through the logistics of conducting an experiment, by determining the sequence of the experimental procedures and the type of test, so that data would be collected adequately, how the experiment might be introduced, how the interviews might be phrased, and how the instructions might be given. The process also helped think about how to clear up the confusion that might arise from the study at any stage of the experimental procedure. Moreover, piloting allowed for ideas and the interview questions to be evolved, which could be included in subsequent experiments. Details such as deciding if the time length taken to complete the test was acceptable for participants gave a more comprehensive account of the study. Improvement of the experimental design was further made possible by addressing technical issues brought up by participants and by assessing the strategies used to gather and analyse data.

As shown in the next chapter, outcomes of the pilot study confirmed that checking feasibility of the planned work was relevant, and that a mixed-methods approach was appropriate for the research for quantifying the effectiveness of different display designs appended by participants' feedback.

3.4.2. Laboratory-based study

In addition to the features of experimental research outlined above, the laboratory-based method gives the experimenter a high level of control over the experimental arrangements in a contrived environment. It enables them to reduce the number of possible extraneous variables that are not intended to be included in the testing but could affect the results (Bryman, 2012).

Laboratory experiments were undertaken in this research as described in Chapter 4 to identify the design condition in which information shown on the display that was easier for participants to read and understand. To do this, different types of "pure" display design and design features carrying the same energy information were compared in computer-based simulation tests, which were designed to measure participants' task performance in terms of accuracy and response time. Additional tests were carried out to determine if there was any evidence that participant variables, such as demographic characteristics or socio-economic status, could influence the results.

Despite being conducted in an artificial environment which may not be typical in real-life situations or related to real-world contexts, with the use of systematic, standardised methods and a relatively precise control of variables (compared with field studies), laboratory experiments can be replicated, making it possible for other researchers to assess the reliability of results, and allowing for the research to build more confidence in the findings and the validity of the theory being tested (Holah, 2006c).

Whilst it is possible that even under highly controlled conditions, participant's response can be influenced by their awareness of taking part in the experiment (reactive effect), or by the unintentional cues coming from the experimenter (experimenter effect) (Bryman, 2012), laboratory experiments still give the researcher more control over the extraneous variables, and help identify a connection between variables. Further, with the quantitative data being yielded from the experiments and analysed through the use of statistical tests, laboratory experiments make it easier to draw conclusions about the effect of the manipulated variable.

3.4.3. Field-based study

The research examined the impact of IHDs in a "live" context through two experiments, more specifically quasi-experiments, conducted in a student residence at the University of Bath[14] (see Chapter 5). Quasi-experiments are

[14] Permission to conduct the study and access to the student residence were granted by the Student Accommodation Services. Support (purchase of materials and installation of equipment) was provided by the Department of Estates, in exchange, a report was produced after the experiments had been concluded.

like the classic experiment-based studies with control and experimental groups for comparisons, but there is no random assignment of participants to the experimental or control condition because sometimes it is not possible for practical or ethical reasons to manipulate variables such as age and gender. In the experiments reported in Chapter 5, there was a limitation on having control over the allocation of the students; they came pre-grouped and had an uneven number of males and females in each kitchen group that could not be re-grouped for the experiments. Often quasi-experiments are the only method available when studying phenomena in real-world settings (Dancey and Reidy, 2011).

Even though the experiments were classified as quasi-experiments, they were only partially true in nature: while the research took advantage of a natural situation, it undermined the internal and external validities in the selection of sample, setting, timing, and in the history of participants' previous experimental treatment, all of which could lead to biased results. Due to the constraints on randomization, the experiments used a narrower range of participants than the laboratory experiments – a group of students from a particular university residence. The same group of students took part in both experiments and might become more experienced in the second one; they might know what was hoped to achieve and how to increase the likelihood (reasons for using the same group of students in the field-based experiments are given in Section 3.5.1).

Although the absence of random assignment makes quasi-experiments highly internally invalid primarily due to the issue of participant variables, studies conducted in real-world settings are more practical and applicable to a natural situation, and are more likely to be ecologically valid. In contrast to a true quasi-experiment, the students were aware that they were in an experiment. Moreover, the experiments were conducted in a setting where participants carried on with their lives in their living environment. Therefore, it was reasonable to assume that they would behave more naturally as they would in their everyday social settings, the results would represent their real-world experiences, and that the experimenter effect would be less of an influence on their responses to the experimental treatment, thus the ecological validity of the study was likely to be improved. Through careful experimental design, it is possible to account for effects that may influence the validity of research.

Whilst the study monitored energy use in a residential environment to trial the effects of display designs and information on occupants' energy-consumption behaviour, people living in university accommodation might not, to some extent, be representative of typical householders. Even so, university accommodation provides a well-controlled environment to study the effects of short-term energy-saving interventions on occupants' behaviour for a number of reasons:

- The study venues are in buildings with similar physical and construction characteristics, building services, room layout and size, and domestic appliances. These properties cannot be modified by their inhabitants.
- Participants may have similar demographic features in terms of age, education level and environmental attitude.
- Student households may have similar size, lifestyle and composition.

On the other hand, there are ways in which university accommodation may show differences from residential settings. Students, unlike homeowners or tenants, are charged the same all-inclusive fees as their neighbours and do not receive bills or information on their energy consumption. This means they do not have a financial motivation to reduce consumption and might not be conscious about the energy demands or their behaviours (Petersen *et al.*, 2007). Conversely, however, as many of the students are living away from home for the first time in their lives, this may be the best time to introduce the concept of energy awareness before their habits have been formed (Verplanken and Wood, 2006). If students can be made aware of their energy use by providing them with direct feedback, and if they feel motivated to save energy through other incentivizing measures, such as rewards, taking part in the experiments could potentially become a useful learning opportunity for them to develop energy-conscious behaviour.

Whilst it may not be possible in quasi-experiments to control the extraneous variables as well as in laboratory experiments, which can make it difficult to replicate, the research experiments incorporated two types of groups for comparisons, equivalent to the control and experimental groups in a true experiment. In doing so, alternate explanations of the experimental results could be eliminated, and the confidence in the findings could be enhanced (Bryman, 2012).

Despite the fact that the experiments were carried out at two points in time (six weeks each) and so the results might not be generalized at a different time of the year, generalizability could be improved in further empirical research, by replicating the experiments using the same procedures in the same setting at different time points in the following academic years. This could help establish the patterns of energy-use behaviour in this particular residence under the influence of the experimental treatment. This might provide an opportunity to develop the study and apply it to other university residences.

3.4.4. Experimental design: repeated-measures

A repeated-measures design is a type of experimental design, in which every participant takes part in all the conditions of the experiment. It, unlike an independent-measures design which uses different participants for each condition, has a key advantage of controlling some of the individual differences between participants, and therefore reducing the possible confounding variation between conditions. As the same group of people go through all the conditions, each participant acts as their own control, and the design requires fewer participants (Holt and Walker, 2009).

In the laboratory-based experiments, between 100 and 200 display design conditions were tested, which would put constraints on the recruitment of participants as well as on the time and cost for conducting the experiments. Similarly, with three types of display design to be tested in the first experiment of the field-based study, multiples of three experimental groups were needed, making it a resource-consuming study. From a practical point of view, the number of student residences that met the requirements of the experiments and were available for carrying them out was very limited. Given the requirements above, it was sensible to use a repeated-measures design for the purposes of the research.

However, utilising the same group of participants in all the experimental conditions can result in a potential problem of order effects because of a boredom, fatigue effect and/or practice effect. Fatigue and practice are extraneous variables associated with repeated-measures designs. The experiment could be affected as the level of performance may deteriorate due to physical exhaustion (fatigue), or improve due to participants figuring out the logic of the experiment (practice) (Bryman, 2012).

Order effects can be offset by varying the order in which the experimental conditions are conducted, and all the possible orders should be completed to fully counterbalance the design (Holt and Walker, 2009). In the field-based experiment, where three display designs were tested, there were six possible display orders in total (3 x 2 x 1 = 6) in the repeated-measures design; therefore, multiples of six experimental groups were needed. On the other hand, when facing a large number of possible orders like in the laboratory-based experiments, it was acceptable to randomize the orders without a full counterbalancing (*ibid.).*

3.5. Participation in research

3.5.1. Participants

The ability to generalize findings from a sample to the population is important (Dancey and Reidy, 2011). While simple random sampling is likely to reduce bias in the sample selection, however, due to time and cost constraints, opportunity sampling was chosen over the random approach in the research.

Opportunity sampling is a common sampling strategy in social research, where research is done on a group of individuals who are available to the researcher by the virtue of accessibility (Bryman, 2012). This sampling technique was acceptable in this research because the laboratory experiments tested different types of display design and people's basic abilities to spot changes between images, whose eyesight and comprehension abilities were not different to anyone else's. People who have a knowledge of the existence of energy use in daily life and have normal or corrected eye sight (non-colour defective vision), who can understand simple verbal and written instructions, and can communicate their thoughts to other people were considered as candidate participants and were recruited on a first-come, first-served basis.

Aside from being constrained by the availability of the material and cost, student residences were chosen based on the virtue of convenience. They also presented an excellent opportunity for conducting the field-based study for three reasons. Firstly, university accommodation provides an ideal experimental environment for being a well-controlled setting and for carrying out repeated-measures studies as mentioned previously in Sections 3.4.3 and 3.4.4. Secondly, the number of suitable student residences that were available for conducting experiments was very limited. Thirdly, when selecting a sample, the narrower a range of participants the more desirable, so that possible variation in subject characteristics could be eliminated, and a greater precision in the estimate of the effect of the experimental treatment could be achieved (Hopkins, 2000). By taking a sample in student residences, the differences between subjects could be reduced, assuming that the sample was more homogenous. The implication of this is that generalization from opportunity sampling is limited, although the confidence in findings could be improved through the use of statistical tests.

A common methodological issue for experiment-based studies that involve voluntary human subjects is the motivation of participants. Due to self-selection bias, there are a number of differences between those who choose to participate and those who choose not to, and there may be a purposeful intent on the part of volunteers (Hayes and Cone, 1977; Staats *et al*., 2004; Abrahamse *et al*., 2005) – people who volunteer to partake could be highly interested in the subject of the experiment being conducted, or tend to be motivated by the incentives proffered. This may not seem to be detrimental, but can make it difficult to evaluate the effects of the experimental treatment. A recent study that recruited two groups of participants to investigate users' interactions with IHDs through focus groups and interviews might illustrate this point (the study did not investigate the relationship between engagement and consumption) (Oltra *et al.*, 2013). Group 1 consisted of voluntary participants, Group 2 was composed of random participants. It was reported that Groups 1 showed higher levels of interest and engagement with the display than Group 2. For these reasons, non-voluntary participants were studied in the field-based experiments in order to minimise the effects of self-selection bias in the research (details of the field study are presented in Chapter 5).

3.5.2. Incentives and rewards

In the pilot study, participants were not given any incentives, only refreshments were offered for their taking part after the computerised test was completed, in the hope to avoid them being demarcated from others who were not amenable to inducements (Bryman, 2012). This, however, was a difficult approach to recruit participants.

Therefore, monetary incentives were used for participation in subsequent experiments as a way of expressing appreciation to participants, and as a way to encourage higher levels of participation. As discussed in Chapter 2, incentives can initiate behaviour, in this case, participation, and they are particularly useful to recruit participants in one-off or short-term experiments. However, the use of payment to incentivize participation is often seen as a form of coercive offer by some researchers, particularly for participants from financially disadvantaged groups who may be more vulnerable to this kind of enticement (Boddy *et al*., 2010).

Grant and Sugarman (2004) argued that the use of incentives or rewards is harmless most of the time, but they also identified the following likely circumstances where incentives could become problematic:

- The subject is in a dependency relationship with the researcher.
- The risks are particularly high.
- The research is degrading.
- The participant will only consent if the incentive is relatively large because the participant's aversion to the study is strong, and/or
- The aversion is a principled one.

As the intentions of this research were not in conflict with these factors, a small monetary payment in voucher form was given in the laboratory-based study to ensure that an adequate number of participants were recruited. In the field-based study, rewards were offered to participants to simulate the financial savings accrued from using less energy in the real life.

3.6. Data collection

3.6.1. Computerised experiments

In the laboratory studies, the ability to use computers to precisely measure response times and accuracy rates was useful to understand participants' reactions to various display designs and the effects of these designs on their perception of information. Further, the spot-the-difference test seemed to be appropriate to explore visual attention and to study participant's ability to detect changes between images. To simulate the act of looking at an energy display in the real life, the pre- and post-change images were rather presented in sequence than viewed side-by-side or gradually blended together, in order to avoid "change blindness", which occurs when a person fails to detect the change when viewing an original image and a modified image (Verma and McOwen, 2010). An alternative experimental approach to study the attention-capture effect was to flicker, or repeatedly flash, images. The task presented by

Rensink *et al.* (1997) inserted an interval between the pre-change and post-change images and again after the post-change image. The sequence repeated until the participant made a response. A concern with this alternative is that the pre-change information can be overwritten or forgotten even by a briefest moment of a blank screen between images, and so the attention effect is disrupted.

Recent research regarding the impact of information representation on energy-consumption behaviour has largely adopted an approach that measures actual energy consumption, and then feedback is given to participants through methods such as direct display devices, e-mails or letters (e.g. Ueno *et al*., 2006; Jain *et al*., 2013; Vassileva *et al.*, 2013). This method was considered appropriate for the field-based study in this research work because it required for the effects of different energy displays being compared to be related to real-world contexts. Energy consumption of both the control and experimental groups was monitored during the baseline period and the experimental period. Baseline period is the time period during which no energy-saving interventions, in this case, the display, are installed and the consumption data from which are representative of the average level, so that the data can be compared with those from the experimental period (when interventions are installed) in order to determine the effectiveness of these interventions. The consumption data collected were stored and sent to individual corresponding display devices and gave participants visual feedback on their energy consumption.

3.6.2. Subjective feedback

It has become clear that in order to study how best to design the IHD, information characterising people's experiences is as essential as the measurable data. Personal views on energy use and display design can be gathered using a number of methods. Those that were considered applicable to the research are discussed here.

From their semi-structured interviews, Hargreaves *et al.* (2010) explored a number of households' experiences of using different IHDs, the effects of the displays on their awareness and behaviour, and their suggestions to help improve the devices. Similarly, Karjalainen (2011) conducted semi-structured interviews to learn about people's comprehension of eight paper prototypes of IHD design and their preferences for the features of feedback that they valued the most. Interviews essentially aim to elicit information from the interviewee and, like the questionnaire, to detect patterns of association (Bryman, 2012). Semi-structured interviews have features of both structured and unstructured interviews. The semi-structured interview has specific topics to cover and follows an interview schedule. All the questions are asked, with similar wording, and they can be open and closed ended. Because the emphasis of the interview is on the interviewee's perspectives rather than on the researcher's interest, new questions that follow up interviewee's replies are asked, and so the order of questions can vary from interview to interview. The questioning style is informal (*ibid.*). For these reasons, the semi-structured interview method was chosen for participants in the laboratory-based experiments to reflect on their task performance after the completion of the computerised tests and to express their preferences for the display designs through a number of core questions.

Questionnaires were used in a study conducted by Anderson and White (2009), who surveyed their participants' knowledge and interest in domestic energy issues, and recorded their use of, and responses to, IHDs. Bonino *et al*. (2012) collected 992 responses in their online survey in a period of three months on feedback mechanisms in the IHD design. An obvious advantage of this method is that it is quicker to administer (Bryman, 2012) than the other methods described in this section. Questionnaires, either paper- or web-based, can be distributed in large quantities, keeping costs low and giving participants the convenience of answering the questions in their own terms, while it would take a long time to conduct interviews with a sample of the same size. Questionnaires eliminate variation in the ways in which questions are asked, but may suffer from question order effects at the same time (Bryman, 2012). In the instance where the researcher is present, there is a possibility that the answers that respondents give are biased due to social desirability, particularly with questions that people find sensitive or anxious about (e.g. Tourangeau and Smith, 1996). However, the presence of the researcher can help respondents if they are having difficulty answering certain questions, and ensure that all the questions are answered (Bryman, 2012).

Through the use of diaries and a series of reconvened focus groups, Oltra *et al.* (2013) studied how their participants reacted to the feedback on their energy consumption from the display. The diary method produces data that record people's own behaviour through self-observation and provide information on the time sequencing of events. This method is viewed as more accurate and valid than the questionnaire method (Bryman, 2012). However, the diary method was rejected for this research as participants may self-select their entries of activities. It was also considered as a time-consuming task for the student participants in the field-based study, who could become less diligent over time about record keeping and eventually fail to complete the task (*ibid.*).

On the other hand, the focus group interviews a group of people on a specific topic that is relevant to them or about a particular situation in which they are known to have experienced (Merton *et al*., 1956 in Bryman, 2012). This technique allows for the researcher to get participants' perspectives through discussion, for example, that may not be revealed in individual interviews (Bryman, 2012).

In the first field-based experiment, post-study semi-structured group interviews were conducted to allow for further discussions on how the display affected energy-use behaviour from participants' points of view. They were interviewed as members of an individual group for their joint effort. By and large, the sequence of questions was similar in each interview, and a few opening questions on the overall impression of the study helped to start the interview. By following a flexible interview process and asking open and closed questions around a number of core questions in a conversational manner, participants were encouraged to talk about their experiences and elaborate their answers. Some of them were even able to offer explanations for their energy-use patterns. Questions brought up by participants on the intermittent check-up visits during the course of the experiment were also addressed. Like interviews, focus groups have an issue with the social desirability effect and group effects. As there might be a tendency in participants towards answering questions in ways that are socially or culturally acceptable, or an attempt to stay consistent with their own opinions in the discussion after hearing the views of others, or to agree with an emerging group view, the use of questionnaires containing questions similar to the interview questions could help to draw out a variety of individual views held privately and publicly (Bryman, 2012).

3.6.3. Confidentiality

A research concern was the confidentiality after the data had been collected. Participants were informed that the data they provided would only be used for research purposes. Their details would be coded and kept anonymous, so that they would not be identified personally by any means, especially in the case of the publication of the results. This was explained to participants at the start of each experiment.

3.7. Data analysis

3.7.1. Quantitative data

The statistical tests used in the research were conducted in the statistical package for the social sciences (SPSS) (version 18 (SPSS Inc., 2009), versions 19 and 21 (IBM Corp., 2010, 2012)).

3.7.1.1. Estimation

In the tests below, the level of statistical significance was set to 5%, i.e. $\alpha = 0.05$. This means that results were deemed significant if the probability of finding them by chance (*p*) was equal to 0.05 or less if the null hypothesis were true. This would give a power level of 0.95, and a 95% probability of correctly rejecting the null hypothesis when it is not true. Power, therefore, is the ability of a study to find a significant effect between variable means in a relationship (Dancey and Reidy, 2011), ranging from 0 (no power) to 1 (100% power). In essence, the greater the power of a study, the more likely an effect will be found, and the chances of correctly rejecting a null hypothesis increase. The *p*-value of 0.05 was considered appropriate for the research because it provides the balance between making Type I and Type II errors (rejecting and accepting a null hypothesis wrongly, respectively) without risking a devastating consequence when concluding the results, unlike in the case of medical tests, for example, which would require a more stringent level of error probability. It is noteworthy, however, that 0.95 is an arbitrary measure driven more by culture and tradition in this type of research rather than any inherent internal validity. Therefore, one may hypothesise that a level of 0.94 or 0.96, for example, is as valid as 0.95.

In addition to the level of significance expressed as the *p*-value, the power of a study is also influenced by the number of participants in the study, the type of experimental design (discussed previously in Section 3.4.4), the type of statistical test (discussed below), and the size of the effect expected to find (*ibid.*). The effect size indicates the magnitude of the difference between the means of two experimental conditions in terms of standard deviations, and is calculated utilising Equation 3.1.

$$\text{Effect size } (d) = \frac{\text{mean of condition A} - \text{mean of condition B}}{\text{mean SD of conditions A and B}} \qquad \textbf{(3.1)}$$

In the first field-based experiment, for example, one display design type had an effect size of 0.58 (Table 5.3), which indicates that the given display condition outperformed the baseline condition (no displays were installed) by more than half a standard deviation. Therefore, effect sizes help to interpret the results, as statistical significance is heavily dependent on sample size but does not equal practical importance, which is the worthiness of spending time, money and/or resources to pursue in the real world. It is possible that a study has a large number of participants and yields a statistically significant finding, but has a very small effect, while the opposite situation could also be true. For example, there may be a significant difference between two new medical drugs that one is more effective, but more expensive, than the other one in treating a certain disease, but their clinical risks of developing severe side effects are in the same category, such as “High”; therefore, it may not be practical to develop the more expensive one while patients would probably not be able to tell the difference in the effectiveness and the side effects between the two drugs.

In the laboratory-based studies, due to lack of reports on effect sizes in the previous work in the area, this research used an effect size of 0.3, which is a conservative estimate of effects according to the guidelines developed by Cohen (1988), to determine the sample size. Irrespective of the statistical significance, for Cohen’s *d*, an effect size of 0.2 is considered as a small effect, meaning that the difference between two groups’ means only differs by 0.2 standard deviations and is seen as trivial. It can probably be picked up in carefully designed study. On the other hand, a 0.8 effect size means a substantial difference between the two means (Walker, 2007-2008).

Data were evaluated visually for approximating a normal distribution by means of frequency histograms. Where the distribution of a set of data was skewed, a square-root transformation was applied. A square-root transformation can correct for positively skewed distributions that show a left-sided skew, which was found in all cases where data were not normally distributed in this research, by taking the square root of the entire set of data and changing the *x*-axis values. To reduce positive skew, the higher values on the right-hand side of the *x* axis are the ones that need to be changed more than the lower values on the left-hand side. The effect of square rooting a number is larger the bigger the number was originally because large numbers change a lot more than small numbers when taking the square root. Large values on the *x* axis are brought closer to the centre (the mean) as a consequence (Holt and Walker, 2009; Field, 2013).

3.7.1.2. F-tests

Analysis of variance (ANOVA) was used to test whether there was a significant difference between the display designs used in the research by comparing their means with the grand mean. ANOVA is a relatively robust test for small violations of skewed distributions and unequal variances between conditions being compared when group sizes in different conditions are equal (Dancey and Reidy, 2011; Field, 2013).

The accuracy of ANOVA depends on the assumptions that the data points in different conditions are independent, i.e. one data point does not influence another; and that the average spread of the data points of one variable is relatively similar at all condition levels of another variable, i.e. homogeneity of variance (Field, 2013). Therefore, in repeated-measures ANOVA, an additional assumption of sphericity is made and assumes that the level of dependence between pairs of experimental conditions is similar (*ibid.*). To check for the homogeneity of variances of the differences between conditions, Mauchly's test is used. If the *p*-value in Mauchly's test statistic shows a significant difference between the variances, the assumption of sphericity is violated. On the other hand, if Mauchly's test statistic is non-significant, the variance of the difference between the means of the two experimental conditions in question is roughly equal (*ibid.*). When the condition of sphericity is not met, there is a risk of making a Type I error (rejecting the null hypothesis wrongly) and a loss of power. An alternative when sphericity is not assumed is to use multivariate test statistics (see MANOVA below) because they are not dependent upon the assumption of sphericity (O'Brien and Kaiser, 1985), and they take account of the correlations between dependent variables (Huberty and Morris, 1989). As this research carried out a repeated-measures design, which used the same participants in all experimental conditions, there was likely to be some correlation in the conditions. In all cases where an unequal variance was found, the Greenhouse-Geisser estimate within Mauchly's test tables was used, which adjusts the degrees of freedom associated with the F statistic for the effect of sphericity, and the corrected *p*-value was reported in the results (Field, 2013).

In the research studies where there was more than one independent variable, there existed a possibility of an interaction between the independent variables, because the effect of one independent variable on the dependent variables may depend on the condition of the other independent variable (Dancey and Reidy, 2011). For instance, the gender type and display design type in the laboratory-based tests might interact to influence task performance. If gender was found to have an interaction with the design type, then it would not be a simple question of whether males performed better than females, because it depended on the type of design: males might have a higher accuracy score with the numerical design than females, but females might have a better performance in the ambient condition. Similarly, it would not be a straightforward conclusion that the numerical design was the easiest design in which to see changes; it depended on the gender group.

When the first laboratory-based experiment was compared with a different sample group in a comparative experiment that used the same experimental design and procedure as the first laboratory experiment (see Section 7.4 Appendix D), a multivariate analysis of variance (MANOVA) was used to determine whether task performance differed between the two groups due to the differences in participant characteristics. MANOVA is an extension of ANOVA that measures more than one dependent variable (Field, 2013). An alternative approach for comparisons was to conduct multiple ANOVAs or t-tests (see below) with each of the display design conditions as a dependent variable to see if there were any differences between the two sample groups (the independent variable) (Dancey and Reidy, 2011). The main concern with carrying out several tests on a set of data is the increase of the likelihood of making a Type I error due to running a set of tests that come from the same family on the same data set. MANOVA reduces the familywise error rate by allowing all the dependent variables to be analysed in one analysis, and takes account of the relationship between these variables (Dancey and Reidy, 2011).

Analysis of covariance (ANCOVA) was also used in the research. In the second field-based experiment, the increasing day length was identified as a continuous variable (covariate) that was not part of the main experimental manipulation but could affect the change in energy consumption during the experimental period. Nonetheless, it was possible to control the influence such a variable had on energy consumption by including it in the analysis (Field, 2013). After controlling for the effects of the covariate, the resulting test was ANOVA.

3.7.1.3. T-tests

In situations where there was a significant interaction between the independent variables, t-tests were carried out to break down this effect, looking at how one independent variable interacted with the other one at individual condition levels (*ibid.*), by comparing the means of two conditions at a time. In determining the effects of the gender type and display design type on task performance as mentioned in the previous section, an independent-samples t-test was used, where male participants and female participants were treated as independent groups (one cannot be male *and* female), to see which condition was contributing to this effect. On the other hand, when there was an interaction between the display design type and colour type, a paired-samples t-test was conducted because each of the display design types could be presented in different colour conditions due to the repeated-measures design of the research.

3.7.2. Qualitative data

As qualitative data are exploratory in nature and are used to gain an understanding of underlying reasons and motivations from a small group of people, they are not amenable to statistical analysis, although tests can be done to determine the association between variables and the strength of the relationship. This implies that findings are not conclusive and cannot be used to make generalizations about the population of interest. Instead, it falls to the researcher to organise the data in a meaningful way, and to interpret what they mean (Dye, 2001), by sorting responses into themes and looking for patterns of recurring themes.

In the laboratory studies where open and closed interview questions were used, the range of themes was small, even with open questions. In considering the disadvantage of open questions that require greater effort from respondents, the questionnaire used in the field study asked closed ended questions. In order to gather responses that were not covered by the fixed questions, and to give participants an opportunity to elaborate their answers in the questionnaire, follow-up open-ended questions were asked in the interview. Once again, the range of response themes was small (see the relevant discussion sections in Chapter 4 and Chapter 5).

3.8. Chapter conclusion

This research, in summary, used a mixed-methods strategy, in which quantitative data were collected through an experimental approach and questionnaires, and qualitative data through interviews. A pilot study to determine if the planned work was worthy of further testing was conducted before the implementation of the main laboratory-based experiment. Live data on energy consumption were collected in the field-based study along with participants' subjective feedback and were analysed to assess the effects of different IHD designs.

Chapter 4 Designing in-home energy displays

4.1. Introduction

Chapter 2 outlined the literature on the design of IHDs and summarised that in order for the display to successfully act as an interface between people and energy information, and to convey comprehensible messages, the design of the presentation of information plays a pivotal role, which could influence people's perception of information. To gain a better understanding of how different display presentations work and if they differ from one other, this research compared three “pure” display designs in laboratory- and field-based studies. This chapter describes the laboratory work.

Despite the general support for a positive effect of IHDs on reducing energy consumption (e.g. Petersen *et al*., 2007; Fischer, 2008; Faruqui *et al*., 2010), previous research has been marked by a lack of detailed descriptions of how their experiments were designed. As a result, a pilot study was first conducted to determine if the proposed experiments would work (design-wise), and if the results found in the experiments were worthy of further testing (subject-wise). Experiment 1 incorporated the results learned from the pilot study and focused on a narrower scope of experimental work.

4.2. Pilot study: display design types, colours, character sizes and locations of display components, and participant preferences

The objectives of the study were threefold:

a) Compare different “pure” display design types to determine if they vary in the way they provide information.
b) Examine three design features, namely colour, character size and location, of display components in each of the display designs to

determine how effective they are in attracting attention to the change in information shown on the display.

c) Investigate the effects of age and gender on task performance.

The study tested three “pure” display designs categorised according to Darby’s classification of feedback presentation types (2009) (see Section 2.4.3) to see how well they could present energy information to people in the time span of a glance. Typically, the information about energy use on an IHD changes on an ongoing basis, and people are not focused on the display all the time. If their interaction with the display is only an occasional glance, then the display must be designed in such a way to attract people’s attention and to minimise their search time to give them comprehensible and sufficient information that is needed to modify their behaviour (Wood and Newborough, 2003).

The design of commercial energy displays generally tends to include more than one display component at a time on the display screen. This inevitably brings in a hierarchy of relevance, which requires using highlighting features in order to get people’s attention to the information that is important to them. The study incorporated different colours, locations and character sizes of the display components in the design to determine how these design features could facilitate the detection task.

In addition, demographic variables may have an influence on task performance, but previous work on display design has not put sufficient focus on these factors. For a feasibility study like the present one, age and gender were included in the analysis (the outcomes of this study will determine what other variables may also be added in subsequent experiments).

The results of this study have been published at a conference (Chiang *et al*., 2011).

4.2.1. Method

To mimic the changing information on an energy display, the experiment involved a computerised spot-the-difference task, using pre-change and post-change versions of energy information on computer-simulated energy displays. Participants were interviewed after the task to self-evaluate their performance and to choose the display design they liked and disliked.

4.2.1.1. Participants

A total of 18 male and 22 female volunteers[15] aged between 23 and 59 years (mean = 34.1, compared with national median = 39.7 (ONS, 2013), SD = 10.9) (Table 4.1) were recruited through opportunity sampling. Participants were students and staff members of the university where this study was based at. Advertisements for participants were put on the University's internal web pages, asking for volunteers of male and female of any ages. The only requirement was that participants had normal or corrected to normal vision, and were not suffering from any eye diseases that may affect everyday tasks.

Table 4.1. Age and gender details of participants in the pilot study

Age	Male	Female	Total
20-29	9	11	20
30-39	5	4	9
40-49	3	3	6
50-59	2	3	5
Total	18	22	40

4.2.1.2. Materials and experimental design

Tasks ran on a personal computer with a 17-inch colour LCD monitor. Ergonomically, to maintain the neck in a neutral, relaxed posture, the viewing distance between the monitor screen and the participant was 600-700 mm, which is roughly an arm's length (Ergonomics in Australia, 2010), and the monitor was positioned at eye level. The inclination of the monitor was about

[15] The number of participants required to achieve a power level of 0.95, assuming an effect size of 0.30 and an error probability of 0.05, was determined using G*Power 3.1.2, a programme developed by Faul *et al.* (2010) to compute power analyses for a number of statistical tests.

100 degrees from horizontal. To ensure glare on the monitor screen was minimised, the testing was set up in the corner of a lecture room, and the screen was placed facing away from the window (Figure 4.1).

a) b)

Figure 4.1. Setup of experimental environment

The experiment used a repeated-measures design, in which participants performed under all the display design conditions, and consisted of 3 design types x 5 display components x(6 colours + 3 sizes + 4 locations) = 195 pairs of test images which were displayed using the process shown in Figure 4.2 for each participant.

The test images were produced by using CorelDRAW X5 (Corel Corporation, 2010). As a result, the test images were pre-designed and were stored on a local computer. The application developed for the experiment was written in C# using Visual Studio Express (Microsoft Corporation, 2010). The experimental data were stored on a Structured Query Language (SQL) server (Microsoft Corporation, 2008). The programme read the image file paths and saved these paths to memory as references in a collection, from which the images were randomly selected, displayed, and the file paths were removed. The process repeated until there were no more image files left in the collection, the score was then calculated and given to the participant.

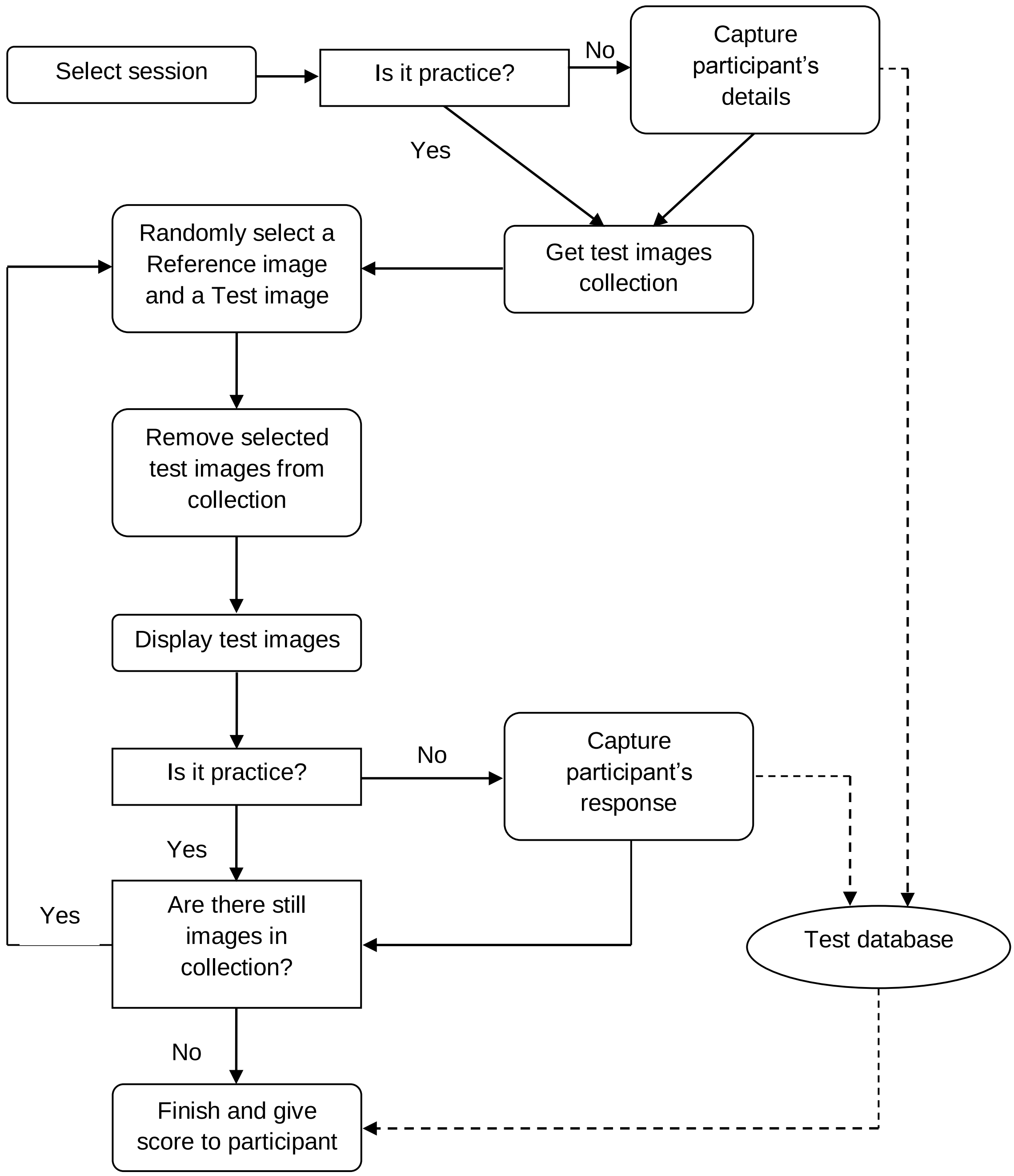


Figure 4.2. Flowchart showing how the pilot experiment was designed

The file names of the test images were formulated to indicate the type of display design, display component and the type of manipulation (see descriptions in (a),

(b) and (c) below for the experimental design of display types, display components and design features), so that participant's accuracy rate could be calculated. For example:

File name: 11-C-R0-S	
1	Display type: numerical
1	Target display component:" Today so far"
C	Design feature: colour
R	Red
0	No change in value
T	"Same", i.e. no change in value
File name: 22-S-LM-B	
2	Display type: analogue
2	Target display component: "Last 24 hours"
S	Design feature: size
L	Original size: large
M	New size: medium
B	"Better", i.e. decrease in energy use
File name: 33-L-32-W	
3	Display type: ambient
3	Target display component: "Power now"
L	Design feature: location
3	Original location
2	New location
W	"Worse", i.e. increase in energy use

a) Display designs

The three types of display design that were used to examine their effects on presenting the same energy information (Figure 4.3) were:

- Numerical design that used purely numbers to test for participants' familiarity in daily activities.
- Analogue design that showed information in speedometer dials and bars to test for subjective preference.
- Ambient design that used two-dimensional cartoon-like faces with appropriate emotions representing different levels of energy use to test for their attention-capturing quality.

a) Numerical design b) Analogue design c) Ambient design

Figure 4.3. Types of display design

b) Display components

The design of the display components was based on Wood and Newborough's work (2003) who studied householders' reactions to energy information displayed by energy consumption indicators (ECIs) on their electric cookers. The design also adopted Anderson and White's (2009) design principle of "Keep it simple" (discussed in Section 2.4.2). Thus the present experiment consisted of six display components, representing six states of energy consumption: "Power now", "Today so far", "Last 24 hours", "This week", "Last week" and "Ranking".

As discussed previously in the literature review in Chapter 2, comparisons can be effective in motivating behavioural change (Wood and Newborough, 2007a). Here, self-relative comparisons (historical feedback) and other-relative comparisons (normative feedback) were embedded in the display components. The component "Power now" represents the power value required by the current energy-use event. "Today so far" shows the cumulative energy consumption since the start of the day; while "Last 24 hours", "This week" and "Last week" provide the total cumulative consumption values for different lengths of time period in the past. These four components illustrated self-relative comparisons, whereas the component "Ranking" represented other-relative comparison that enables one to identify where they stand in the situation and how well they have done compared with others with similar characteristics and situation.

The consumption values ranged between low and high levels. Low levels of consumption were represented by smaller numerical values in the numerical design, dials and bars pointing towards the left-hand side of the display in the analogue design, and happier faces in the ambient design. Conversely, “Ranking” was presented in a reverse order – the smaller the value, the higher the rank level, thus the lower the consumption level – to associate with the concept of “first place”, “second place” and “third place”. Note that the consumption values in the design were merely used for illustration purposes; therefore, the consumption level was relative to the one with which it was compared.

c) Design features

   i) Colour of display component

   Each display design had a black version (RGB (0, 0, 0)) and a coloured version. The overall background colour for all test images in both versions was white (RGB (255, 255, 255)). In the black version, only black was used to represent the energy information. The black version was, however, not included in the colour test. Six colours were tested in the coloured version. Five of them were chosen from the primary and secondary colour ranges in the colour-mixing methods (discussed in Section 2.4.5), and a non-chromatic colour was included (see Section 2.4.5). For this study, the colours had no associative meanings of energy consumption.

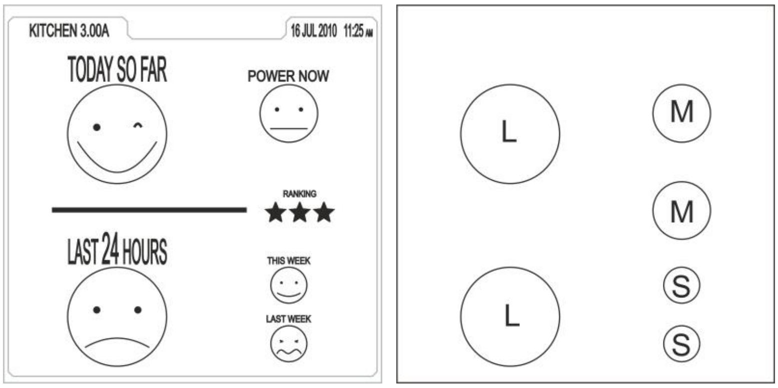
   - Chromatic colours: red (RGB (255, 0, 0)), blue (RGB (0, 0, 255)), yellow (RGB (255, 255, 0)), green (RGB (0, 255, 0)) and orange (RGB (255, 128, 0)).
   - Achromatic colour: medium grey (40% black, RGB (153, 153, 153)).

ii) Character size of display component

The size for each display component was determined by the hierarchy of relevance and was preset to small, medium or large. The most important information was expected to be the one about the recent consumption events, which should, therefore, be in a large character size. Components "Today so far" and "Last 24 hours" provide cumulative consumption values that are the most relevant to the present; therefore, they were set to a large character size. The component "Power now", which provides an instant consumption value resulted from a current event, such as boiling the kettle, may only be useful at that particular moment. Thus the character size was set to Medium. "This week" and "Last week" give the total cumulative consumption values in the past, which could be used as references for projected consumption. They are assumed to have a less immediate impact on the current situation and may not be as interesting to people as other components; therefore, they were in a small character size. The component "Ranking" was not included in the size test due to its inconsistent design compared with other display components.

Figure 4.4 shows the sizing system of the display components. The size of each display component was relatively proportional to the size of the display as shown in Table 4.2.

a) Numerical design　　b) Analogue design　　c) Sizing system for numerical and analogue designs



d) Ambient design

e) Sizing system for ambient design

Figure 4.4. Sizing system for the display components, showing their proportional relationships to the length and width of the display

Table 4.2. Ratios of display component sizes to display size

	Numerical & analogue designs		**Ambient design**
Size	**Length**	**Width**	**-**
Large (L)	50%	25%	25%
Medium (M)	30%	10%	15%
Small (S)	30%	5%	10%

The ratios were determined by increments of 5% to facilitate calculations. On a 17-inch monitor screen, for example, the size of the display would appear to be 140 mm x 140 mm, then the length of size Large in the numerical design would be 140 mm x 50% = 70 mm, and width 140 mm x 25% = 35 mm. The legibility of the display components from a viewing distance of 600-700 mm was taken into account in the design process, keeping the smallest character size no less than 7 mm in width, which was equivalent to font size 20 in Microsoft Word documents, on a 17-inch monitor screen.

Table 4.3 shows the increase and decrease percentages of the display components from their original sizes. The percentages were determined by the availability of space on the display. For the numerical and analogue displays, the shapes of the display components were seen as rectangles. The components “Today so far” and “Last 24 hours”, representing size Large, were reduced to sizes Medium and Small in their lengths and widths as per Table 4.3. But the components “Power now” (medium size), “This week” and “Last week” (small size) were changed by an increase or a decrease in their widths, not their lengths, because 1) there was no more space on the display for the components to expand horizontally, as shown in Figure 4.4; 2) it helped to align the components vertically on the display when they changed their sizes. For the ambient design, the display components were seen as perfect circles in shape, i.e. equal length and width; therefore, the components were changed proportionally according to the Table.

Table 4.3. Changes in size of display components

	Numerical			Analogue			Ambient		
Original size	**L**	**M**	**S**	**L**	**M**	**S**	**L**	**M**	**S**
Large (L)	-	85%	67%	-	85%	67%	-	75%	55%
Medium (M)	140%	-	67%	140%	-	67%	140%	-	67%
Small (S)	200%	150%	-	200%	150%	-	150%	125%	-

iii) Location of display component

The six display components were grouped into five blocks on the display. Except for the components “This week” and “Last week”, which were grouped together as one block for being on the lowest level in the hierarchy of relevance, the rest of the components stood as individual blocks in the layout. To organise five blocks on the display and to keep the layout simple, three options were considered: 1) place them linearly across the display, be it vertically, horizontally or diagonally; 2) lay one block in the centre and the rest in each of the four corners or four sides of the display; 3) arrange two rows of blocks vertically or horizontally, one row containing two blocks and the other row containing three blocks. From a design point of view, Option 1 gives a simple, uncluttered layout, but the display space would be underused, leaving a lot of space around the row of blocks and reducing the size of each block considerably. This layout also becomes less visually effective when with more than three objects because the positioning of objects becomes less obvious. Nevertheless, Option 1 may best be used in testing the positioning of two or three blocks. Option 2 gives a loose layout that leaves gaps between the blocks sitting in the corners or on the sides of the display, which could, again, forfeit the possibility of maximising the size of the blocks. It would probably serve as a useful layout if a display component that is of interest to people is shown in the centre of the display with the use of the design feature, such as colour, large character size, etc. to distinguish it from the rest of the display components. Option 3 gives an advantageous layout with two linear rows of two and three blocks, and overcomes the shortfalls of Options 1 and 2, thus creating a compact layout. The only downside of this layout is that the central location of the display cannot be examined. Figure 4.5 shows the division of five blocks on a numerical display used in the experiment. Each of the display components was tested in four locations on the screen as shown in Figure 4.6.

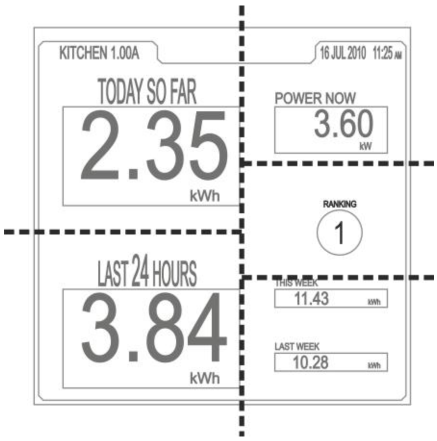
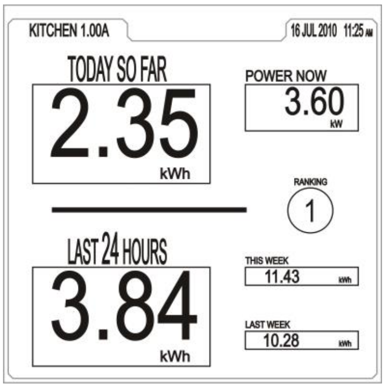
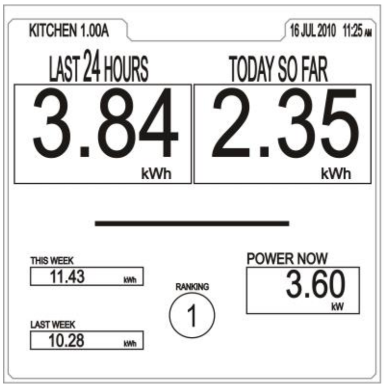


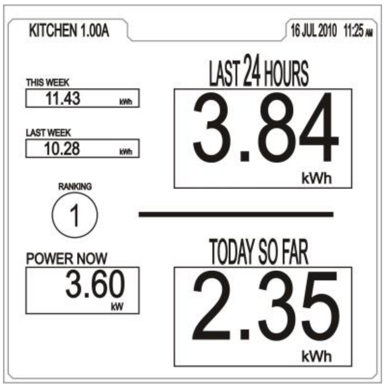
Figure 4.5. Display components arranged in a five-block layout



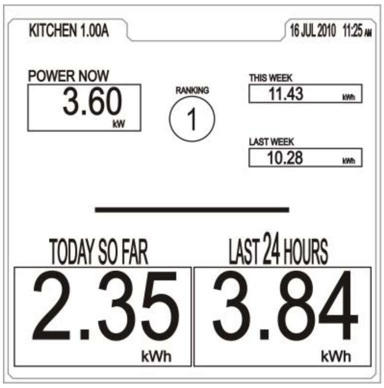
a) Layout 1



b) Layout 2



c) Layout 3



d) Layout 4

Figure 4.6. Display components tested in four locations

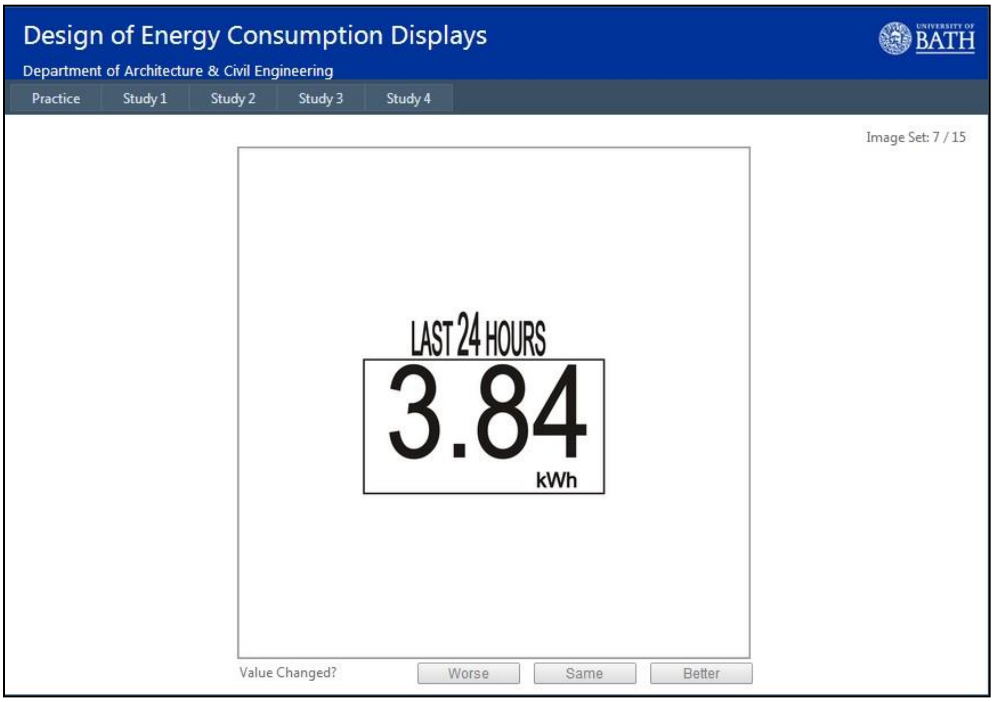
d) Measures of task performance

Tasks were measured in response time and accuracy rate. Response time was measured in milliseconds (ms). Accuracy rate was calculated in percentages (%) of correct answers, incorrect answer and no answer.

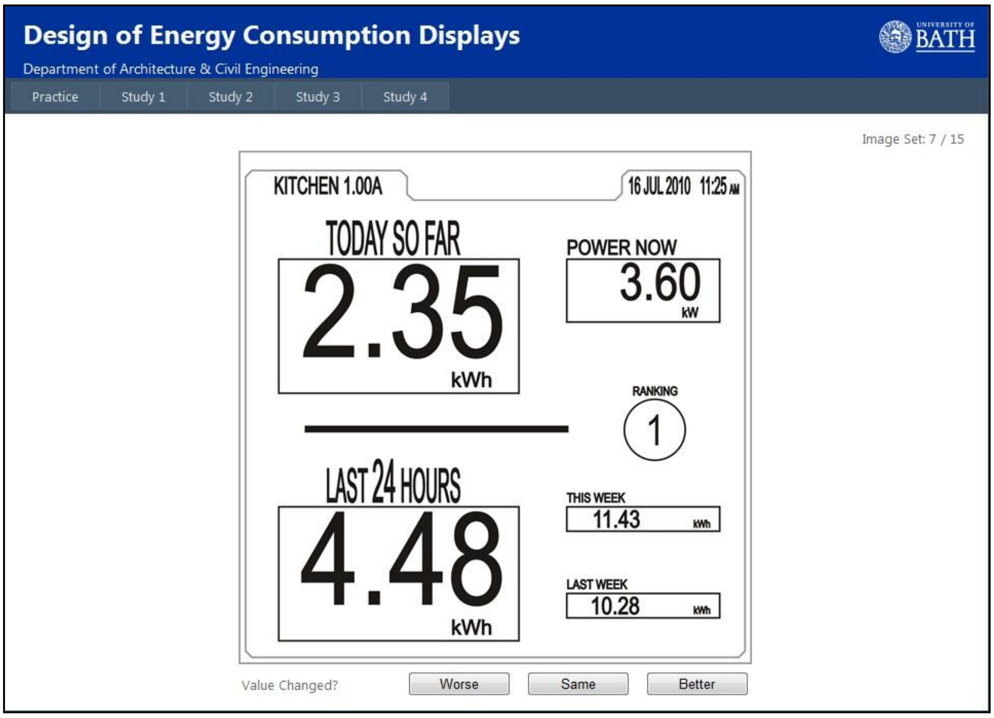
4.2.1.3. Experimental procedure

An information sheet introducing the purpose of the study was given to participants at the beginning of the test session, followed by them signing a consent form after agreeing to take part (see Section 7.1.1 for the information sheet and Section 7.1.2 for the consent form in Appendix A). Participants then received oral instructions and a written version of the same instructions on the computer monitor. The instructions outlined the procedure for the experiment and what participants were expected to do. Printouts of the three display designs and their pre- and post-change versions were shown to participants, before they proceeded to a practice session of 15 pairs of test images. Participants' attention was drawn to the time limit imposed on the test images and they were told that their score would be given at the end of the test session. All these were done to ensure that participants were fully aware of what the experiment involved, and that they had a chance to ask questions before and after the practice session. Due to the time limit in the test, participants might not always have enough time to re-check all the display components before making a response during the test session. Therefore, the practice session served as a warm-up exercise and showed participants what displays they were about to see without them getting familiar with the designs.

The computerised task involved detecting the nature of the change in information between two images. The first image of each pair, called the "Reference" image (Figure 4.7a), displayed a target display component in the centre of the monitor screen for three seconds. The target display component in the "Reference" image was always displayed in black and in its preset character size. The second image, called the "Test" image (Figure 4.7b), showed both the target display component and other components for another three seconds. The reaction time was estimated by running a quick test on two male and three female volunteers. Three seconds was found to be close to the time span of a glance, and was long enough for the eyes to fix on the target display component in the "Reference" image. Another three seconds was enough time for the eyes to search for the target display component among other components in the "Test" image and for making a response.



a) The “Reference” image



b) The “Reference” image

Figure 4.7. An example of the paired test images

Each pair of images used the same display design (numerical, analogue or ambient). The display design and the design feature (colour, location or size) changed randomly from pair to pair. The target display components in the "Reference" image and the "Test" image might differ in value. Participants were asked to determine as quickly and accurately as possible if there was a change in the value of the target display component, and if the value had got better (decrease in energy use) or worse (increase in energy use). In order to ensure that the time lapse between comprehension and response was minimised, the response for "Worse" was mapped to the keys "Alt" and "A", the response for "Better" was mapped to the "Alt" and "L" keys, and the response for "Same" was mapped to the keys "Alt" and "J" on a standard UK keyboard.

Given that the total number of test images was 390, and that the amount of time required to finish all the test images was 19 minutes 30 seconds per participant, it was possible that fatigue and practice effects might occur (discussed in Section 3.4.4). To counterbalance these effects, the orders were randomized. The test images were divided into four sub-test sessions. Each sub-test session consisted of an equal number of test images of the design features and design types (48, 49, 49, 49 pairs). The test images and the sub-test sessions ran in random order for each participant, the maximum time length required to complete a sub-test session was approximately 5 minutes, and a short break was taken after a sub-test session was completed.

After the computerised task session, participants were interviewed to provide feedback on the display designs, components and the design features with regards to the ease of reading, understanding and comparing information in the test images. They also expressed their likes and dislikes for the display designs.

4.2.2. Results

The interaction effects of age and gender were first examined on accuracy rate and response time of design types, colours, character sizes and locations of the display components.

4.2.2.1. Age

Results showed that age had no effect on the type of display design, colour, character size or location; only the difference among the age groups affected task performance, but not significantly.

Figure 4.8 and Figure 4.9 show that the 50-59 years group in this experiment, on average, took longer to make a response, and had a lower accuracy rate than younger groups (70.5% versus 82.7% for 20-29 years, 76% for 30-39 years, 77.3% for 40-49 years), regardless of the design types, colour, location and size of the display components. Further, their 18.9% of non-response rate (3000 ms) resulted in a higher average in response time than younger groups (2576 ms versus 2324 ms for 20-29 years, 2445 ms for 30-39 years, 2449 ms for 40-49 years).

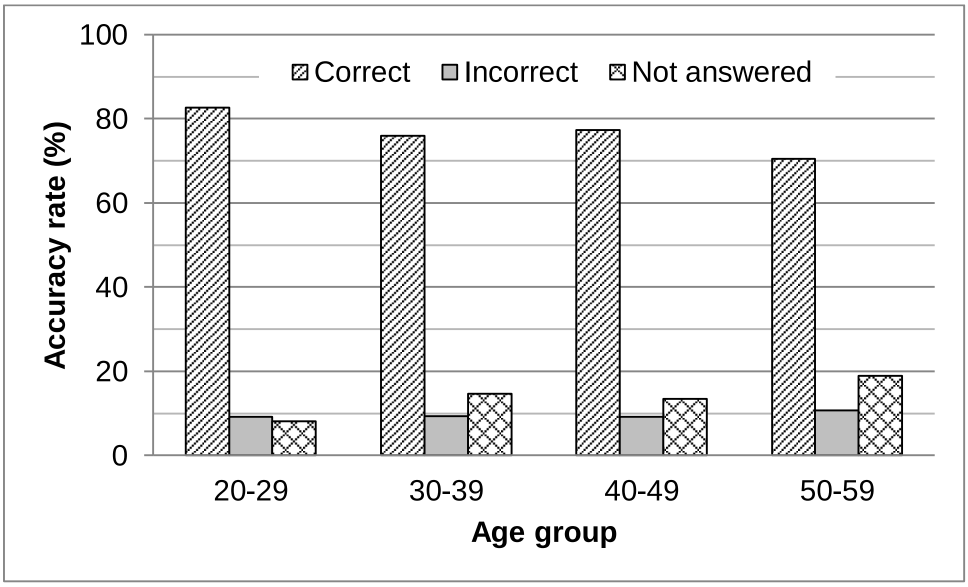


Figure 4.8. Effect of age on accuracy

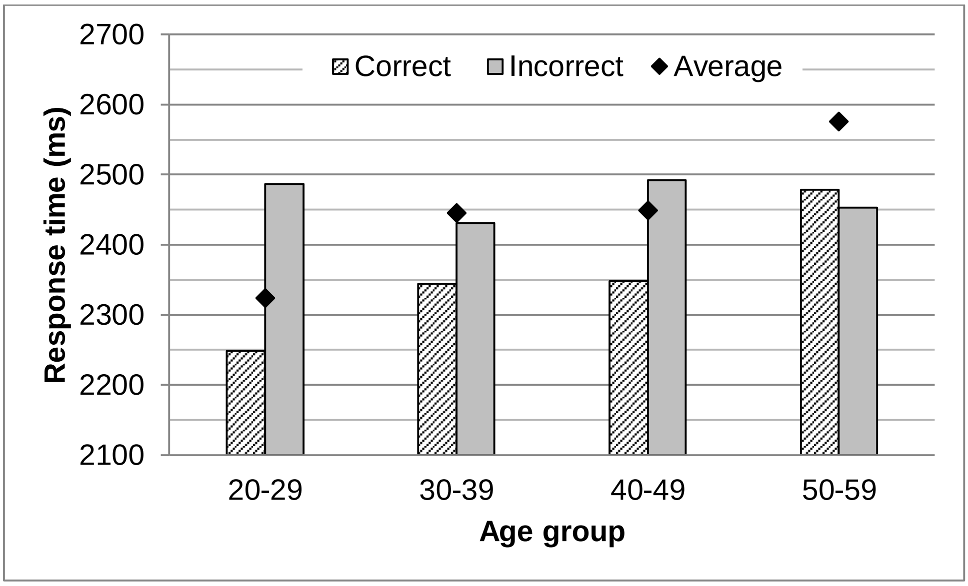


Figure 4.9. Effect of age on mean response time

4.2.2.2. Gender

Gender type was also found to have no effect on the overall accuracy rate and response time across the design types, colours, character sizes and locations of the display components.

Figure 4.10 and Figure 4.11 show that male and female participants, on average, had similar performance in accuracy (80.1% for male, 77.8% for female) and response time (2395 ms for male, 2407 ms for female). Although males were slower than females in the ambient design, an independent-samples t-test confirmed that the difference between males (mean = 2409 ms) and females (mean = 2380 ms) was small (Levene's test p = .289, $t(38)$ = .617, p = .541).

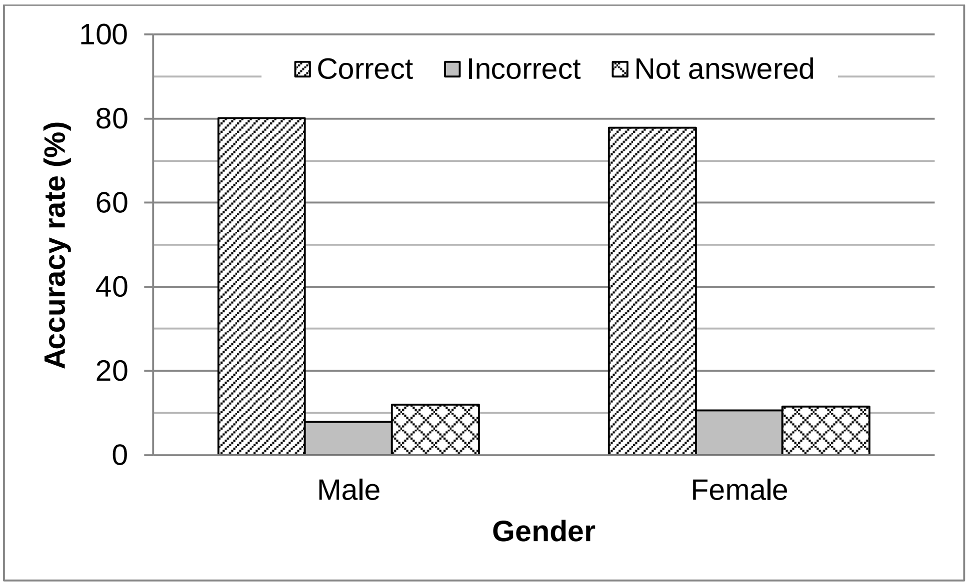


Figure 4.10. Effect of gender on accuracy

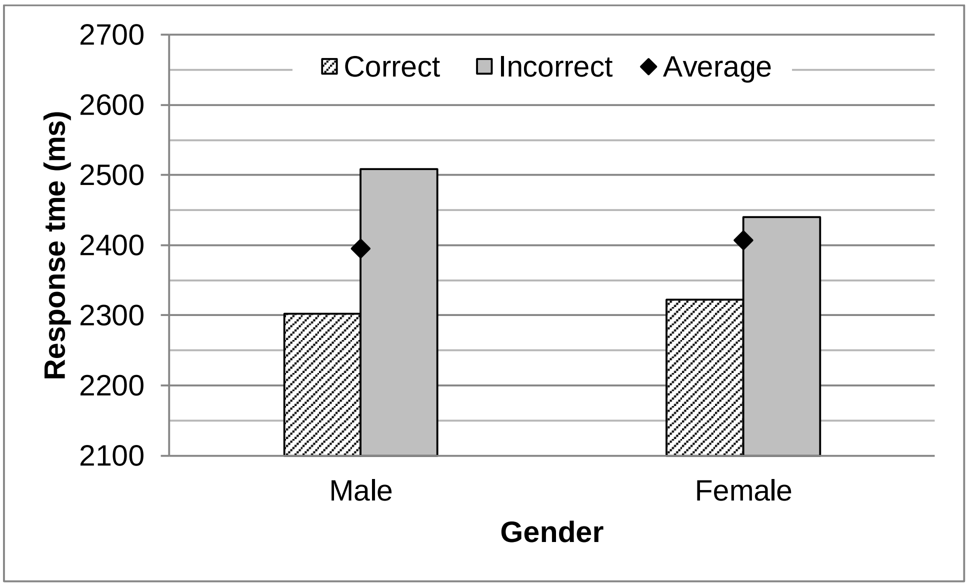


Figure 4.11. Effect of gender on mean response time

In light of the results above, in which the interaction effects of age and gender were ruled out, a repeated-measures analysis of variance was conducted to assess the effects of the design types and the design features on accuracy and response time. Detailed results are presented in tabulated form in Section 7.2 in Appendix B.

4.2.2.3. Display design type

Data from the experimental task were collated to obtain, for each participant, a mean response time and a mean accuracy score for each design condition. Results showed that the three designs differed in accuracy ($F(2,78) = 7.335$, $p = .001$) and response time ($F(2,78) = 20.932$, $p < .001$). The analogue design was found to have the highest accuracy rate (81.9% versus 76.5% for numerical, 78.4% for ambient), the lowest non-response rate (9.8% versus 14.9% for numerical, 10.4% for ambient), and the shortest mean response time (2364 ms versus 2446 ms for numerical and 2393 ms for ambient) (Figure 4.12, Figure 4.13). The numerical design led to poorest performance on accuracy and response time, with its high non-response rate indicating that participants had difficulty with finding the changes in the numerical condition. Lastly, the ambient design had response time similar to that of the analogue design, but it was associated with the highest percentage of incorrect answers (11.2% versus 8.6% for numerical and 8.3% for analogue), suggesting that this design type is more likely to be interpreted wrongly than the other two designs.

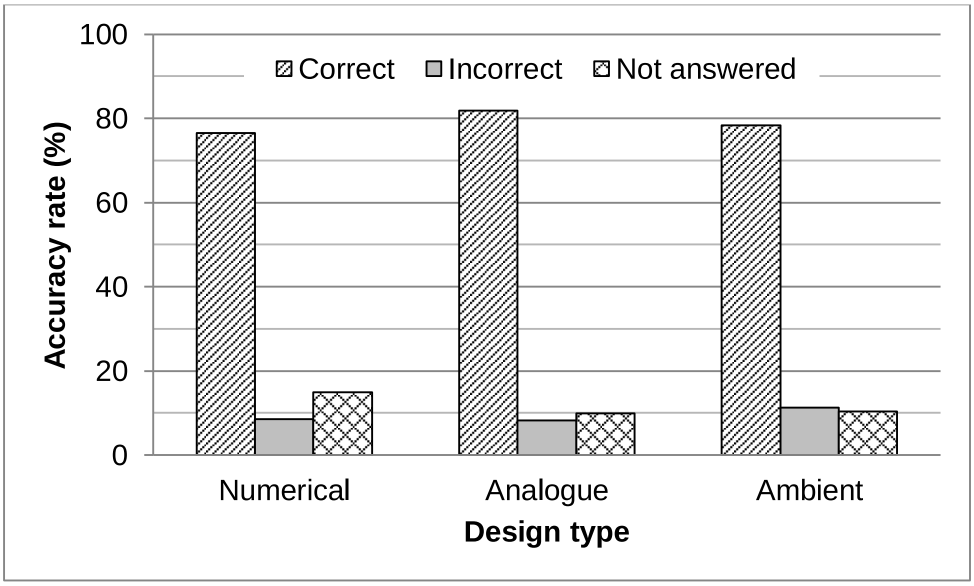


Figure 4.12. Mean accuracy rates of design types

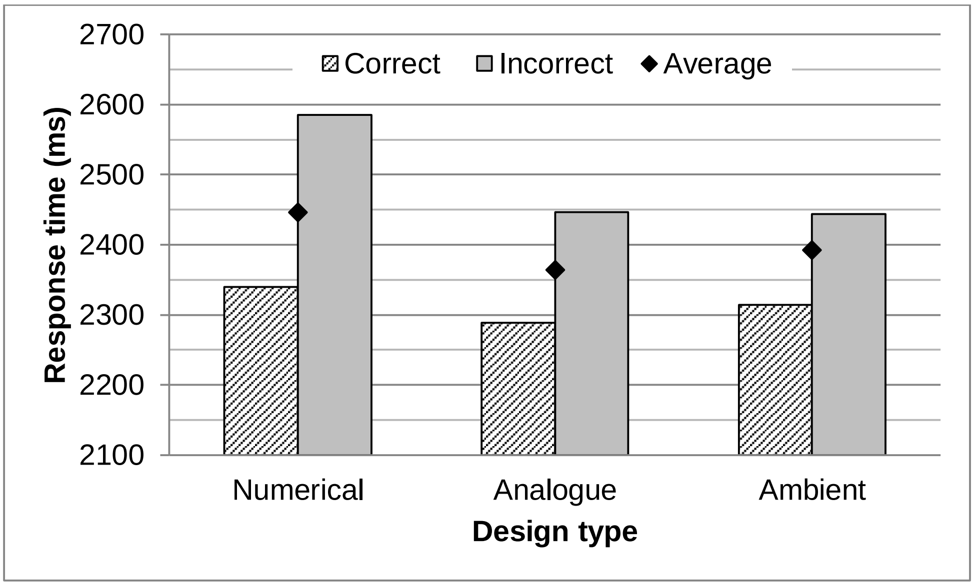


Figure 4.13. Mean response times of design types

4.2.2.4. Colour of display component

All six of the colour types used in the experiment had similar accuracy scores ($F(5,195) = .783$, $p = .563$), but differed in response time ($F(5,195) = 8.265$, $p < .001$).

Figure 4.14 and Figure 4.15 show that even if participants spent longer time in the yellow condition (mean = 2441 ms, correct response = 2356 ms, incorrect response = 2616 ms), an accuracy rate similar to the other colours was achieved (see Table 7.4 in Appendix B for mean differences of accuracy rate and response time of colour types). Red appeared to outperform all the other colours.

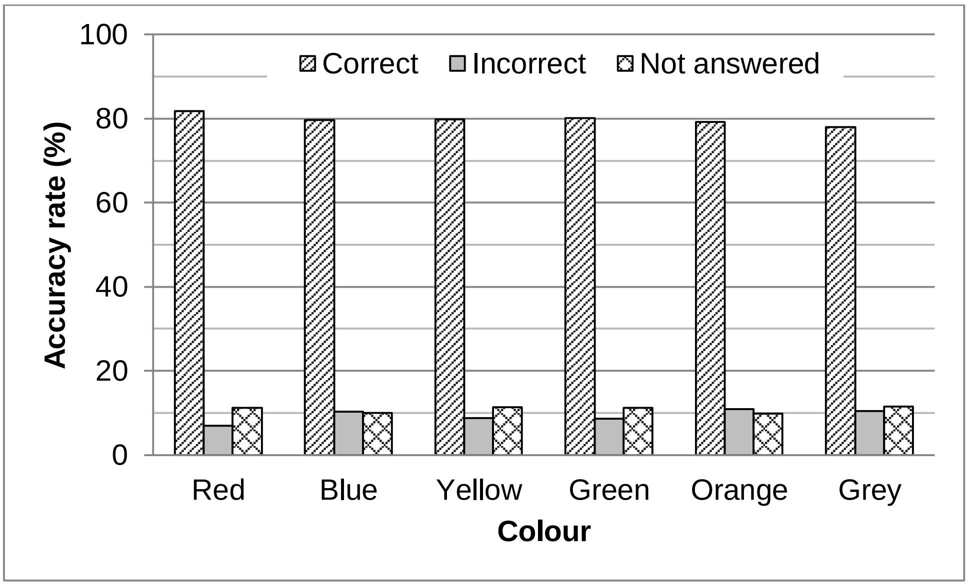


Figure 4.14 . Mean accuracy rates of colour types

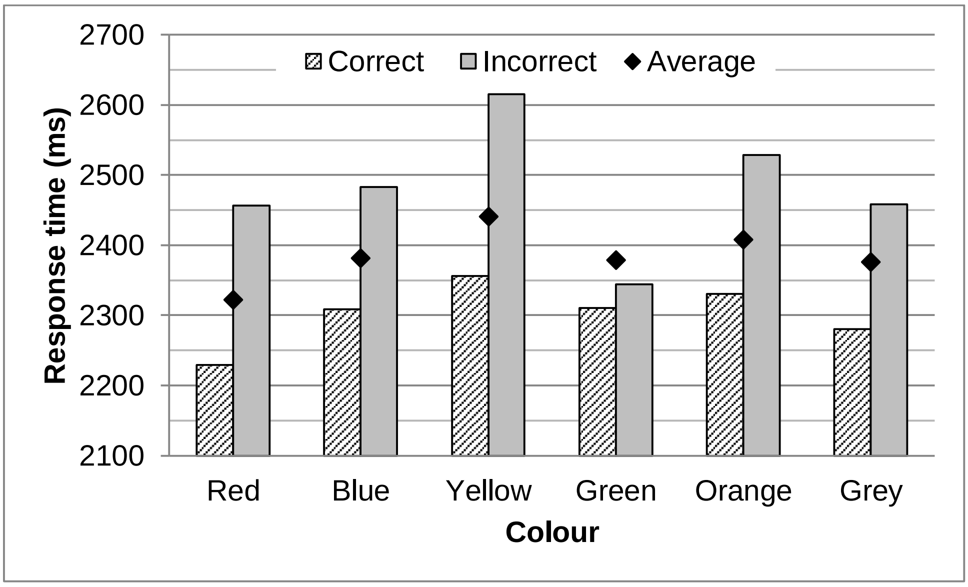


Figure 4.15. Mean response times of colour types

4.2.2.5. Character size of display component

The effect of character sizes of manipulated display components was analysed. Results showed that the three sizes differed in accuracy (F(2,78) = 16.178, p < .001) and response time (F(2,78) = 10.115, p < .001). The display components that changed to the medium size had the least accurate responses, the large and small sizes had slightly, but not significantly, different scores (82.4% for large, 70.7% for medium and 80% for small) (Figure 4.16).

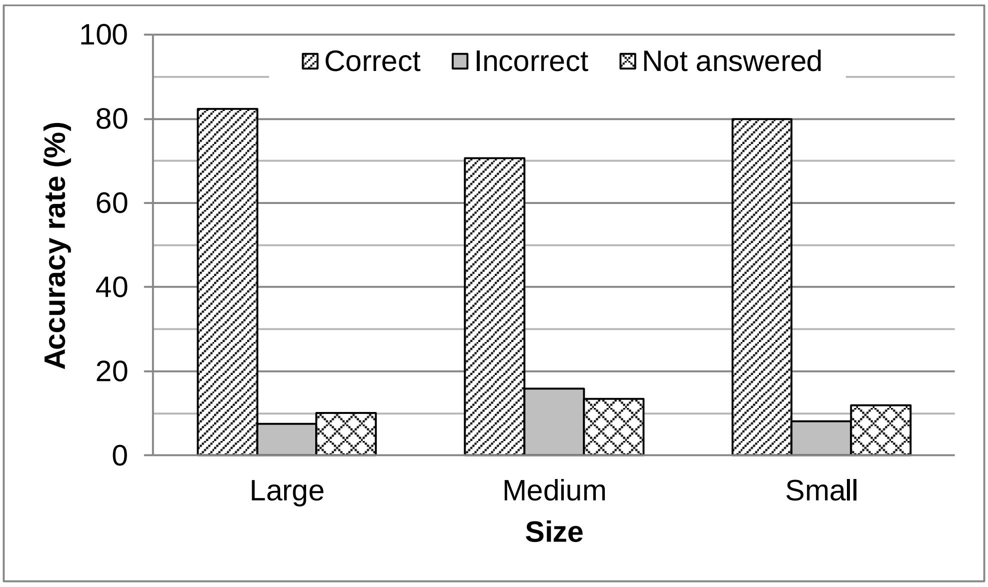


Figure 4.16. Mean accuracy rates of character sizes

A similar performance pattern was found in response time (Figure 4.17), with the medium sized components being associated with the slowest responses, and the large and small sized components having similar response times (2336 ms for large, 2435 ms for medium, 2337 ms for small). Although the medium size had a reaction time for incorrect responses similar to that of the large size, it had the highest inaccurate response rate (15.9% versus 7.5% for large, 8.1% for small), suggesting that participants were inclined to making mistakes when looking at the changing information in the medium size.

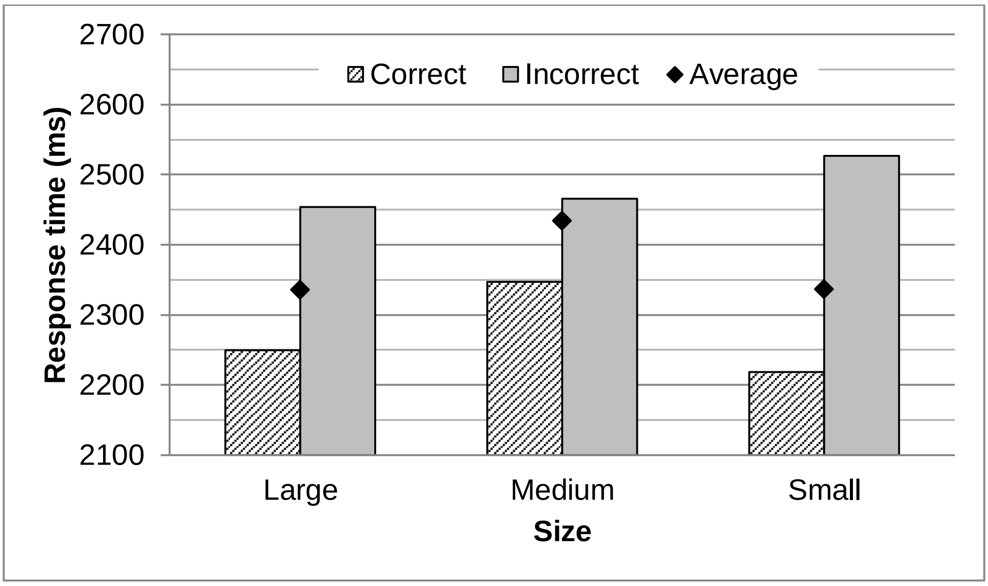


Figure 4.17. Mean response times of character sizes

4.2.2.6. Location of display component

Results showed that the four locations of the display components differed in accuracy ($F(3,117) = 2.879$, $p = .039$) and response time ($F(3,117) = 32.352$, $p < .001$). The manipulated components in the top left corner of the display had more accurate responses (80.7%) and a lower non-response rate (10.1%) than the components in the bottom left (75.7%, non-response rate = 13.9%) and bottom right corners (75.6%, non-response rate = 16.3%), while the top right location achieved a score (78.1%, non-response rate = 13.1%) that was similar to the other three locations (Figure 4.18, Figure 4.19).

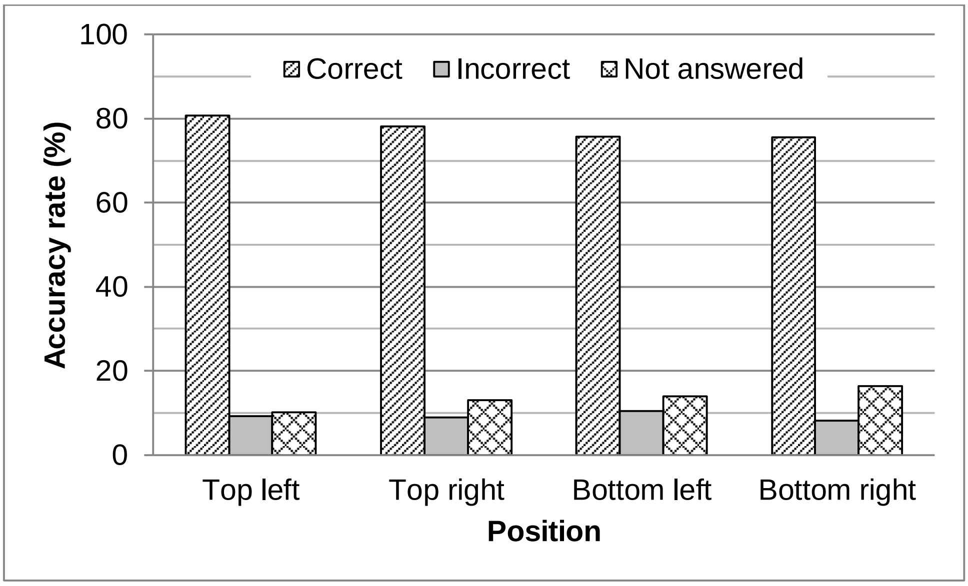


Figure 4.18. Mean accuracy rates of manipulated display components in four locations on the display

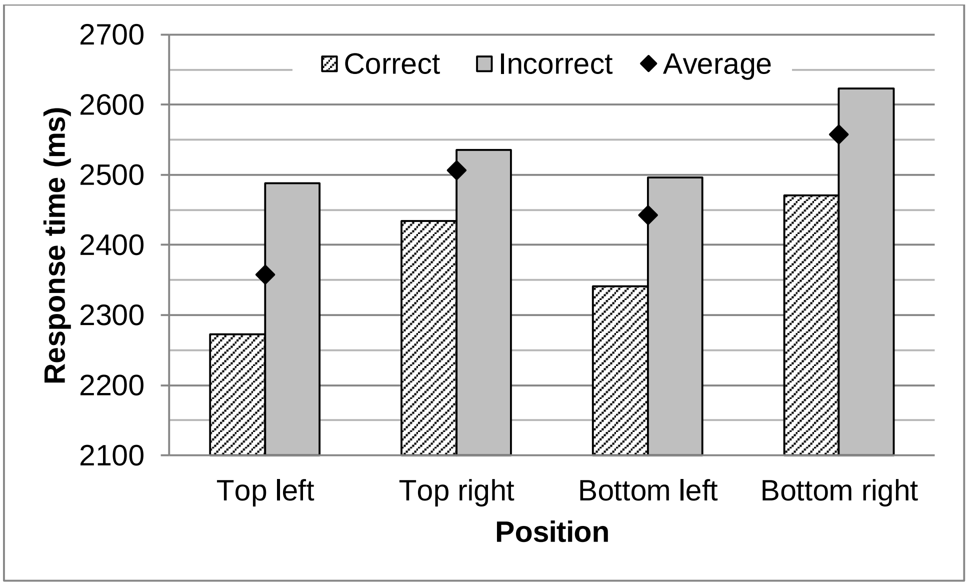


Figure 4.19. Mean response times of manipulated display components in four locations on the display

All four locations differed in response time, with the top left corner being associated with the shortest response time (2358 ms versus 2507 ms for top right, 2443 ms for bottom left and 2558 ms for bottom right).

4.2.2.7. Preference

An interview survey of participants' preferences (Figure 4.20) showed that the analogue design was the easiest design for seeing changes (67.5% versus 35% for numerical and 65% for ambient), while the numerical design was the most difficult design on which to spot changes (42.5% versus 20% for analogue and 37.5% for ambient).

When asked to choose only one display design that they would be willing to spend money on to have at home, 45% of participants chose the analogue display (32.5% for numerical and 22.5% for ambient) for reasons of ease of reading with a glance, balance between the information and the graphics, and familiarity associated with items such as analogue clocks and car gauges found in everyday life.

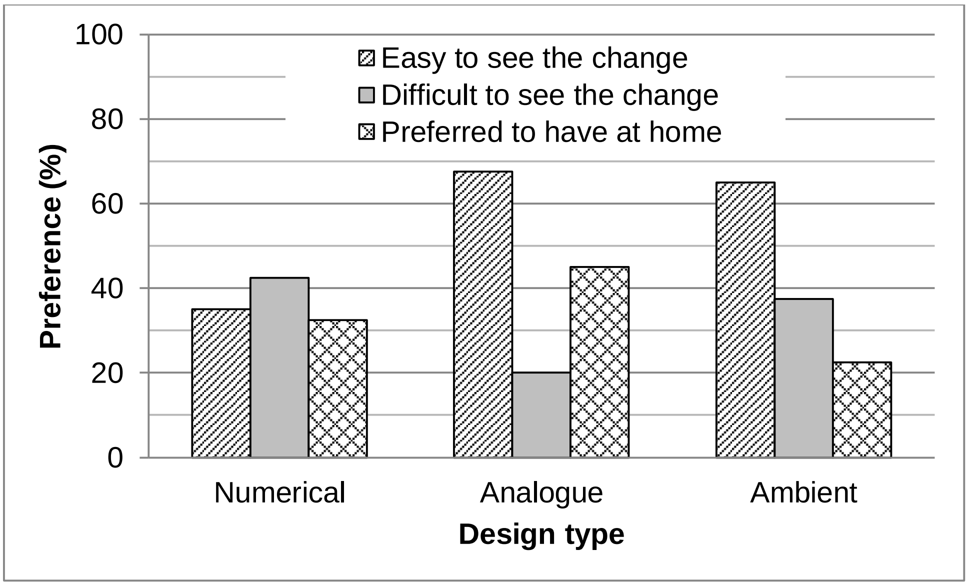


Figure 4.20. Display design preferencs

4.2.3. Discussion

Different display designs presenting the same information did not appear to communicate equally well to participants in this experiment. Despite participants' daily encounters with numbers, the numerical design was found to be the most difficult one for seeing changes in the information displayed, possibly due to the detailed information it provides that would require more effort and longer time to study. The analogue design, on the other hand, was superior on both accuracy and speed measures, leading to best performance, possibly due to the simplicity in design that made the information presented on the display easy to understand. The cartoon-like emotional faces used in this experiment benefited, only to a limited extent, from the attention-capturing effect of faces found in earlier research (e.g. Theeuwes and van der Stigchel, 2006). Although the faces design was meant to provide an impression to the situation, participants were prone to making more mistakes than with the other two designs. This could be attributed to the less straightforward translation between emotional representations and the increased/decreased energy use.

Although participants took longer time to respond in certain colour conditions, they all achieved similar accuracy rates. Red was associated with the fastest responses, possibly due to its attention-capturing effect that might have facilitated seeing changes in information in a shorter period of time than the other colours. With the exception of yellow, the chromatic colours did not appear to differ vastly from the non-chromatic colour (grey) used in this experiment, possibly due to lack of difference in brightness in colour between foreground object and background (e.g. Ojanpää and Näsänen, 2003). The experimental results did not provide clear enough evidence to make a conclusion, more tests are therefore needed.

Unexpectedly, display components changing to the large and small sizes were associated with higher accuracy rate and shorter response time than components changing to the medium size. It could be due to the increase and decrease percentages which were not equally scaled in the experiment. For example, Table 4.3 shows that large sized display components of the numerical design were reduced to the medium size by 15% and to the small size by 33%. But components that were originally medium sized were changed to the small size by 33%, too. Perhaps these changes to the medium size were so small that they did not help to make the pre-change and post-change images visually distinct enough for participants to see the difference.

The findings revealed that accuracy and speed of spotting changes were affected by where the manipulated component was placed in the display. Components located on the upper side, particularly in the top left corner, of the display had more accurate responses than on those on the lower side. The bottom right corner had the longest response time for correct and incorrect answers compared with the other three corners. Results seemed to reflect the reading patterns in the Western cultures (from left to right, top to bottom) which were also found in other studies (e.g. van Schaik and Ling, 2001), which subsequently suggested to have this assumption confirmed by cross cultural comparisons. It is recommended to enhance the components placed on the lower side of the display to improve performance.

In the preference survey, participants who liked the numerical design felt that the numbers provided information that was meaningful and more logical to them than the other two designs. The main disadvantage of the numerical design was that it provided a lot of information at a time. Participants who were not familiar with reading numbers with three or four digits, or with two decimal places, like the ones used in the experiment, found it difficult to memorise or see them on the display in a short span of time. It required even more effort when there was a change in the colour, location or character size of the display component.

Participants who preferred or performed well with the analogue design felt that the simplicity of the dials design helped them see changes quicker and easier. In particular, they found the direction in which the needle pointed intuitive, and required little effort to translate it into the notion of energy use. The bars used in the analogue design were generally well received for giving a clear scale of consumption, although a minority of participants found it confusing when reading between shaded and blank bars.

The same view on simplicity in design was also expressed to the emotional faces design in the ambient displays. The little information that the faces conveyed gave the advantage of focusing solely on the overall situation, but it was disliked for the same reason by participants who did not find the faces intuitive or trustworthy, and preferred to receive information in more detail. Further, some participants found it confusing with the energy consumption system when switching between display designs, particularly with the rank in reverse order.

For IHDs, participants' preferences for the analogue design gathered in this experiment were similar to the results reported by Anderson and White (2009), in which their focus groups also showed a liking to the speedometer dial in their participatory design. Although the numerical design in this experiment was voted as the most difficult design type for seeing changes, it was preferred over the ambient design. Participants believed that numerical information would be more suitable than pictorial information for displaying purposes in the domestic environment, as householders may be interested in taking time to study the information shown on the display. This assumption will, of course, need to be attested in the field studies. Ambient displays, on the other hand, may have the advantage of giving an impression to the overall situation with a quick glance, but the information they provide may not be detailed enough for self-relative comparisons.

4.2.4. Limitations

The study investigated the effects of display design, and the colour, character size and location of the display components on task performance in *one* computerised change detection task. If the design of the experiment were simpler, testing one variable at a time to reduce the complexity of the analysis, the results might be more conclusive.

The study examined whether age or gender affected task performance. It may be useful to include display design in the analysis as well to determine its interaction effect on the colour, character size and location of the display components.

The experiment could also be improved methodologically if a control colour was used, such as black, with which the six colour displays were compared, to measure the colour effect more definitively. It may also be useful for future work to assess the readability and the effects of colours with associative meanings on detecting changes, include more colour combinations in the foreground and background of the display, and properly control their luminance (brightness of a colour) and saturation (purity of a colour) levels (discussed in Section 2.4.5).

The display components were preset in different sizes for the reason of the hierarchy of relevance. This could result in affecting participants' perception of information. The design could be improved by setting all the display components to the same size in the "Test" image, and only the size of the manipulated component changes to a different one. Also pointed out in the discussion are the increase and decrease percentages in the sizing system, which need to be defined more systematically between the sizes.

The experiment used Layout 1 (Figure 4.6a) for all the test images. It was only when the positioning of manipulated display component was tested, that the other three layouts were incorporated. Again, a preset layout differed to the test layouts should be included to avoid participants becoming familiar with the locations of the display components.

There was a concern with pre-designed test images used in the experiments. By manually manipulating the images and making decisions about how to make a change, the influence from the experimenter could cause human bias. It may be helpful to use a computer-based algorithm (e.g. Verma and McOwen, 2010) and let the computer decide what and where to change the images, so that subjectivity could be eliminated (PhysOrg, 2010).

The perception of information could be influenced by some of the design decisions made in constructing the displays. For example, the font type used in the numerical design was Arial Regular, which is a computer font commonly used in word processing documents. The dials used in the analogue design borrowed the concept of speedometer and fuel gauge from the car dashboard, and the battery icon was used to produce the bar component as it is commonly found in electronic devices. The design of the emotional faces in the ambient design, which used only three facial features to represent two eyes and one mouth, was kept minimalistic to avoid distractions, but some participants might find them uninteresting and could quickly lose their attention. Other decisions made in the design process, such as the way in which the display components were organised on the display, the type of information and the number of display components included, and whether the information presented in the chosen way gave a sense of logic and/or trustworthiness to participants, could also have an effect on test results.

4.2.5. Conclusion

This study was undertaken as a preparation work for the main experiments. It aimed to test the experimental design and procedure by comparing three types of display design and examining the effects of colour, character size and location of the display components on attracting participants' attention to the changing information.

The effects of age and gender on task performance were analysed, but none were found. Effectiveness (accuracy and response time) and subjective preferences were used to measure how useful each display design and design feature were for seeing changes. The analogue design was the all-round winner in task performance as well as in user preference compared with the numerical and ambient designs. Character sizes and locations of the display components were found to have an influence on enhancing task performance to some extent. The colours used in the experiment, on the other hand, did not help to improve participants' abilities to identify changes in information.

A general observation from the experiment is that this pilot study has served its purposes by identifying the limitations in the experiment and the adjustments that needed to be made to improve the design of subsequent experiments. Even though the data of a pilot study may not be relevant, or the results may not be definitive, a number of insights have been gained from carrying out the study, as well as from participants' feedback, that may be useful for designing smart meter displays in general. It was noted that a display design could be liked and disliked for the same reason(s); therefore, designers should take account of user preference and provide options of switching between different designs on a display device to improve user experience, (although it may not necessarily improve the performance of the display or its impact on energy use). While some participants found the rank in reverse order confusing, many responded positively to including the ranking component in the design. Further, the presence of colour might have helped participants perform tasks better if the colours had associative meanings in the context of energy use. Lastly, the internal validity (see Section 3.3.2) of the study would greatly be improved by narrowing down the focus on fewer variables in the test.

4.3. Experiment 1: display design types, colour, participant preference

The pilot study showed that participants' perception of information was largely influenced by the way in which information was presented and the display features were put together. To investigate further how energy displays may best be designed, the present experiment continued to study the three display designs used in the pilot study and examined the role of colour in more depth. The display designs were simplified and the effectiveness of coloured display design against black-on-white display design was investigated.

Based on the pilot study's findings, it was expected that the analogue dials design would have a higher accuracy rate and shorter response time than the numerical and ambient faces designs, and that changes in information would be detected faster in coloured displays than in black-on-white displays.

The results of this study have been published in a peer-reviewed journal (Chiang *et al*., 2012).

4.3.1. Method

The experiment used a spot-the-difference computerised task that was similar to the task designed in the pilot study, in which participants had to find the change in information in a series of paired images that represented energy displays. Their response time and accuracy rate were measured in milliseconds (ms) and percentage (%) of correct answers, respectively, and their subjective feedback and preferences were gathered in semi-structured interviews.

4.3.1.1. Participants

Forty-one participants (20 male, 21 female) aged between 18 and 55 years (mean = 26.6, SD = 8.9) were recruited from the same university as in the pilot study. All participants reported to have normal or corrected to normal vision and were accustomed to reading from left to right.

4.3.1.2. Materials and experimental design

Tasks ran on a laptop connected to a 19-inch colour LCD monitor. The positioning of the monitor replicated the setup conditions as in the pilot study. In order to recruit a wider range of participants from the general public, the experiment was conducted in an off-campus building that belongs to the University of Bath Innovation Centre, which is situated in the city centre of Bath.

The experiment used a repeated-measures design and consisted of 3 design types x 5 display components x 3 consumption ranges x 2 colours = 90 pairs of test images which were displayed using the process shown in the flowchart (Figure 4.21) for each participant. The flowchart shows how the experiment was designed so that that all the design types, display components, consumption ranges and colour schemes were tested, before the score was given to participant.

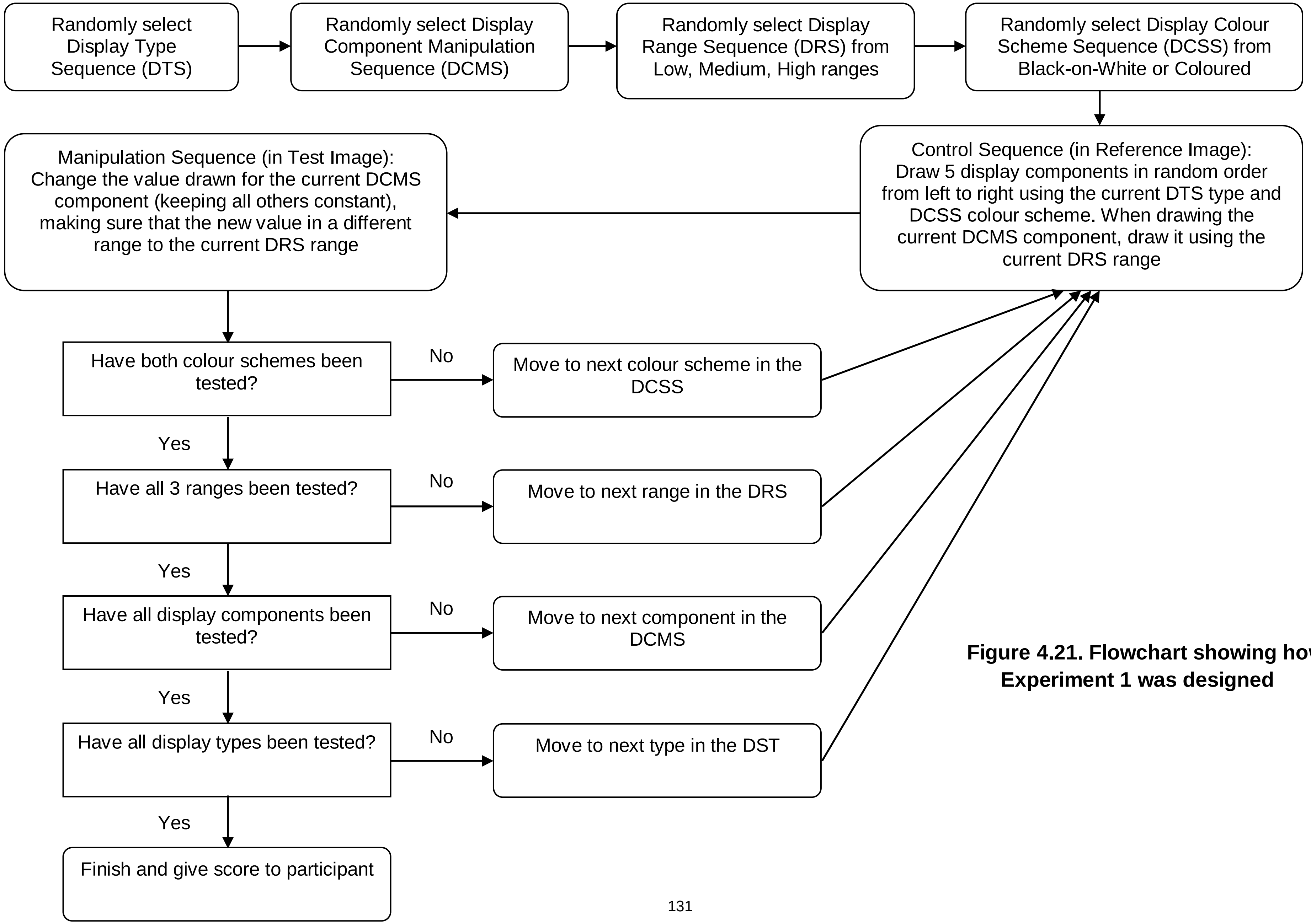


Figure 4.21. Flowchart showing how Experiment 1 was designed

Within each design type, there were five display components representing five states of energy consumption arranged linearly from left to right in random order. This provided the possibility of investigating the effect of the central location of the display component. In order to remove potential distraction, and to keep the design purely graphical and the layout simple, no text was used, and all the components were in the same size. Participants were told about the abstract connection between the display components and the energy information they represented.

For each display component, there were three consumption ranges: low, medium and high, which were derived based on data from an average UK household's annual electricity consumption. For example, to determine what the average day-to-day ("Today so far" and "Yesterday") consumption range was, the average annual electricity consumption of 3,300 kWh (OFGEM, 2011) was divided by 365 days to give an average daily consumption value of 9 kWh. The figure was then doubled to give the maximum value and divided by 3 for three daily ranges, i.e. the low range would be between 0 and 5.9 kWh, the medium range would be between 6 and 11.9 kWh, and the high range would be 12 kWh and higher. It is worth noting here that these are realistic, albeit crude, approximations appropriate to the experiment. While ranges in the real world will no doubt be different, these are not expected to significantly affect results since participants were focused on changes to displays rather than the values themselves.

Each display design had a black version (Figure 4.22) and a coloured version (Figure 4.23). The overall background colour for all test images was white. In the black version, no colour other than black was used to represent the three consumption levels. In the coloured version, red and green were chosen for their associative meanings, representing high and low consumption ranges, respectively, and black was used to represent medium consumption range. Low consumption levels were represented by lower numerical values in the numerical design, the left-hand end of the dial in the analogue design, and a happy face in the ambient design.

a) Numerical design

b) Analogue design

c) Ambient design

Figure 4.22. Display designs in black-on-white version (left column)

Figure 4.23. Display designs in coloured version (right column)

4.3.1.3. Experimental procedure

The task involved identifying which display component had changed in addition to detecting the nature of the change. The test session began by following the same procedure of the pilot study, in which participants received an information sheet (see Section 7.1.3 in Appendix A), a consent form, oral and written instructions before proceeding to a practice session of 10 pairs of test images. The number of practice images was reduced to 10 pairs instead of 15 pairs like in the pilot study because there was no time limit imposed on viewing the “Reference” image in this experiment. The time limit was removed to relieve the feeling of anxiety, and to reduce the possibility of being distracted by the thought of it, which some participants in the pilot study reported having during the course of the task. As a result, instead of seeing the test images flash by, participants might feel more in control if they could make responses at their discretion.

As shown in Figure 4.24, the first image in each pair was the “Reference”. Considering the number of display components participants had to look at in the “Reference” image, the display time was increased to seven seconds, rather than three seconds like in the pilot study. This was followed by the “Test” image, which was displayed until the participant responded.

a) The “Reference” image

b) The “Test” image

Figure 4.24. An example of the paired test images

In considering the data of response rate collected from the pilot study, the percentage and the speed of correct response were more relevant for assessing the effects of the design types than non-responses, which could also include correct and incorrect responses. As a result, the non-response category was removed, leaving with either correct or incorrect responses in the analysis, and the display time was increased[16].

To reduce the confusion caused by mixing design types, the test session was divided into three sub-sessions, so that all the test images of one design type were tested in one sub-test session. The test images and the sub-test sessions ran in random order for each participant to eliminate order effects, and a short break was taken after one sub-test session was completed. The “Reference” and “Test” images differed by a change in the value of one of the five display components. Each pair of images used the same colour scheme, which changed randomly from pair to pair. Participants were asked to determine as quickly and accurately as possible if the consumption value of the changing

[16] To detect a change in signal, research has found that with an event rate of once every two seconds, test subjects showed a 20-60% signal detection rate; the correct detections increased to 100% when the signal lasted between four and eight seconds (Jerison and Picket, 1964; Warm, 1984 in Wood and Newborough, 2003).

display component had increased or decreased. The response for “Higher than before” was mapped to the “@” key (next to the “Enter” key) and the response for “Lower than before” was mapped to the “A” key on a standard UK keyboard.

4.3.2. Results

Detailed data are tabulated in Section 7.3 in Appendix C. Standard errors of the mean (SEMs) are included on the plots to indicate the uncertainty around the estimate of the mean measurement from the population mean and the statistically significant difference between display conditions.

4.3.2.1. Display design type

Results showed that the three designs differed in accuracy ($F(2,80) = 46.683$, $p < .001$) and response time ($F(2,80) = 19.904$, $p < .001$). The numerical design had the highest accuracy rate (95.7% versus 81.7% for analogue, 92.0% for ambient) (Figure 4.25) and fastest reaction time (2505 ms versus 3615 ms for analogue, 3177 ms for ambient) (Figure 4.26).

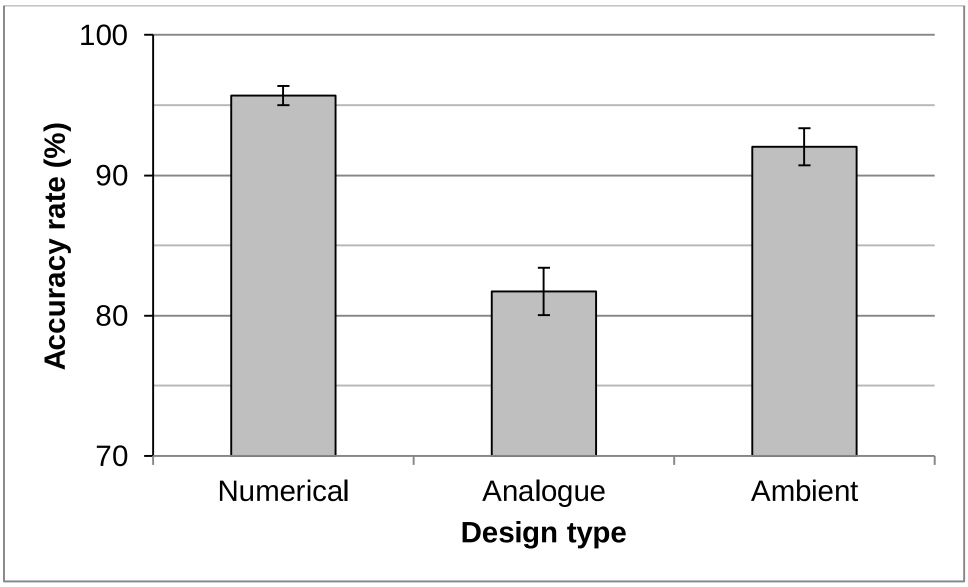


Figure 4.25. Mean accuracy rates of design types

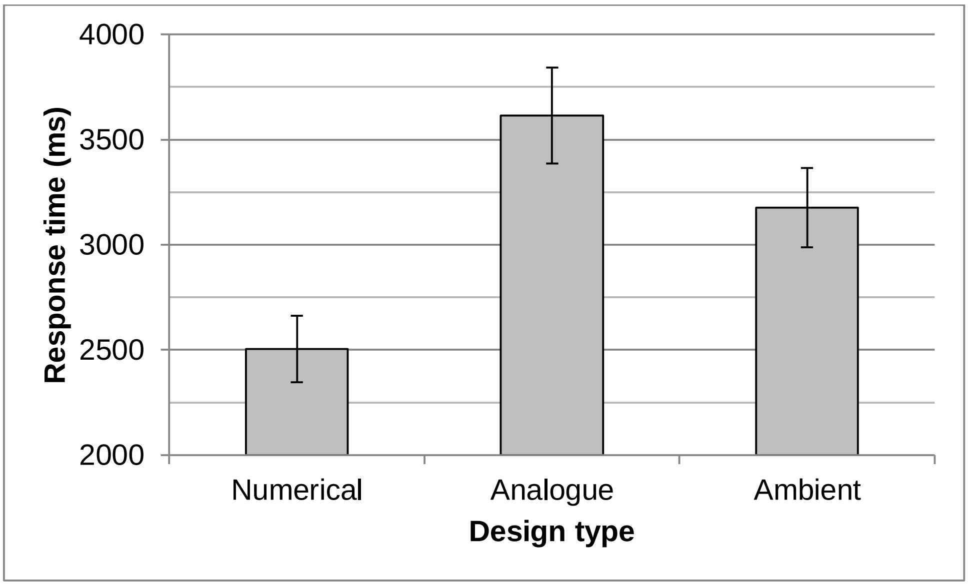


Figure 4.26. Mean response times of design types

4.3.2.2. Colour of display component

Results showed that overall accuracy for coloured displays was slightly, but not significantly, increased compared with black-on-white displays (90.5% and 89.1%, respectively) (F(1,40) = 1.738, p = .195) (Figure 4.27).

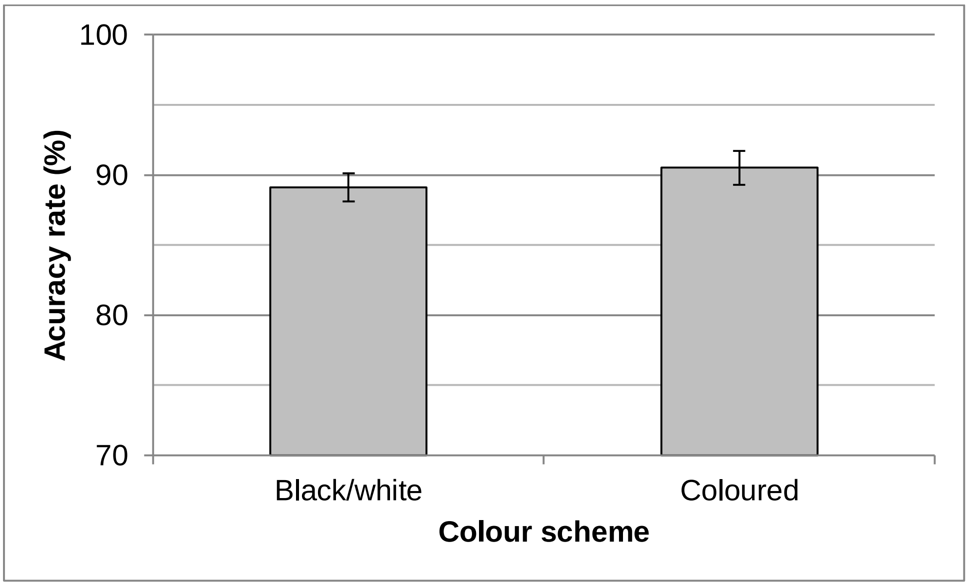


Figure 4.27. Mean accuracy rates of black-on-white and coloured displays

Within each design type, there was no major difference in colour performance for the numerical and analogue designs, but response time in the ambient design was affected by the presence of colour as shown by a Design x Colour interaction (F(1.588,63.505) = 3.706, p = .040) (Figure 4.28). This interaction was carried by response time being shorter for coloured displays than for black-on-white displays (2979 ms and 3373 ms, respectively) in the ambient condition (t(40) = 2.645, p = .012).

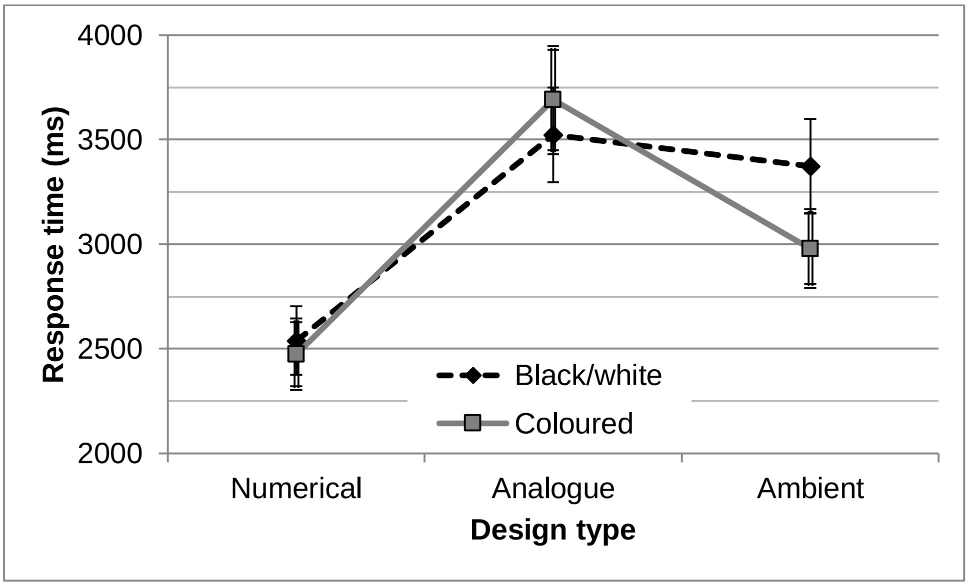


Figure 4.28. Mean response times of display designs in black-on-white and coloured versions

4.3.2.3. Location of display component

The location of manipulated component in each display was also analysed. This showed no significant difference in accuracy rate (F(4,160) = 2.088, p = .085) (Figure 4.29) nor in response time (F(4,160) = .834, p = .505) (Figure 4.30) between the components on the left, right or in the centre of the display screen.

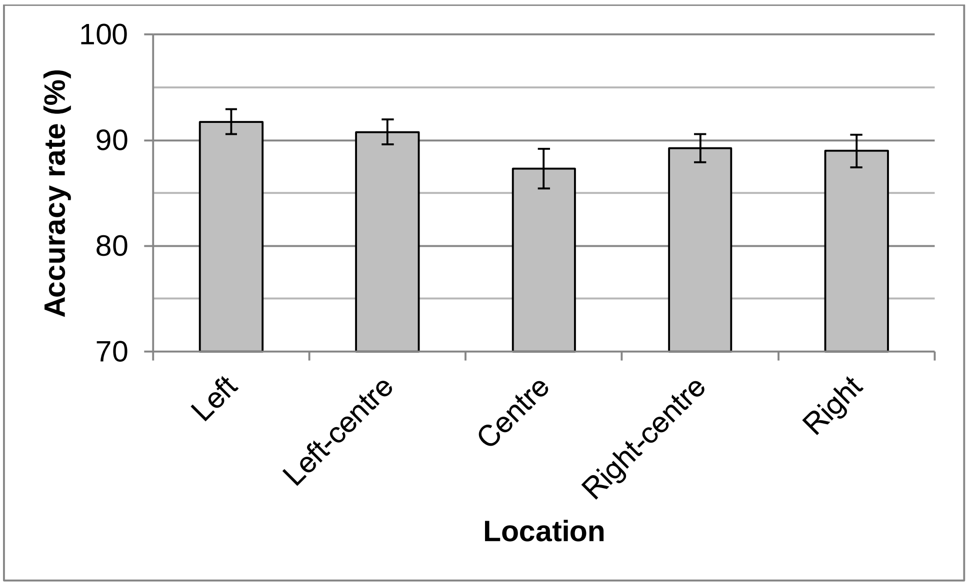


Figure 4.29. Mean accuracy rates of locations of manipulated display components

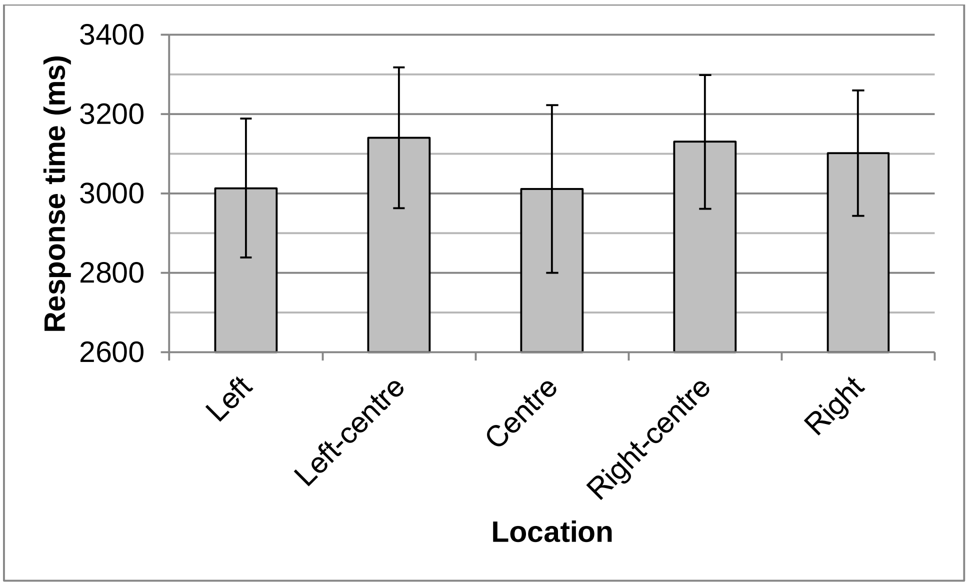


Figure 4.30. Mean response times of locations of manipulated display components

4.3.2.4. Range of display component

An analysis on the effect of display range was carried out. This was to see if participants were better at picking up a reduction than an increase in consumption value. It was found that there was no difference between the two in terms of accuracy rate ($F(1,40) = .023$, $p = .880$) (Figure 4.31) and response time ($F(1,40) = .556$, $p = .460$) (Figure 4.32).

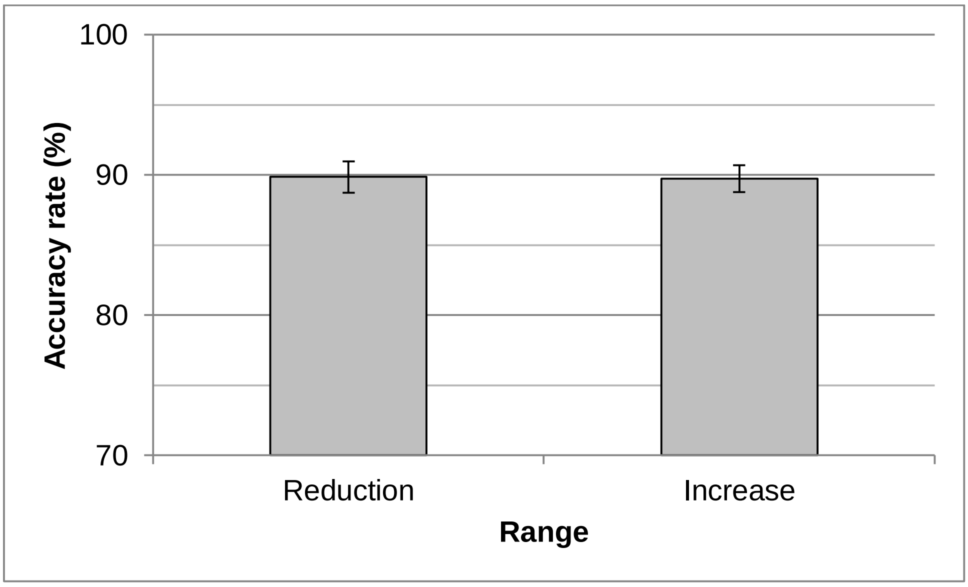


Figure 4.31. Mean accuracy rates of ranges of manipulated display components

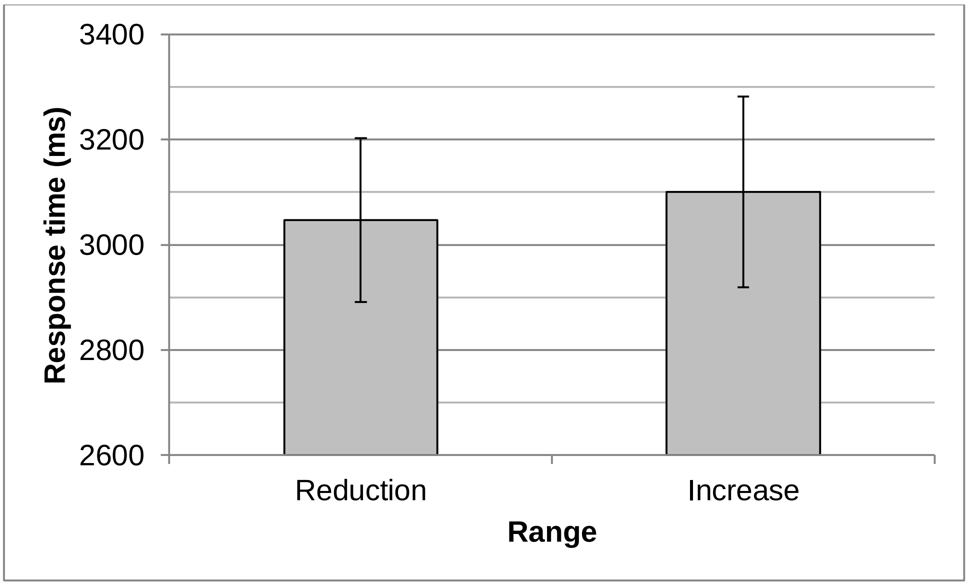


Figure 4.32. Mean response times of ranges of manipulated display components

4.3.2.5. Preference

Participants were interviewed after the computerised task to express their views in the following core questions:

- Which type of display design was the easiest to read?
- Did you find the coloured version more helpful for seeing the change?
- How did you read and compare the information?
- Which type of display design would you prefer to have at home?
- Would you prefer to have the display design at home in colour?

The interviews were semi-structured, such that discussion stemmed from the core questions. In many instances, more than one display design type was chosen, and various display components were preferred in combination.

Results of participants' stated preferences showed that the numerical design was most preferred (53.7% versus 31.7% for analogue and 34.1% for ambient) (Figure 4.33). The analogue design was voted as subjectively the most difficult design on which to spot changes (63.4% versus 14.6% for numerical and 22% for ambient). When asked if colour was helpful for seeing changes, 80.5% of participants responded positively. However, 61% also said that the presence of colour was distracting and made the reading more difficult, particularly with the analogue design (80% versus 10% for numerical and ambient). As a result, 63.4% of participants chose to ignore the colour completely and concentrated on the information alone. For IHDs, 78% preferred them in colour (77.3% for numerical, 84.6% for analogue and 85.7% for ambient), the rest who did not find colour appealing or useful preferred the numerical design in black-on-white.

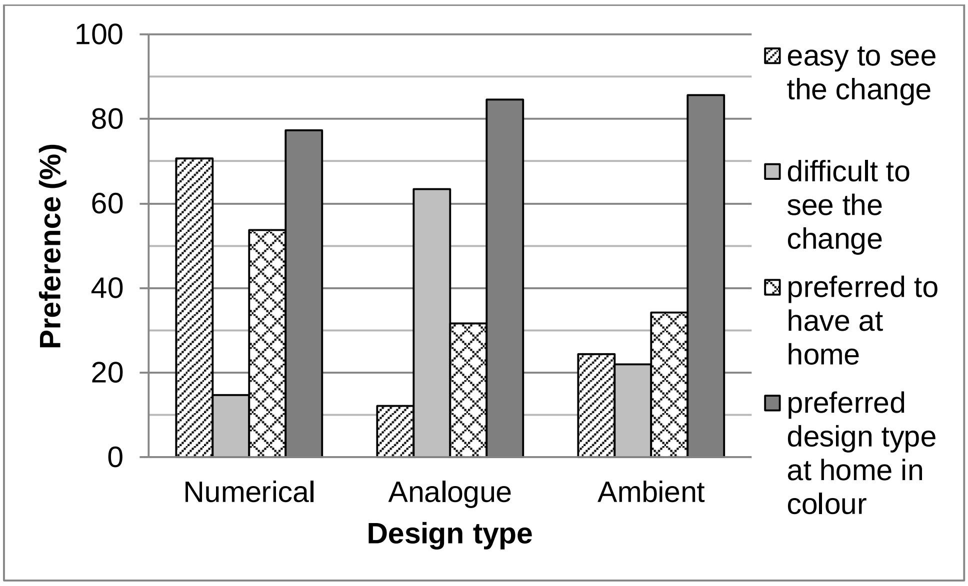


Figure 4.33. Display design preferences

4.3.3. Discussion

This study was based on the design of the pilot study. The findings, again, showed that different display designs presenting the same information communicated differently to participants. However, the performance pattern was reversed in this experiment – numerical presentation led to faster and more accurate detection of changes in the information displayed – possibly due to the changes made in the experimental design. Participants' improved performance could also be attributed to their daily encounters with numbers. Accordingly, it has been found that if users find the product features similar to their previous experience, they are more likely to perform tasks better (Blackler and Popovic, 2003; Canham and Hegarty, 2010). This raises the question of why the dials used in the analogue design, which should similarly be familiar to participants from analogue clocks, gas and electricity meters and from car gauges, led to poorest performance in this experiment. Whilst it is possible that analogue displays, which may be common in everyday life, are substantially less common than numerical displays. At present, the advantage of numbers over dials is not clear, and future work could usefully look at the effect of participants' familiarity with electronic products with a visual display, and in more depth at analogue representation, including other forms such as graphs and charts. Despite the special attention-capturing quality of faces seen in earlier research, the emotional faces used in the experiment gave no advantage to identifying changes in consumption nor did they have much appeal for many of the participants subjectively. However, for the minority who performed well with or preferred the ambient design, the simplicity of the facial expressions was said to be the key feature that helped them see the changes quicker and easier.

The presence of colour only slightly increased the accuracy rate of all design types, but this was not statistically significant. It was more helpful in reducing the response time of the ambient design than in the numerical condition, but the response time increased in the analogue design. However, even if participants took longer to respond in the coloured analogue design, a higher accuracy rate compared with black-on-white was achieved like with the other two designs. Field testing may be useful to assess whether coloured displays communicate information to people just as well as black-on-white displays.

Although the presence of colour did not help them perform tasks better, a majority of participants believed that colour was helpful in reading information and seeing changes, and preferred information to be colour coded, for reasons of extra information, ease of distinguishing differences, visual aesthetics and learning experience. Participants who felt colour was unhelpful were unfamiliar with colour coding and found it “untrustworthy” and “distracting”. They did not find colour coding intuitive and felt that they had to spend more time on re-checking the information, and were still not sure if they had made correct answers. Although colour helped provide extra information, for some participants it was too much to take in at a time; therefore, they reverted to ignoring the colour. Some participants were not aware that colour was used even though they reported to have normal vision. This could be due to either mis-reporting of normal vision or the possibility that not everyone is receptive to the use of colour. Testing for colour blindness with the Ishihara test might have helped to eliminate the possibility of colour vision deficiencies (protanopia and deuteranopia) among participants. In summary, then, designers might note that whilst coloured displays are likely to be aesthetically pleasing to the majority of the people, they appear to convey no advantage for highlighting changes in energy information and seem to be actively disliked by a minority.

4.3.4. Limitations

The experiment was conducted under "laboratory conditions" and therefore might not adequately capture perception in a real-world setting. On the other hand, by removing the distractions people are likely to experience in their domestic environments, it could be argued that this study provided a useful upper bound on people's ability to spot changes in smart meter displays. If they were poor at using a certain type of display when they were entirely focused on the task, it seems unlikely they would work well with that display when their attention was divided as in a household setting, although this is an empirical question.

In the experiments, participants were asked to undertake a specific task with the goal of identifying which one of five display components in a series of test pairs had changed. In a real-world setting, information will change unpredictably and people will not be focused on detecting changes. Again, however, this could be argued that by asking people specifically to focus on spotting changes, the study provided the upper bound on the ability of these displays to communicate changes in energy use to people.

Particular design decisions were made in constructing the experiment, which could affect the perception of information and influence test results. For example, the numerical display design was constructed using a seven-segmented format, which is a common format found on simple LCD displays. Similarly, the JFreeChart 1.0.13 (2009) Java library (funded by Object Refinery Ltd[17]) was used to produce the analogue display as it is a freely available resource, but it led to a specific design of dial being displayed.

[17] http://www.object-refinery.com

The design of the computerised task might affect how participants performed in the experiment. Some participants reported taking part in computer and/or TV games and found the features of the task familiar from their gaming experiences. It was possible that participants who were familiar with the gaming mode found the task easier than those who were not. Several variables were also identified that might have confounded the results. For example, some participants might have taken stimulants to alertness (e.g. coffee) before taking part in the experiment; participants' energy levels or concentration might vary at the time of the day when the experiment took place, which could be dependent on their food consumption prior to the experiment or the quality of previous night's sleep. Further, the motivation of volunteers taking part in the experiment might also result in a skewed task performance compared with non-volunteers, as found in some earlier research (e.g. Abrahamse *et al*., 2005).

4.3.5. Conclusion

Three types of display design (numerical displays, analogue displays using dials, and ambient displays using emotional faces) were compared in this study to see which design best communicated changes in energy information to participants. The usefulness of colour coding was also examined. A summary of results is shown in Table 4.4.

Table 4.4. Summary of response time, accuracy rate and participant preference by design type and colour scheme

	Response time	Accuracy	Preference
Design type[4a]	Nmr < Ang Nmr < Amb Ang > Amb	Nmr > Ang Nmr > Amb Ang < Amb	Nmr > Ang Nmr > Amb Ang = Amb
Colour[4b]	BoW = Clr Amb BoW > Amb Clr	BoW = Clr	Nmr < Ang Nmr < Amb Ang = Amb

[4a] **Nmr** means numerical design
Ang means analogue design
Amb means ambient design
[4b] **BoW** means black-on-white display
Clr means coloured display

> means significantly greater than
< means significantly less than
= means marginally different to

Numerical displays were associated with faster and more accurate responses in seeing the changes than the analogue dials and ambient faces designs. A finding of particular interest was that colour coded information did not appear to have advantage over information in simple black; the differences observed between them were small. Although the presence of colour had no significant usefulness in improving the effect of displays, participants subjectively tended to prefer coloured displays to black-on-white displays. Further, while the analogue dials and ambient faces designs were not as effective in detecting changes as the numerical design, a majority of participants preferred them in colour, as shown in Figure 4.33.

In considering the inconsistency between participants' subjective preferences and their performance that is often found in research (e.g. van Schaik and Ling, 2001; Humar and Turk, 2008; Krishnamurti *et al*., 2013), it does not seem that tailoring the design to personal preference is relevant, nor is it particularly useful for improving task performance. Work is needed to confirm whether the same notion can be applied in real-life settings, if the primary goal of the display is to reduce energy use.

Further work may be useful to test on a larger sample to explore why numerical displays are working better, and to see whether it is true for all people[18]. More studies should systematically test individual design presentation in more depth, such as graphs, pictorial icons, flashing light and dynamic motion of the display components, to identify the best type of feedback. Further research is also needed to explore displaying live energy consumption data using combinations of display designs (numerical and analogue, numerical and ambient, analogue and ambient, or all three designs in one display), as hybrid displays may be more likely to be useful in the real world.

---

[18] See Section 7.4 Appendix D for a comparative study that used the identical experimental design and procedure as in Experiment 1 to assess whether the findings were true for people who are in fuel poverty, and whether education or income affects performance on the computerised tasks. The results showed no difference in task performance between the two experiments.

4.4. Chapter conclusion

This chapter presented a pilot study and a main experiment in a laboratory environment, in which the effects of display designs and design features on facilitating detecting changes in the information displayed were examined. Both studies showed that accuracy rate and response time were strongly associated with the type of display design. When given the choice, many participants seemed to select the display design that they believed they did best with, as both studies shared similar performance-preference patterns. Another common finding was that simplicity in display design was important, which is much in line with some earlier research discussed in Chapter 2. This design approach should not only be applied to the overall display layout considering the extent of information shown on the display, but also to the individual display components.

While the ambient faces designs used in the pilot study and Experiment 1 were similar, and their effects did not seem to have been affected by the differences between the two studies (neither the best nor worst design type), the numerical and analogue designs swapped their task performances from one experiment to the other. In addition to the specific font format used in the numerical display and the dials design in the analogue display as mentioned in Section 4.3.4, the many subtle changes made in Experiment 1 might have led to the different results. For example, the display components were arranged linearly from left to right on the screen, instead of being clustered in groups. Participants' concentration might or might not have been improved in the absence of time limits for making responses in the computerised tasks, or by the lack of text in the display. The computerised task contained three sub-test sessions; each session tested only one type of display design at a time, which might have made the logic of the experimental procedure clearer for participants to follow.

In conclusion, it has been learnt that the ambient faces design and the presence of colour do not have advantage over the other display design conditions in the context of energy use, and perhaps either the numerical display or the analogue dials display is better at communicating changing information in task-focused tests. The outcomes of these laboratory experiments present opportunities for the development of improved display designs, and are incorporated in the implementation of the subsequent field-based experiments to investigate how effective these display designs are in real-life settings.

Chapter 5 Influencing energy-use behaviour

5.1. Introduction

In Chapter 4, the efficacy of display designs and colour coding in communicating changes in energy information to people was dealt with in laboratory tests. Although laboratory-based experiments have advantages, as discussed in Chapter 3, of giving the experimenter a better control of factors that are not relevant to the study, improving the internal validity and making the experiment replicable, studies conducted in such a controlled environment often lack in ecological validity, and participants may behave differently; therefore, the findings may not be true in the real world. To address this issue, this chapter presents the field-based study that examined the impact of energy display design in a “live” context.

A pre-field study was proposed to assess the feasibility of setting up experiments in a student residence at the University of Bath (see Section 7.5 Appendix E). Although the pre-field study was not implemented owing to technical difficulties, two succeeding experiments using a different technique were carried out – one looking at the effect of different types of display design, one investigating self and peer comparisons.

5.2. Experiment 2: display design types

This study built upon the laboratory-based Experiment 1 by using the three display designs to see how they worked to influence energy behaviour in a residential setting, where people might or might not be actively looking for information on their energy use. This issue is important because numerical displays, which are commonly used on current IHDs, provide detailed and quantitative information but will likely require users to make a specific effort to study the information. Therefore, they might reasonably be expected only to work in real-world settings with people who are already engaged with issues of energy use. Analogue displays (speedometer dials were used in the experiment) might make it easier to compare and evaluate past, current and future states of energy use than numerical displays (Frankish, 2009). The two-dimensional cartoon-like faces with emotions representing different energy use levels that were introduced in the ambient design in the laboratory experiments for their attention-capturing property (Ro *et al*., 2001; Theeuwes and van der Stigchel, 2006) might be useful in real-world settings as they provide a general impression to the energy use pattern and do not require people's detailed attention (Darby, 2009).

The working hypothesis was that the extent to which a display influenced behaviour would be a function of the extent to which it required active engagement from a user, with the ambient design likely to have the greatest influence and the numerical design the least.

The results of this study and the next have been published in a peer-reviewed journal (Chiang *et al*., 2014).

5.2.1. Method

5.2.1.1. Participants

The study evaluated electricity consumption of a first-year undergraduate student residence in an on-campus building at the University of Bath in a six-week period (see Table 5.1 for participant profile). Measuring electricity consumption was considered appropriate because the experiment was designed to test differences in presentation for the same end use, rather than responses to different end uses. Further, on-campus electricity sub-metering is widespread with over 1,100 sub-meters, whereas meters for other end uses are at aggregate level (typically four to five), limiting the possibility to use them in these experiments. The residence chosen for the study, unlike most of other campus residences at the university, had Wi-Fi coverage and separate meters for each kitchen, which met the requirements for the wireless data technology to be used to monitor individual kitchen groups. Each kitchen group had two separate sub-meters measuring electrical lighting and power in the kitchen, corridor, shared bathroom and study bedrooms. As a result, all the students' residential energy use was captured. A total of six kitchens, shared by seven students each, were selected as experimental groups. Two of the remaining non-participating kitchens, whose historical consumption data were retrievable, were used as controls.

Table 5.1. Participant profile (n = 41)

	Count	%
Age		
18	13	32
19	23	56
20	5	12
Gender		
Male	16	39
Female	25	61
Colour vision		
Normal or corrected	41	100
Defective	0	0
Payment method for accommodation		
Self/family	33	80
Sponsored	4	10
Other e.g. loan	4	10

5.2.1.2. Data baseline

Twelve days prior to the start of the experiment were used as the baseline period in the analyses. Neither the control nor experimental kitchens were informed of when the baseline period was at any time during the experiment. These baseline data were used to show participants how their current energy consumption compared with their consumption before the experiment began. The idea of establishing baseline from historical data was rejected as there was no clear way to establish whether consumption by the groups under study would be comparable to student groups in previous years.

5.2.1.3. *Sensing and software architecture*

The sensing and software architecture of the experiment was based on the existing network and smart metering systems in the university campus buildings. Smart meters installed in this residence are part of a commercial campus wide deployment. In this context, a “meter” represents any device that reads and transfers a building’s total consumption, while a “sub-meter” represents a device that reads and transfers information of parts of a building. All meters and sub-meters were connected to a gateway device, which allowed for communication between the meter network and the campus network to take place. The installed system collected data from the meters through gateway connections and stored them in Microsoft Access database files. These files were saved on a networked on-campus computer. While the system could poll the meters and sub-meters at sub-minutely level, owing to the particular design of the system and the large number of meters on campus, readings were half-hourly.

At the front end of the system architecture, 10-inch Android touch screen tablets, running a custom-written application, were used to present meter readings in each kitchen. The tablets required continuous power supply and were fitted in the kitchens in a custom-modified polyester cabinet with a tilted viewing panel and a lockable door, which was mounted approximately 1.8 m above floor level (Figure 5.1, Figure 5.2).

The tablets and the Electronic Data Store (EDS) were on different data networks. Therefore, an integrated system architecture design was necessary to procure the tablets’ frequent communications with the database. As shown in Figure 5.3, the link between the tablets and the EDS was established through the use of a local Extensible Messaging and Presence Protocol server (XMPP, a messaging protocol used in online “chat” environments such as “Google Talk”) and a “data feed” application. Each tablet used this service to “chat” with other tablets and the experiment monitor application. The XMPP server used the public jabber.org server for communications. While this meant that the data being posted could notionally be seen by any online users, no publicly identifiable (human-readable) data were posted. This setup could easily be replaced with a custom installation on a local machine in future for more rigorous data security. The “data feed” application acquired half-hourly data from the EDS using SQL queries, which were then transmitted to the tablets. Similarly, visual presentation application “Sensor Visualiser” on the Android tablets also had an XMPP client to receive the meter data to display. Lastly, a “heartbeat” monitor application was written to monitor the experiment remotely. Using the same XMPP, this application could detect any malfunction or latency in data updates so that fixes could be issued or the tablets could be reset.

Figure 5.1. Tablet installation setup

Figure 5.2. Tablet affixed to cabinet

Although the building separately sub-metered lights and small-appliance power for each kitchen, these data were combined to present an overall consumption figure for each kitchen group to reduce complexity for the participants.

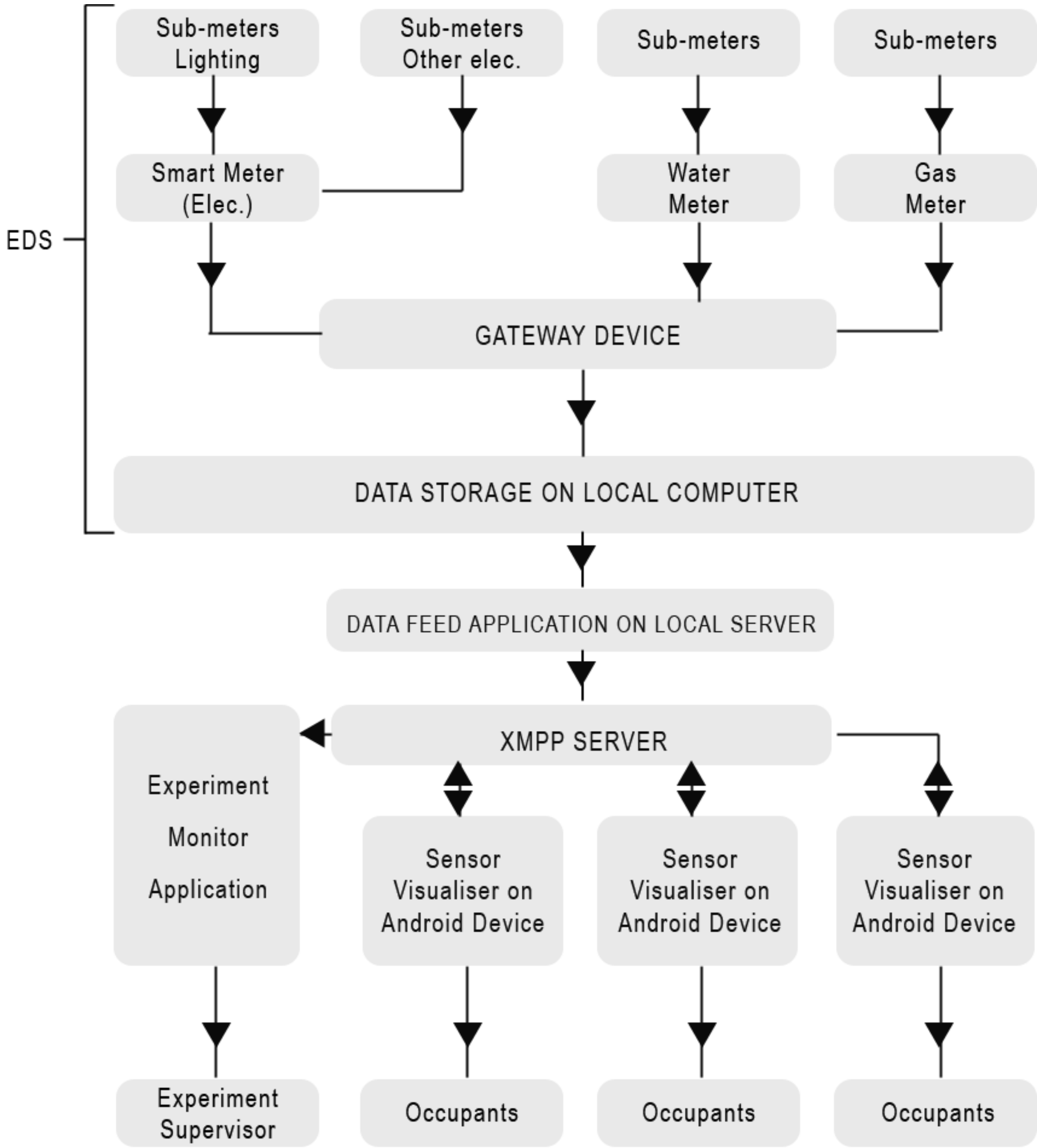
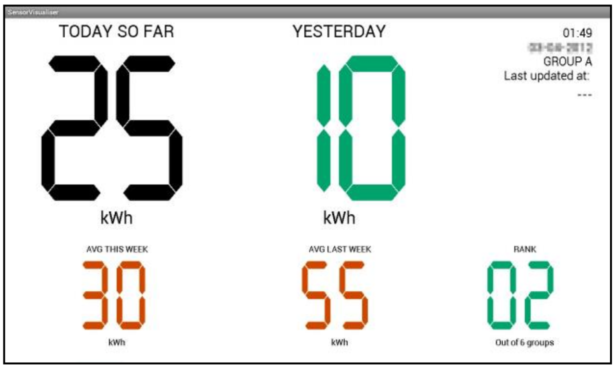


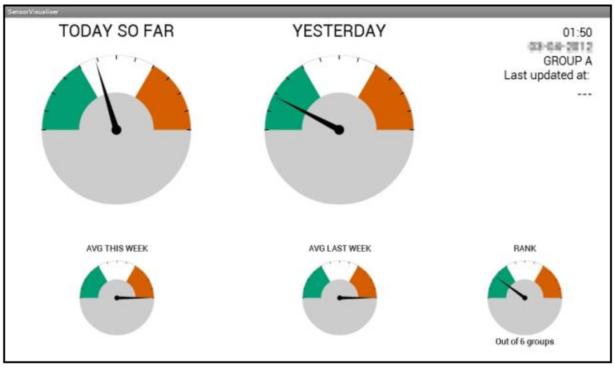
Figure 5.3. Integrated architecture of the experimental setup and the existing infrastructure for the EDS (courtesy of Gokhan Mevlevioglu)

5.2.1.4. Experimental design

Three display designs were used to represent energy information: numerical design, analogue dials design and ambient faces design (Figure 5.4).



a) Numerical design



b) Analogue design

c) Ambient design

Figure 5.4. Types of display design

Each design was displayed to participants for two weeks before changing to the next one. Table 5.2 shows the rotation schedule, in which all six possible orders of the three display designs were tested (hence six experimental groups).

Table 5.2. Display designs on two-weekly rotations

	Group A	**Group B**	**Group C**	**Group D**	**Group E**	**Group F**
Weeks 1-2	Numerical	Numerical	Analogue	Analogue	Ambient	Ambient
Weeks 3-4	Analogue	Ambient	Numerical	Ambient	Numerical	Analogue
Weeks 5-6	Ambient	Analogue	Ambient	Numerical	Analogue	Numerical

The design consisted of five display components:

1. The component "Today so far" in the top left corner of the display showed the cumulative energy consumption in kWh from 00:00:00 for that day at the time of data update. The range information was obtained from (a) below.
2. The component "Yesterday" in the top centre of the display showed the total cumulative consumption value of the preceding day between 00:00:00 and 23:59:59, and the value stayed the same throughout the current day. The range information was obtained from (b) below.
3. The component "This week average" in the bottom left corner of the display showed the average daily consumption in the current week computed for all completed days (i.e. the display was blank for Monday, and Friday showed the average between Monday and Thursday). The range information was obtained from (c) below.
4. The component "Last week average" in the bottom centre of the display showed the average daily consumption in the previous week and the value stayed the same for all of the current week. The range information was obtained from (c) below.
5. The component "Group ranking" in the bottom right corner of the display showed the given group's rank compared with the other five groups at the time the data were updated. The values ranged between 1 and 6, the smaller the value the higher level the rank. This component was updated half hourly and was calculated based on the total energy consumed from the start of the experiment.

The consumption ranges were determined from the baseline period. Three types of ranges were computed:

a) Half-hourly: a maximum and minimum range limit for each half hour of the day was calculated cumulatively from midnight. For example, if the limits for 09:00:00 to 09:29:59 are 10 to 22 kWh (i.e. energy consumed since 00:00:00), the range is divided by 3 to give three ranges. Low range would be between 10 (or less) and 13.9 kWh; average range would be between 14 and 17.9 kWh; high range would be between 18 and 22 kWh (or more).
b) Daily: average daily weekday and average daily weekend.
c) Weekly: an average daily range for the entire week from a weighted average of the weekday and weekend averages in (b) above.

Consumption ranges were updated every half hour on all displays along with the range information for that half hour. Bluish-green (RGB (0, 158, 115)) and vermillion (RGB (213, 94, 0)), which can be distinguished by people with colour vision deficiency (Okabe and Ito, 2002), were used to represent low and high consumption levels, respectively, with black[19] used for average consumption level for each of the three displays. For the ambient faces design, happy face, neutral face and sad face were used to represent low, average and high ranges, respectively, combined with appropriate range colour for consistency. This effectively overloaded the information content for this display (i.e. information on consumption levels was being conveyed through colour and emotion mechanisms simultaneously).

5.2.2. Experimental procedure

Three weeks prior to the start of the experiment, an introductory e-mail was sent out to each member of the experimental groups by the Department of Student Accommodation Services, making it an official research investigation on energy use in the student residence of interest. The e-mail outlined the aim of the study, the purpose of the display devices that had been installed, the length of the

---

[19] Experiment 1 did not reveal significant difference in task performance between coloured and black-on-white images, and could, therefore, be considered to have set an upper bound of the effectiveness of the use of colour. The present experiment did not intend to establish the validity of these results; therefore, more work would be required to confirm if they continue to be true in a "live" context.

experimental period and a “winner takes it all” monetary reward of £20 that would be given to each member of the group that showed the lowest electricity consumption by the end of the experiment. A second e-mail was sent out a week later to individual groups giving details of a briefing session that was to be held in the following week. The aim and the scope of the experiment were introduced to the experimental kitchens in the briefing session, and a pre-study questionnaire (see Section 7.6.1 in Appendix F) was filled out. Questions related to the students’ attitudes on the environment and energy consumption, and their energy-use activities were put forward in the questionnaire. During the course of the experiment, frequent but irregular visits were made to the experimental kitchens to check on the displays. A week before the experiment was due to end, students were notified that the experiment would end in a week’s time, and a group interview would take place in their group’s kitchen, in which they would be able to talk about their experiences and find out how they had done compared with other groups. Post-study questionnaires (see Section 7.6.2. The original version of the questionnaire was designed for the pre-field study (see Section 7.5 in Appendix E), it was later modified for Experiment 2 and included an additional Part C) to survey to the students’ recent energy-use activities and their feedback on the experimented display designs were filled out during the interview sessions, as they might help provide some leads in the interview. Interview sessions were each scheduled to last for 60 minutes, although they typically ranged between 30 and 40 minutes.

The information gathered in the questionnaires was not intended for analysis, but only to assist with the interpretation of the experimental results for two reasons. Firstly, one methodological issue is that the data obtained from self-reported questionnaires are not robust enough due to social desirability and self-perception. This could produce biased answers and lead to a weak statistical power of designs. Secondly, due to the design of the experiment and time constraints, there were no control groups included in the experiment (their consumption data were only obtained later during the experimental period). This effectively decreased the power of the questionnaires comparing participants' energy-related behaviours and behavioural determinants such as environmental attitudes before and after the study, as there was no control to compare with.

5.2.3. Results

5.2.3.1. Display design type

Table 5.3 and Figure 5.5 show changes in mean daily energy consumption for the users of the three display designs and the control compared with their mean baseline consumption of 18.27 kWh and 29.33 kWh, respectively, per day (see Section 7.7.1 in Appendix G for explicit data). Ninety-five percent confidence intervals are included on the graph, so that any error bar ranges that do not cross zero show a change in mean daily consumption that is statistically significant different from zero change. This works because, in line with the central limit theorem, replicates assessing a true population effect size will produce a sampling distribution normally distributed around that true effect size. It is therefore justified, on the assumption that the population standard deviation can be estimated from the sample standard deviation, to apply confidence intervals derived from a normal distribution to a point estimate to assess the plausibility of that point estimate including or not including a given value – in this case, a change of zero (Baguley, 2012).

Table 5.3. Mean reductions in electricity consumption by display design type and the range of reductions differed from zero

	Mean daily change compared with baseline[5a] (kWh)	**95% confidence interval for difference**		**Effect size (*d*)**
		Lower interval boundary	**Upper interval boundary**	
Numerical	-1.157	-1.816	-0.497	0.371
Analogue (dials)	-1.025	-1.569	-0.480	0.360
Ambient (faces)	-1.770	-2.397	-1.143	0.582
Control (no displays)	-0.491	-1.529	0.548	0.115

[5a] Negative value indicates a reduction in electricity consumption

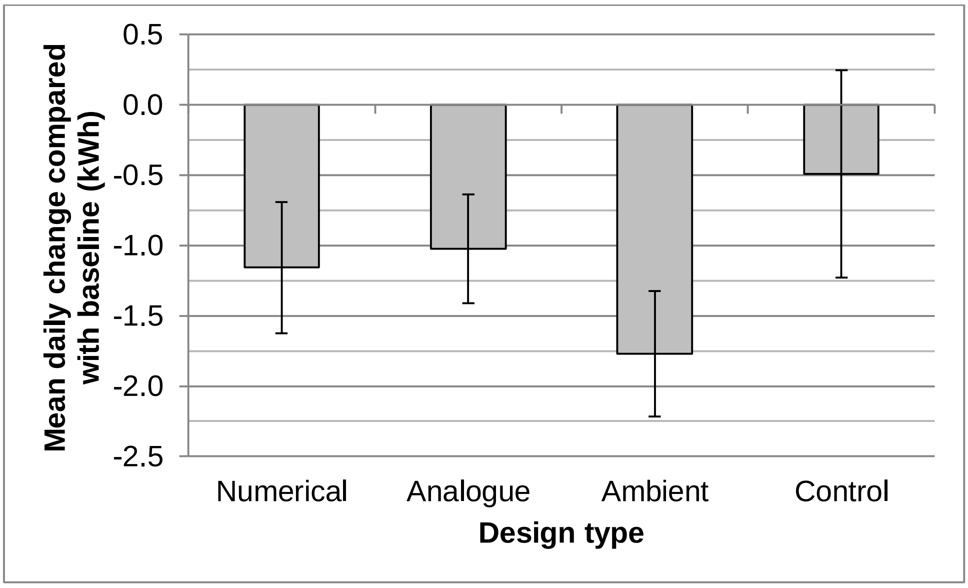


Figure 5.5. Comparison of mean reductions across display design types

A mean daily reduction of 1.32 kWh, approximately 7.2% below baseline, was achieved with the three display designs, making 0.83 kWh lower than the control per day. Given that the 95% confidence intervals of all three designs excluded zero change, the changes were each significant at the 0.05 level. The confidence interval for the control group's change included zero, indicating that their change from baseline is not reliably different from zero. The effect sizes also supported the idea that all three designs showed non-trivial changes in energy use, but the ambient faces design appeared to be the best-performing display type, and it was significantly different to the control as shown by the non-overlapping intervals in Figure 5.5.

5.2.3.2. Preference

Results of the post-study survey conducted to gather the students' feedback on their preferences for display designs are shown in Figure 5.6 and Figure 5.7 (see Section 7.7.2 in Appendix G for tabulated survey results). The following questions were asked in the interview:

- Which type of display design did you like the most, and the least?
- Which display components(s) did you find easy to understand, useful to have, or irritating to look at?

- Did you like or dislike the use of colour coding on the display? Did you find it understandable, useful, or useless?

The numerical design was voted by 28 of 34 students (82.4%) as the most preferred design type for reasons of providing detailed, informative consumption data, ease of reading and understanding the information displayed; only 1 in 33 students liked the ambient display.

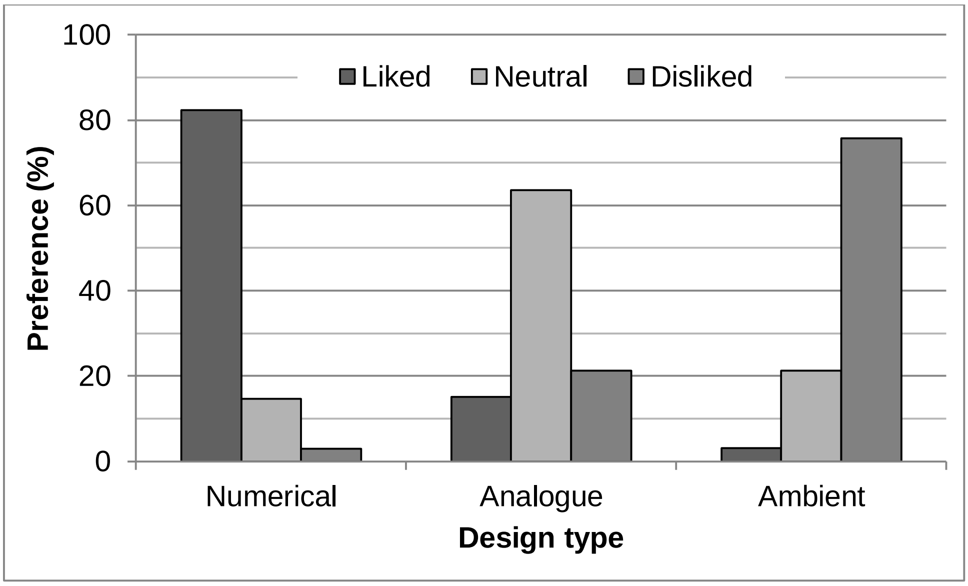


Figure 5.6. Design type preferences

Figure 5.7 shows that the students appeared to be more interested in the consumption data in the present than in the past. Weekly averages were not seen as easy to understand as the other three display components (67.6% for “Today so far”, 64.7% for “Yesterday”, 73.5% for “Group ranking”, 58.8% for “This week average”, 55.9% for “Last week average”). In particular, consumption data in the last week were viewed as the least useful information (58.8%). Interestingly, the group-ranking component was voted as subjectively the easiest type of feedback information to understand (73.5%), but it was the least favourite display component to have on the display (17.6%). This might be due to the negative feeling associated with competing with other groups and the lack of control as an individual in a group. However, when asked if they would like to know how other groups had done, 85.3% of the students responded positively.

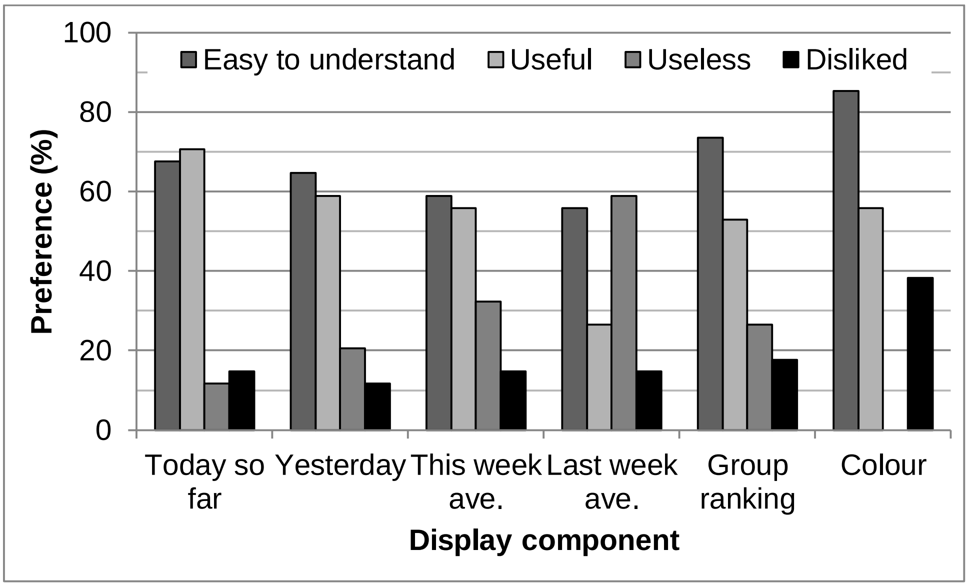


Figure 5.7. Display component and colour coding preferences

Like "Group ranking", a majority of the students found colour coding easy to understand (85.3%), but it was not seen as useful (55.9%), and its presence was not entirely welcomed (38.2%).

In responding to the feedback shown on the display, many participants expressed a wish to receive information on current energy usage and cost while an energy-use event was taking place, preferably a breakdown of energy consumption by appliance, bedroom and kitchen. A comment on the future design was to include user interactivity where users could control what is seen on the display by adding, mixing and removing the type of display design, information presentation and other features shown on the display. It appeared in the survey and the interview that, of the five display components, "Group ranking" noticeably affected participants' general impression to the overall display design. Many expressed a feeling of frustration as to not knowing how far their group was standing from the group ranked before them, in other words, they would like to see other groups' consumption data as well as their own, so that they could decide on how much and where to adjust their energy use as a group. Further, tips and advice on reducing energy consumption would be appreciated, as well as comparable average usage or daily consumption in the last seven days to indicate the group's performance relative to their own consumption on the same day of the week in the past.

5.2.3.3. Other survey results

Results of the questionnaires on participants' environmental attitudes and their feedback on the experiment are presented in Table 5.4 (pre-study) and Table 5.5 (post-study). Overall, the students appeared to be conscious about the environment and took repetitive actions, such as taking carrier bags to shops, switching off the lights and saving paper usage, to reduce their waste. They also acknowledged the impact of climate change on the environment, but they were not as diligent in turning down the radiator as in switching off the lights when the rooms were not occupied for a long time. One possible explanation is that heating up a room to a satisfactory temperature takes time, unlike the lights that provide sufficient lighting level almost instantly when switched on. As the students pay an all-inclusive fee for their accommodation, the level of concern for their energy consumption might be lower than keeping the room warm all the time. Another reason might be that the radiator valve switch is not located near the exit door; in other words, it is not as conveniently accessible as the light switch. One aspect also worth highlighting from the pre-study questionnaire is that the answers to Question 9 in Table 5.4 served to illustrate the power of financial incentives to motivate energy conservation, as the students presumably do not have a financial motivation to use less energy, a majority of them were still interested in making the effort in exchange for getting a reduction in their accommodation fees.

Table 5.4. Pre-study survey of participants' attitudes on the environment, consumerism and energy consumption (%)

	Agree	Neutral	Disagree
1. I prefer online shopping	43.9	31.7	24.4
2. I learn / read about environmental issues in the media (TV, newspapers, magazines, books, online, etc.)	61.0	24.4	14.6
3. I take bags with me when I go shopping	53.7	22	24.4
4. Climate change and its effects on the environment are mainly caused by human activities	80.5	9.8	9.8
5. I switch off the lights when I am not in the study bedroom, even if I am just eating in the kitchen	51.2	24.4	24.4
6. The threat of environmental problems has been greatly exaggerated	34.1	22.0	43.9
7. For scribbling or making notes, I take paper that is already used on one side	63.4	24.4	12.2
8. I turn off / down the radiator in my room when I go out	39.0	17.1	43.9
9. I would make efforts to reduce my energy consumption if I knew it would bring on a 10% reduction in my accommodation fees	97.6	0.0	2.4
10. I look for certified organic foods whenever possible when I shop	12.2	24.4	63.4

In the post-study survey, the students generally became aware of their energy consumption as a result of participating in the experiment. In contrast to their responses in the interview as discussed in the previous section, they also showed a low level of interest in acquiring more information about reducing energy consumption, possibly due to their believing that they already had a good knowledge of how to save energy. Further, the students seemed to be more conscious about their energy use in the kitchen than in their study bedrooms, possibly due to the display being installed in the kitchen that provided a visual cue of being mindful of their behaviour. If this assumption was true, the presence of the display would be significantly meaningful, as it helped raise awareness, and connect energy consumption to related behaviours, serving what an effective feedback intervention is likely to do.

Table 5.5. Post-study feedback survey on Experiment 2 (%)

	Agree	Neutral	Disagree
1. The study has made me think more about my everyday energy consumption	70.6	14.7	14.7
2. I have tried to reduce my energy use in my study bedroom	44.1	17.6	38.2
3. I have tried to reduce my energy use in the kitchen	50.0	20.6	29.4
4. I have told my friends about the study	58.8	26.5	14.7
5. The study has made me want to know more about energy consumption of different appliances (in the study bedroom / kitchen)	26.5	44.1	29.4
6. The study has made me want to know more about where and how I can reduce my energy use	38.2	32.4	29.4
7. I am curious about how other groups have done in the study	85.3	11.8	2.9

Figure 5.8 shows that there were slight changes in the energy-use activities between pre-study and post-study. Similarly, changes in energy use by appliance were also observed as shown in Table 5.6.

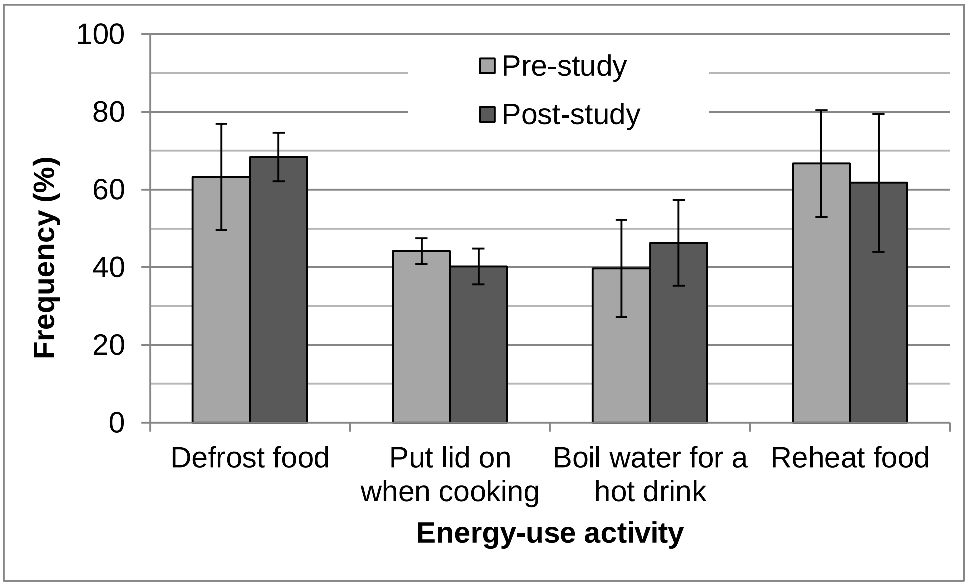


Figure 5.8. Comparison of energy-use activities by category between pre-study and post-study

Table 5.6. Comparison of energy-use activities by appliance between pre-study and post-study

	Pre-study (%)				**Post-study (%)**			
	Frequency of n = 34	Often	Sometimes	Occasionally	Frequency of n = 34	Often	Sometimes	Occasionally
Defrost food	**63.2**				**68.4**			
M/wave oven	94.1	75.0	25.0	0.0	82.4	75.0	14.3	10.7
Warm water	32.4	27.3	18.2	54.5	52.9	16.7	11.1	72.2
Room temp.	76.5	46.2	19.2	34.6	73.5	36.0	20.0	44.0
Fridge o/night	50.0	17.6	35.3	47.1	64.7	22.7	9.1	68.2
Put lid on	**44.1 (excl. "No lid on")**				**40.2 (excl. "No lid on")**			
Pot	50.0	82.4	11.8	5.9	52.9	44.4	27.8	27.8
Pan	47.1	68.8	25.0	6.3	35.3	25.0	16.7	58.3
Wok / other	35.3	25.0	16.7	58.3	32.4	0.0	9.1	90.9
No lid on	47.1	93.8	6.3	0.0	41.2	100.0	0.0	0.0
Boil water for a drink	**39.7**				**46.3**			
Kettle	76.5	76.9	11.5	11.5	79.4	88.9	3.7	7.4
M/wave oven	23.5	12.5	0.0	87.5	35.3	0.0	8.3	91.7
Hob	23.5	12.5	0.0	87.5	35.3	0.0	8.3	91.7
New	35.3	75.0	8.3	16.7	35.3	58.3	0.0	41.7

	Pre-study (%)				Post-study (%)			
	Frequency of n = 34	Often	Sometimes	Occasionally	Frequency of n = 34	Often	Sometimes	Occasionally
Reheat food	**66.7**				**61.8**			
M/wave oven	94.1	87.5	9.4	3.1	97.1	78.8	9.1	12.1
Hob	52.9	33.3	22.2	44.4	41.2	42.9	14.3	42.9
Oven/grill	52.9	27.8	27.8	44.4	47.1	12.5	25.0	62.5

5.2.4. Discussion

Although the ambient faces design seemed to work the best among the three display designs, it was not a big enough difference to achieve statistical significance – there is currently the possibility, in the absence of further data, that the three designs presenting the same information might communicate equally well to participants.

In the previous laboratory-based Experiment 1, the numerical display was found to perform better than the other displays when the task was specifically to spot changes in the information displayed. In the present study, where participants were not focused solely on the task of distinguishing changes in information, but rather were asked to carry out their other daily tasks as usual, the numerical display had no advantage. This demonstrates that low-level usability studies, which focus on the perceptibility or interpretation of displays rather than the influence of those displays on energy-consumption behaviour, are likely not a good guide to whether a smart meter will influence energy use in real-life settings.

There is also room for exploring the potential of the ambient design further in the feedback literature. Research has suggested that ambient displays have great potential for learning through raising and enhancing awareness and giving feedback, and that the interactive element and the motivation to learn are fundamental themes in the learning process but are not well investigated (Börner *et al*., 2013). Although ambient displays have a low capacity to convey explicit information, research has indicated a positive user experience associated with learning from basic ambient signal, and the confidence that ambient displays are suitable to present information (Börner *et al*., 2013), as average householders may not be familiar with energy units, and may be alienated by an overly numerical display (Darby, 2009).

In a similar vein, in both the previous laboratory study and the present field study, participants reported a subjective preference for the numerical design – given the choice, they said they would rather see numbers than other displays. Despite this, there was no increased reduction in energy use amongst participants seeing this display – indeed, the ambient faces display appears to have the advantage. This suggests that simply asking people what they prefer in a display is also not good enough for energy display design if the primary goal is to reduce energy use.

In addition to the disjoint between participants' stated preferences for display designs and their actual energy-use behaviour, it was noted that although their energy use might have been altered by the presence of the displays, many of the students reported that they paid very little attention to the information being displayed. Given this claim, it seems that ambient displays may, again, have particular advantage in IHD design as they do not require active user engagement and can be read at a glance to get a feel for the general pattern of energy use, even by people not motivated to seek out energy information.

Although about half of the students showed an interest in the group-ranking component, about 85% were happy to know how other groups had done. This suggests that the students were more interested in establishing their behaviour by comparing with other people's behaviour than in the competition element stimulated by the group-ranking component on the display.

Like the previous laboratory-based experiments, this experiment showed that colour coding was not as effective or appreciated as expected. It appears that by loading the information that is already conveyed by the display type (numbers, dials, emotional faces), colour coding becomes redundant. Accordingly, many participants reported that the presence of colour did not improve the quality of information in addition to what was already represented by each display component. Instead, they found the system annoying rather than helpful. They also anticipated seeing changes in energy consumption, hence changes in the colour, on a weekly, if not daily, basis particularly in the first two weeks of the experiment when they had made efforts to reduce energy use. For the numerical display, the numbers might have decreased, but the colour remained the same. The other two designs were only more confusing to them than the numerical display. As a result, distrust and loss of interest developed, which may explain the negative views on the use of colour coding. Despite the woeful feeling towards the use of colour, these subjective views demonstrate the importance of participant feedback given in the survey and interview, which would probably not have been revealed in the measured consumption data.

5.3. Experiment 3: self-relative and other-relative comparisons

According to social comparison theory, comparison with others reduces uncertainty and helps establish personal behaviour, suggesting that other-relative comparisons should provide an effective mechanism for providing energy savings (Festinger, 1954). However, as shown in Chapter 2, early trials in the UK suggested that scepticism to the accuracy of readings hindered the use of other-relative comparisons and that self-relative comparisons were much better received (Roberts *et al*., 2004).

To revisit this issue, this study sought to test self-relative comparisons (though remaining in the context of other-relative comparisons) to see if they could motivate additional energy savings over and above those already achieved in Experiment 2. This was supplemented by testing a monetary reward scheme that aimed to make savings obtained via self-relative comparison more salient.

5.3.1. Method

5.3.1.1. Participants

The study again evaluated electricity consumption of the same six groups of students as in Experiment 2. It was carried out four weeks after Experiment 2 ended using the same sensor framework described in Section 5.2.1.3, but with a modified display containing new metrics. The rooms were fully occupied by the same students in both experiments. Twelve of the non-participating kitchens were used as controls. Not all the historical consumption data of the non-participating groups in Experiment 2 and Experiment 3 were retrievable from the university's database; therefore, the number of control groups in the two experiments was different.

5.3.1.2. Data baseline

Nine days prior to the start of the experiment (after Experiment 2 ended and during which the displays were switched off) were used as the baseline period in the analyses. The lengths of the baseline periods were different in Experiment 2 and Experiment 3 to account for the timing of the teaching terms during which the experiments were conducted. Once again, neither the control nor experimental groups were informed of when the baseline period was at any time prior to or during the experiment.

5.3.1.3. Experimental design

To test the effectiveness of self-relative comparisons, the present study used only the ranking component from Experiment 2 with a financial reward component to express the ranking information more clearly. The display was updated once a day and the two display components were produced as follows (Figure 5.9):

a) The ranking component calculated rank based on improvement against one's own baseline. For example, if Group A saved 4% and Group B 3%

compared with their baseline, Group A would rank higher even if its absolute consumption in kWh was higher.

b) It was clear from Experiment 2 that the ranking component by itself does not convey a lot of information because it is an ordinal scale. For example, for three participating groups A, B and C with reductions of 4%, 3% and 8%, respectively, the rank order would be C, A, B. On seeing this, Group A might reasonably, but mistakenly, assume that they are half way between Groups C and B. To convey the degree of separation between groups, an artificial "distance factor" was created. Further, to make the savings more salient, the "distance factor" was converted into monetary units – £0.35 sterling was rewarded for every kWh of electricity saved. The rate was derived based on a survey of electricity tariffs (including unit price and standing charge) averaged from six major energy companies in the UK[20]. These "earnings" were based on daily cumulative savings until the end of the experiment and were split among group members. Unlike Experiment 2, therefore, every member of every group stood to gain a reward provided they had cumulatively saved energy from their own baseline over the experimental period.

Figure 5.9. Ranking design

As shown in Figure 5.9, numerical black-on-white displays were used in this experiment. As found in the previous experiments, the numerical design was well received, and the use of colour was not useful enough to improve the

[20] The "Big Six" are British Gas, EDF, E.On, NPower, Scottish Power and SSE.

performance of the display, which was redundant to the information carried by the display.

5.3.2. Experimental procedure

The procedure for the experiment was similar to that of Experiment 2. As both experiments were conducted on the same group of participants, a one-day notice was e-mailed to the students this time, highlighting the use of self-relative comparison in this study, and apprising of the terms of the reward. The displays were routinely checked on during the running of the experiment. The end of the study coincided with the end of the academic term and the beginning of the assessment days; therefore, no feedback was collected from participants.

5.3.3. Results

An overall daily reduction of 0.40 kWh (approximately 2.5% savings) was achieved with the ranking display compared with the mean baseline consumption of 16.43 kWh (see Section 7.7.3 for detailed data). Figure 5.10 shows that there was an overall decreased consumption trend in both the control and experimental groups over the six-week experimental period, which was likely due to increasing day length reducing the need for artificial lighting[21] (analysis of covariance revealed a significant change in energy consumption over time $F(1,74) = 10.569$, $p = .002$).

[21] The effect of day length is not relevant for Experiment 2 as each design type was tested for two weeks six times, and the change in day length over a two-week period was assumed not to be sufficient to introduce a large effect.

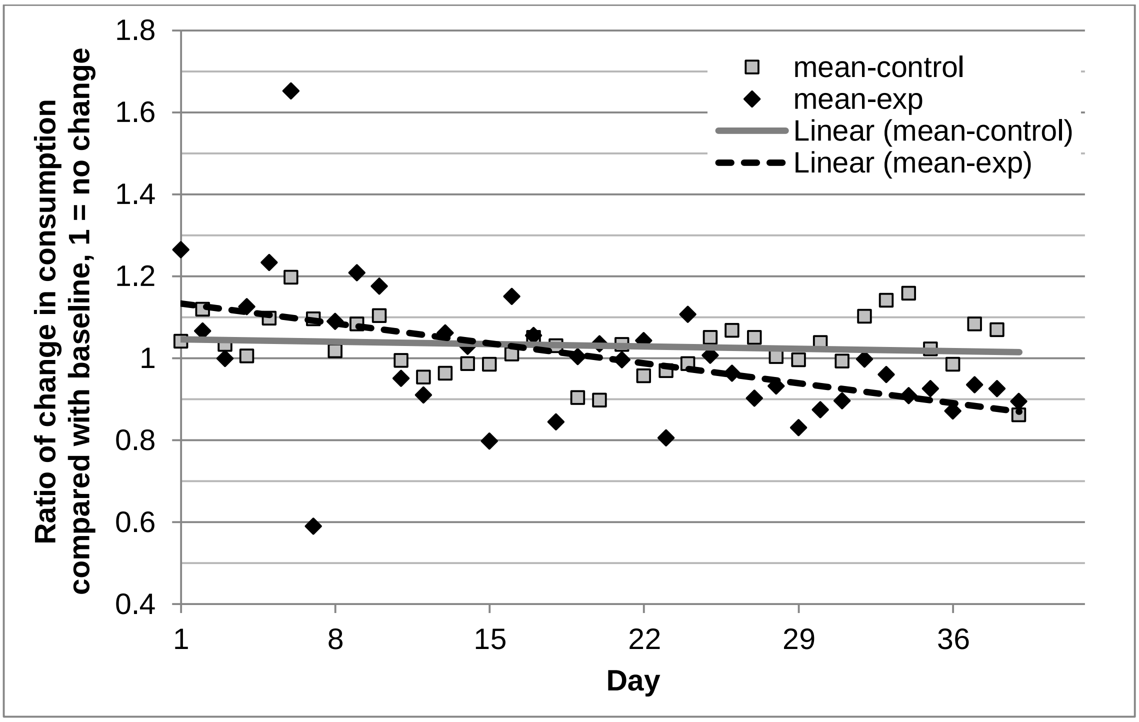


Figure 5.10. Comparison of mean daily change in consumption[22] between control and experimental groups

Although the analysis showed that the control group and experimental group did not differ in their own overall consumption after controlling for the effect of day length ($F(1,74) = 1.144$, $p = .288$), the difference in the downtrend of consumption over time was found to be significant between groups ($F(1,74) = 6.619$, $p = .012$), with the experimental groups showing a steeper declining trend in energy use. The smaller savings could also be a result of the perceived value of the proffered reward (£0.35 per kWh saved), though this would require further testing with a range of reward values.

5.3.4. Discussion

The way participants used energy and the conscious decisions they made to maintain their energy-related behaviour were influenced by the type of information presented on the display. In particular, ranking information seems to

[22] The data value 1 on the *y* axis represents no change, data value above 1 denotes an increase, data value below 1 denotes a decrease.

have powerful and complex effects on behaviour. For comparison, an interesting result from Experiment 2 was that where participants competed with other groups, the high-ranked energy-use groups showed a greater tendency to take action to reduce consumption, presumably motivated by a desire to stay on top of the displayed rankings. The low-ranked energy-use groups, in contrast, showed no evidence of taking action in response to the information shown on the displays. This suggests that peer comparison does not work for everyone, and that high- and low-ranked energy-use groups, when put in comparison, respond differently. High-ranked energy-use groups are likely to react strongly to the feedback and stay motivated to use less energy. Low-ranked groups, conversely, are likely to lose interest in the face of the challenge and stop trying to improve. A different pattern was seen in this experiment, however. Here, participants saw their current energy use compared only with their own past behaviour (in the context of others' savings) and were more motivated even if the savings were comparatively smaller. It is possible that the advantage for self-referenced information over other-referenced information arises because the outcome of a self-referenced process is entirely within one's control, whereas the outcome of an other-referenced study also depends upon the uncontrollable actions of other parties. Further research could usefully explore this in more depth.

It is noteworthy that in real-world settings, the introduction of a pure self-comparison system of this sort could effectively penalise people who have previously been living energy-efficient lifestyles. Unlike people who have been excessively consuming energy, they lack ready opportunities to make substantial reductions. In real-world settings, the results of the experiments taken together suggested that self- and other-relative feedback systems could both usefully be implemented, with other-referenced information given to those already living more energy-efficient lifestyles and self-referenced feedback given to those whose current energy use is high.

5.4. Limitations of Experiment 2 and Experiment 3

The experiments were conducted in a university residence environment, which posed a restriction on the experimental period to term times only, post-study monitoring could not be carried out. Future work will be useful to include revising the experimental design and repeating the experiment over the next coming academic years. Data collected on the short-term basis could be useful for resources management at universities to identify the general trend of resource consumption in each term time and to devise external motivations for reductions. Short-term motivations could be more powerful than those that are long-term based, as recurrent feedback, awareness and rewards could keep the interest going and goals achievable[23].

The experiments were limited to the context of university residences, and a small number of participating groups were involved, results could, therefore, be affected by factors peculiar to this population. For example, a recent study on the same population revealed relatively low levels of environmental concern amongst students at this university (Thomas and Walker, 2011). Similarly, qualitative research recently carried out on this population confirms a tendency amongst some to consume energy without moderation as a result of the all-inclusive payment scheme which does not reward saving energy (van der Broek and Walker, in prep). More studies need to be conducted in real-world households and in other types of campus building for an extended duration to establish the validity of these results.

The financial rewards for achieving energy savings in each experiment did not appear to be universally attractive to everyone involved. The intention of providing this financial payment was to simulate the money savings a

[23] A four-month field trial derived from this study using similar display designs and a competition among colleagues was conducted in an office environment to investigate user response to the visual presentation of electricity consumption of lights and computers (Dara, 2012). The results clearly showed that when the competition and displayed feedback were implemented, energy consumption decreased; when the interventions were removed one by one each month, energy consumption started to increase and eventually back to where it was before the trial began, thus illustrating the usefulness of short-term motivations.

householder might make by reducing their energy consumption – a step that was likely necessary to increase the validity of this study, given that the student participants in this experiment paid a fixed amount regardless of how much energy they consumed. The amount of the reward was set based on usual research practice at this institution, and with a view to keeping the amount of money in the same order of magnitude as the householder savings being simulated. The fact the reward was not equally attractive to everybody raises the question of whether participants reduced their energy consumption for a variety of reasons, including self conscience, a “feel good” state of mind, the competition element, the information provided, and/or existing environmental attitudes. However, in real household settings, it is likely that a similar range of motivations will be at work, with some people addressing their energy consumption as a result of their personal or environmental values, and others doing the same behaviours for reasons of gaining direct benefits, such as saving money or achieving thermal comfort. Given this position, and given that the motivation might vary in depth across people, it will be useful in the future to explore further the relationship between reward structure and individuals’ values and goals, with a view to devising motivations, perhaps tailored to the values and goals of an individual, for developing long-term behavioural change. This sort of motivations will help encourage people keep carrying out energy-saving behaviours until such time as these behaviours become routine or, better, habitual (*cf*. Lally *et al*., 2010), and so become executed automatically even in the absence of reward or feedback structures.

A simplified source of information was studied in this work, but it was not clear if the same energy-use reductions would be achieved with information provided in other units, such as CO_2 instead of kWh. It is possible that energy displays will work best with a mix of information types, so “pure” and “hybrid” studies need to be conducted to get a better understanding of how this works. More studies are also necessary to answer questions on how much information actually influences behaviour, and if people really take advantage of the information provided by the displays, or merely see them as reminders to reduce energy use (Faruqui *et al*., 2010). Furthermore, studies are needed to evaluate the frequency of updating information, as well as the time length of providing information.

This work acknowledges the limitations of the questionnaires used in Experiment 2 that required refinement, particularly in the consistency of questions in the pre- and post-study questionnaires on environmental attitudes and energy-use behaviours, so that they could be linked to the resultant energy usage and explored further. Despite this, the post-study questionnaire revealed a number of positive and negative aspects of the design of energy displays that are valuable to the designer, which could have been overlooked in the measured usage data.

Lastly, although participants might have behaved differently knowing that they were being observed (the Hawthorne effect, a type of reactive effects), it is not known how large such effect might be in these experiments. It might be reasonable to assume that it did not last the full length of the experimental period. Similar studies with a longer period will be required to address this limitation.

5.5. Chapter conclusion

This chapter presented two short-term experiments conducted in student residences, with small financial rewards for participation, to investigate how visually displayed energy information presented in different ways could encourage reductions in energy use. Experiment 2 compared three types of design for energy displays; Experiment 3 examined how well participants responded to self-relative comparison and social comparison ranking information shown on the display in numerical format about their own consumption. Electricity consumption was measured in both experiments.

Average measured daily electricity consumption reduced significantly more than in control groups for all three display designs tested in Experiment 2, achieving a 7.2% reduction below baseline. The same group of participants showed a further 2.5% reduction from their baseline consumption when a self-comparison ranking display was introduced in Experiment 3. Although there was a trend towards the ambient faces display performing best, all the displays led to a reduction in energy use. Whilst it is not clear yet whether one display design works better than the others to reduce energy use, it is apparent that the mere presence of a display influenced participants' behaviour. Even though participants reported not being engaged with the displays often, and making no effort to reduce their energy use, they did lower their energy consumption, although it is not yet clear if this effect would last over longer periods.

Two further insights arise from these experiments. The first is that the extent to which a design requires conscious effort, and so motivation, from the participants appears to be an important moderating influence. Results from the previous task-based laboratory Experiment 1 showed that when the task was merely to detect changes in the information displayed, this was easier with the numerical design than the analogue dials and the ambient faces designs. However, here in a residential setting, all three of the designs led to reductions in energy consumption. This implies that, in real-world settings, detecting changes in and understanding energy information is quite different from a task-driven laboratory environment.

The second insight is that subjective preferences for display designs are not a good indicator of their actual performance. Too often, the success or failure of a display design concept is judged on the specific implementation, and what people like is not necessarily what is most effective in actually changing behaviour (Payne, 2013). This raises the question of whether it is better to use a design that works to reduce consumption but is less preferred than others, or to leave the selection to personal choice, given that all three designs considered here worked to reduce energy consumption.

Chapter 6 Overall discussion and conclusion

6.1. Introduction

This thesis has presented research undertaken with an aim to investigate and progress the existing understanding of the design of IHDs and their effects on energy-related behaviour in three aspects: types of display design, energy information displayed and subjective feedback on the display design and energy information (see Section 6.2). It has reviewed the existing literature and identified the limitations that highlight the need for empirically investigating how IHDs can be designed. It has also provided a body of practical data on the human response to the design of such interventions and on the resultant energy consumption. The experimental results offered insights into the variability in the process of designing IHDs and the factors influencing the quality, and demonstrated the significance of optimising the design of IHDs which will be instrumental in the future work to develop effective smart meter displays and in the area of energy-consumption behaviour.

6.2. Objectives and findings

In fulfilling the aim of the research, several objectives were set in Chapter 1. Key findings meeting these objectives are summarised below:

1. To design “pure” IHD types with different display design features, e.g. coloured and non-coloured displays.

Three display design types were adopted and developed, each using a single presentation format, namely, numbers, analogue dials and emotional cartoon-like faces, to present the same information on energy consumption. In addition to the display type, colour coding was used to represent different levels of energy consumption and compared with non-colour coded (black text on a white background) displays.

A pilot study was conducted to test the proposed display designs. Chapter 4 presented the limitations of the study and suggested from a subsequent laboratory-based experiment (Experiment 1) that different display designs communicated the same energy information on different levels. Among the three design options, the numerical presentation appeared to have the advantage in IHD design, whereas the faces design was shown to be least effective in conveying the same information.

Further, the use of colour did not appear to be any more significantly useful for highlighting changes in energy information than simple black-on-white displays, although it was highly appreciated for providing extra information, ease of distinguishing differences, visual aesthetics and learning experience.

Chapter 5 reported results from the field work where the three display designs were tested in a real-life living environment (Experiment 2) and suggested that all three designs were similarly effective in presenting energy information when users' attention was divided in a domestic environment, although there was a strong indication that the faces design worked better than the other two designs.

2. To measure users' responses to various IHD designs presenting the same information.

The laboratory-based experiments (the pilot study and Experiment 1) utilised computer programmes to simulate energy displays and precisely measured participants' reactions to various display designs in terms of response time and accuracy rate.

The field-based study (Experiment 2 and Experiment 3) also used computerised systems to measure participants' responses to the display designs by collecting their actual energy consumption data as a result of seeing and engaging with the displays. In addition, the consumption data of the days leading to the start of the study were used as the baseline data, which, coupled with control groups, helped to increase the validity of the comparison to be made with experimental groups' data, giving a clear indication of the effect of the display designs.

3. To assess the effectiveness of each tested display design in communicating information to the user.

In addition to measuring the ability to detect changes in the energy information shown on the display, the research also looked at the effects of the experimental display designs on participants' perception of such feedback information.

The literature review in Chapter 2 identified the need for systematic testing of energy display designs as well as of the feedback information they carry in order to find the best type of information to be provided to the user and to increase their understanding and awareness of energy consumption. The display designs tested in the research contained between five and six pieces of energy information, which were referred to as the display components in this thesis, featuring different states of energy consumption in the past and in the present, and in power units and cost.

As suggested in the literature review, too, that people tend to respond well to immediate and informative feedback on their consumption, with context-appropriate motivational interventions such as comparisons (Roberts and Baker, 2003), the effect of comparative feedback was investigated in Chapter 5. Results suggested that the way participants used energy and maintained their energy-related behaviours was influenced by the type of information presented on the display. Results also indicated that participants responded better to self-relative comparisons than to other-relative comparisons, and revealed the differences in the reactions of high-ranked energy-use groups (low energy users) and low-ranked energy-use groups (high energy users) towards these comparisons.

4. To understand the effects of these display designs from the user's perspective.

Chapter 4 and Chapter 5 presented subjective views from study participants regarding the design of energy displays. Participants appeared to be more interested in the consumption data in the present than in the past, as well as in self-relative feedback than peer comparisons.

In theory, a successful implementation of IHDs to encourage efficient energy behaviours requires the user's understanding and engagement with the tool (Petersen *et al*., 2007; Fischer, 2008; Peschiera *et al*., 2010; Jain *et al*., 2012; Krishnamurti *et al*., 2013). Participants in the field study claimed to pay little attention to the displays installed in their living environments, their measured data, however, suggested that they might have made some effort that they probably did not realise in the presence of the display to lower their energy consumption, although further tests are required to confirm this.

This research has shown the disjoint in results from experiments conducted in the laboratory and field environments. In the laboratory experiment, participants' task performance results were positively related to their preferences – the numerical design had the best performance results and was the most preferred design type. However, such relationship was not found in the field-based study where results suggested that all three display designs worked equally well, even if participants liked the numerical design more than the other two designs.

Given the fact that results from laboratory tests do not entirely reflect what will happen in real-life settings, and that claimed preferences cannot substitute for experimental testing and do not always lead to improved performance, subjective views and laboratory tests are poor indicators of the actual performance of IHDs in the real world. However, although user perspectives may not seem to be wholly useful in the design and in achieving the desired behaviour in this work, they can still help designers gain a better understanding of user needs, and how to present energy information that is likely to enhance the user's experience and perceptions of energy displays, and promote user engagement, such as in the case of colour coding, given that the three designs considered in this research have been suggested to perform similarly well in communicating energy information to users and in reducing energy consumption.

6.3. Limitations and future research

Throughout this thesis, limitations of the research and areas of potential future work have been identified, many of which are summarised in this section in addition to other areas of interest for possible future studies.

With limited sources of sample type and size used in this research, future work should use a better representative sample to systematically test the display design options, and use control groups in the computer-simulated experiments (pilot study and Experiment 1 in this case) to trace back the effects of specific types of display design.

Although limited, this work has shown that the various display design options tested in the experiments can be included in real-life energy monitor displays. Whilst there is a clear increase in the number of studies in the last 10 years on the design of feedback and IHDs, there still exists a lack of confidence in the optimisation process of IHD design. Plainly, more work on how to present feedback, how displayed feedback works and the process it involves is needed.

A clear gap in this research investigation is that the effect of colour coding was examined in the laboratory experiments, but not tested further in the field study, which primarily focussed on the efficacy of display design types. Future work should compare coloured and black-on-white displays using one design type at a time to observe the effect of colour on the ability to read energy information and on energy consumption in the real world.

Although the interviews revealed that some participants were more interested in the interventions used in the study (rewards, comparative feedback) than the others, and results might have suggested the effects of IHD design, it was not entirely lucid in the data to indicate the reasons for participants to lower their energy consumption. Further work is needed to examine other factors motivating users to change their minds and behaviours. For example, surveying participants' intentions, energy management, as well as environmental attitudes, may help to identify motivational factors and opportunities that contribute to sustainable and wasteful behaviours, particularly those that have a large energy-saving potential. These factors may then be related back to behavioural models and targeted by appropriate interventions.

Following on from the previous paragraph, an area for improving the quality of the research is to adopt a more holistic approach in the qualitative research method, in which interviews should have been audio-recorded and transcribed, so that each interviewee's feedback on how energy was actually used and what actions were taken to reduce consumption could be closely scrutinised, methodologically analysed and compared with observed performance for validity. This approach would require practice for transcribing verbatim and a keen ear for distinguishing overlapping conversations which often happen in group interviews. Collecting subjective data from interviews will help facilitate learning from feedback more effectively, from which future research can explore the process of developing own methods of energy management to taking control over energy consumption.

While the laboratory experiments successfully established the effect of each design condition separately, the feedback information used in the field study to promote awareness and the visibility of energy use was supported by other interventions (comparisons and rewards), making it difficult to attribute the success of achieving energy savings to feedback, comparisons or rewards alone. Yet the study demonstrated the combined effect of interventions which contributes to providing evidence in the field of interventions making largest and longer-term savings.

Future work can also look into other interventions that were not used in this research:

a) Information

The provision of information has been identified as one of the primary methods to achieving greater energy efficiency (DTI, 2007). Information may help increase knowledge and awareness, by giving advice on how to use less energy and linking consumption to source as part of the learning and evaluation process (e.g. Staats *et al.*, 1996; Henryson *et al.*, 2000; Wood and Newborough, 2003; Roberts *et al.*, 2004; Abrahamse *et al*., 2007). However, research has also noted that, like many interventions to increase motivation and to promote behavioural change, providing information alone is not guaranteed to have the desired effect (Hayes and Cone, 1977; van Houwelingen and van Raaij, 1989; Cialdini *et al.*, 1991; Roberts and Baker, 2003; Darby, 2006; Wood and Newborough, 2007a; Frankish, 2009), or even a change at all (Wood and Newborough, 2003; Abrahamse *et al.*, 2005), because it works on an abstract level that leaves users to link their knowledge to their actions, and thus lacks concrete motivation (e.g. to save energy). It may sometimes lead to boomerang effect, which is the result of deconstructive behaviour when normative information instructing a certain socially acceptable behaviour is presented to people who are already above the norm who now become below-average norm performers (e.g. Schultz *et al.*, 2007). The effect of information could be improved by delivering it with appropriate specificity, timing and placement, so that users may be more responsive to information that is clear and actionable (Geller *et al*., 1982; Froehlich *et al*., 2010).

If future work is to be conducted in a university setting like the work described in this thesis, it may usefully include comparing the effects of information given in different manners, e.g. through media campaigns, websites, pamphlets, workshops, home audits and information packs (e.g. Brandon and Lewis, 1999; Wood and Newborough, 2003; Abrahamse *et al.*, 2005), to see which source(s) of information is more likely to be adopted by the student population. The work may also include comparing information with other single antecedent interventions, and the design of a mixed-interventions approach. Work should consider factors such as trust of information sources, comprehension and presentation of the delivered information, as well as specificity, timing and placement as mentioned before, and how these factors influence the effect of this intervention (Winett *et al.*, 1978; Geller *et al.*, 1982; Brandon and Lewis, 1999; Henryson *et al.*, 2000; Roberts *et al.*, 2004; Brewer and Stern, 2005; Anderson and White, 2009).

b) Goal-setting

Goal-setting entails giving a reference point and is a comparison between the present and a desirable future situation (van Houwelingen and van Raaij, 1989; Abrahamse *et al.*, 2005). Individuals are given a goal to strive for, such as limiting peak-hour energy use, reducing cost, time and duration of use (van Houwelingen and van Raaij, 1989). Consequently, it is often linked to commitment that involves written or oral promises to behave in a specific way. Many studies have found that goal-setting is a strong motivator for improving performance (e.g. van Houwelingen and van Raaij, 1989; McCalley and Midden, 2002). Whether the goal is self-set or externally assigned, similar amount of energy savings can be made, but pro-self individuals with a self-set goal are likely to save more energy than being assigned to a goal, while pro-social individuals respond to the intervention other way round (McCalley and Midden, 2002).

The level of difficulty also has an influence on how well people perform to achieve their targets. A study conducted by Becker (1978) showed that a relatively easy goal of saving 2% electricity resulted in a 5.7% decrease, whereas a challenging 20% goal achieved 15.1% of savings, suggesting that the level of difficulty should be challenging but reachable, and that if a goal is too easy to achieve, its worthiness of the effort and effectiveness is limited. On the other hand, unrealistic goals can cause distress and possibly be abandoned altogether (Wood and Newborough, 2007a). Studies conducted after Becker's work similarly supported the idea that setting specific, reachable and challenging goals can result in better performance (e.g. van Houwelingen and van Raaij, 1989; Harkins and Lowe, 2000).

Thus, future work might look into setting goals of reducing cost, consumption or environmental impact, either assigned for or by study participants, in order to find the optimal range of target savings that leads to energy conservation, bearing in mind individual participants' income and potential for savings, and finding a reasonable goal relevant for them to reach.

c) Tailoring of feedback and information

Tailoring of feedback and information may also be looked into in follow-up studies. Smith and Mosier (1986) supported the provision of only necessary and immediately usable data and the avoidance of overloading displays with extraneous data. This way, users' attention is drawn directly to the information that is relevant to them. Further, customisation of user-specific information provides possibilities for interactive learning and energy savings as it acts as an add-on to the user's existing knowledge (McCalley and Midden, 2002; Wu and Yuan, 2003; Jessa and Burns, 2007; Garaas and Pomplun, 2008).

This intervention, however, may or may not work depending on how users perceive the situation. Take comparisons in the context of tailored information for example. Roberts and Baker (2003) suggested that people are motivated to reduce consumption if comparisons show them to be "above average for a group they perceive to be relevant for comparison". In this instance, the provision of tailored information is seen as potential motives and norms of individuals (Fischer, 2008). However, it was not clear if people are still motivated to reduce their consumption when comparisons show their own consumption to be below average, because they may feel that they have done enough and do not see the need to change their behaviour further, even if there is still room to reduce consumption (Karjalainen, 2011). This is an interesting aspect of energy-use behaviour that certainly requires more work to clarify whether tailoring improves the quality of feedback information.

While the success of tailoring is determined by the appropriateness of information given to meet the needs of an individual, such as home audits in the context of household energy consumption in which energy experts give households energy-related advice based on their situation, further work might also look into giving general and personalised information on energy displays and comparing the effectiveness of each approach (e.g. Krishnamurti *et al*. 2013).

d) Interactivity

Although the interface design of energy displays plays an important role in influencing behaviour and decision-making, people may still be discouraged by the way in which information is presented, and lose interest due to lack of motivation and understanding of the information, and low levels of interactivity.

Previous feedback studies (Petersen *et al*., 2007; Peschiera *et al*., 2010; Jain *et al.*, 2012; Oltra *et al.*, 2013) have suggested that energy savings are correlated with user engagement (e.g. user logins, frequency of interaction). Fischer (2008) found that designs that used an interactive element, through computerised feedback or through required activities like self feedback or self-meter reading, were among the most effective ones in stimulating energy savings. But interactivity with the display may be lost for fear of losing the settings that the users understand (Anderson and White, 2009). Intuitive design and default mode are, therefore, critical, and should be explored further.

Another area of interest for further investigation related to designing IHDs is the capacity limit of visual short-term memory when looking at the information on energy displays. By understanding the temporal mental storage capacity (human’s capacity of considering “chunks” of information at one time), the number of stimulus source on the display should be accounted for to avoid information overload. Although the number of information chunks people can remember at a time is suggested to be between three and seven (Cowan, 2001), the display should be designed in such a way that requires using different senses to help improve remembering the information provided. This aspect of design would be particularly useful for users with hearing or visual impairment. Hybrid design that combines different modes in a single display, alarms and flickering lights are among the many possible options to be explored further.

There is still room in the existing literature to explore energy-use behaviour and how energy displays are accepted, weaved into the home environment and used over time, as interest may fade and lifestyle may change. Thus, feedback needs to be improved in such a way that it captures the user’s attention when needs to, links their actions to effects (Fischer, 2008) and provides intuitive and relevant information; and new ways to increase and maintain motivation need to be devised (Oltra *et al.*, 2013). There are also many questions that still remain, such as whether feedback is more effective if presented in energy price or in non-price information, and the point of specificity and frequency of providing feedback at which awareness ceases to increase and behaviour ceases to change (Abrahamse *et al.*, 2007). Further, the contradictory findings of effective representative units, interventions and display designs (e.g. Wood and

Newborough, 2007a; Jain *et al.*, 2012, 2013) indicate areas of research requiring further examination.

The work undertaken in this thesis contributes to the development of smart metering systems, such as the work that is currently being conducted for a large-scaled residential project including 70 homes over a four-year period using display devices, with an aim to promote energy literacy and internal motivations (ENLITEN[24], 2012-2016). The work will help to contextualise personalised feedback information to householders, not only in display design types, but also in the design of wording, graphics and information relevant to individual households.

Lastly, the field work was done in a student residence environment, but it is possible to apply the generalization of the display design and results to a work environment, where resources are shared and master-metered. Therefore, any intentions to encourage energy savings can be externally incentivized, too, such as normative information and rewards. Energy displays should be designed and developed appropriately, meeting building occupants' needs and motivations.

6.4. Conclusion

Research concerning the design of IHDs is growing in the field as shown in the literature review in Chapter 2, suggesting a progressive recognition of and an increasing interest in the potential of feedback for reducing energy use through technology and behavioural change. Significant contributions towards the existing knowledge of IHD design have been made, still there are areas of research requiring further investigation, many of which were highlighted in Section 6.3.

This thesis has demonstrated that display design is indeed an important moderating influence on energy-use behaviour. It has considered how energy

[24] For further information on this project, see http://www.bath.ac.uk/research/case-studies/enlitening-household-energy-literacy; http://www.cs.bath.ac.uk/enliten/index.php

displays can be designed to increase the visibility of energy use, to draw users' attention to them, and to have an impact on energy consumption. More importantly, this work has been carried out to provide an approach to systematically examine the specific aspects of IHD design, which have not been well investigated previously, but may influence users' understanding and consumption behaviour. The work also provides a basis for understanding how users might learn about energy use better from certain types of display design and information than the others.

Finally, the experimental and subjective data of this work will jointly inform what kind of energy information, presentation design and presentation mechanisms would be most effective in the design of smart meter displays. This will, in turn, assist to improve users' comprehension of feedback information, increase their awareness of energy use, and ultimately encourage them to undertake efficient energy behaviours in the long term.

Chapter 7 Appendices

7.1. Appendix A – Chapter 4 information sheet and consent form

7.1.1. Information sheet for the pilot study

Department of Architecture & Civil Engineering
Research unit for Engineering and the Design of Environments

UNIVERSITY OF BATH

INFORMATION SHEET

Study title

The Design of Energy Consumption Displays

Invitation paragraph

You are invited to take part in a research study. Before you decide, it is important for you to understand why the study is being done and what it will involve. Please take time to read the following information carefully and discuss it with the researcher. Ask us if there is anything that is not clear to you or if you would like more information. Take time to decide whether you wish to take part or not.

What is the purpose of the study?

The aim of the study is to find out what design features (colour, size, location) in the design of energy consumption displays are more likely to catch people's attention.

What are the possible benefits of taking part?

Your answers will provide valuable information, which will improve the existing understanding of display design, and will be used to develop further understanding of social, environmental and economic aspects in user behaviour and energy-saving interventions.

Who is organising the research?

Research student Teresa Chiang from the Research unit for Engineering and the Design of Environments (EDEn) at the Department of Architecture and Civil Engineering, University of Bath, is organising the research and conducting the research. This research is supported by the Research unit and the Department.

Why have I been chosen?

We are looking for volunteers of all ages who are not suffering from any eye diseases that may affect normal eye sight. You are a volunteer and can decide whether to take part or not to. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time, without giving a reason.

What does the study involve?

The study will take approximately 25 minutes to complete. After reading this information and signing the consent form, you will be asked to carry out a computerised task which measures your response time and accuracy rate. At the end of the task, you can give your comments on the design of the study.

What are the side effects of taking part?

Although no negative effects are anticipated, they are possible and you may experience some temporary eye strain under extreme circumstances. If you feel unwell during the course of the task, please inform the researcher. You will be able to stop at any time if you decided that strain is excessive.

Will my taking part in this study be kept confidential?

Data Protection Act 1998: all information that is collected about you and all your answers will be maintained confidential by the University of Bath and remain anonymous in all cases. All information gathered will be used only for research.

What will happen to the information/data provided after the study?

All data collected will be given a unique code number. This means that no information collected will have your details or any other means of identifying you personally. A computer file with all data will be kept, but this will not identify you in any way, i.e. it will be anonymous.

What will happen to the results of the research study?

The results of the research will be published and used as part of Teresa Chiang's Ph.D. research on the subject of energy display design. No individual would be identified in any publication. If the research collected is not published, a report of the findings will be available to those participants who request it.

Contact for further information

Your contact for further information is: Teresa Chiang, Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, tel: [not shown], e-mail: [not shown].

Please note that you will be given a copy of the information sheet and a signed consent form to keep.

****

7.1.2. Consent form for the pilot study and Experiment 1

Department of Architecture & Civil Engineering
Research unit for Engineering and the Design of Environments

UNIVERSITY OF BATH

SIGNED CONSENT FORM

I have read and understood the contents of the Information Sheet provided by the researcher. I hereby give my consent to taking part in the study titled 'The Design of Energy Consumption Displays'.

____

Initials and surname

____________________ ____________________

Participant's signature Researcher's signature

University of Bath, Bath, BA2 7AY

Date (dd/mm/yyyy) Place

****

7.1.3. Information sheet for Experiment 1

Department of Architecture & Civil Engineering
Research unit for Engineering and the Design of Environments

UNIVERSITY OF BATH

INFORMATION SHEET

You are invited to take part in a research study organized by the departments of Architecture and Civil Engineering and Psychology at the University of Bath. Before you decide, it is important for you to understand why the study is done and what it will involve. Please take time to read the following information carefully. Ask us if there is anything that is not clear to you or if you would like more information. Take time to decide whether you wish to take part or not.

What is the purpose of the study?

The aim of the study is to see if the type of energy display design and the use of colour can make a difference in how you read the information being presented in them.

What are the possible benefits of taking part?

Your answers will provide valuable information, which will improve the existing understanding of display design, and will be used to develop further understanding of social, environmental and economic aspects in user behaviour and energy-saving interventions.

Why me?

You are here because we are looking for male and female volunteers aged 18 years and over who are not suffering from any eye diseases that may affect normal eye sight. If you agree to take part, you will be given this information sheet to keep and be asked to sign a consent form. You are free to withdraw at any time, without giving any reason.

What does the study involve?

The study will take 20-30 minutes to complete. After reading this information and signing the consent form, you will be asked to undertake a computerised task that measures your response time and accuracy rate, at the end of which you will have a chance to discuss your thoughts about the design of the study with the researcher.

What are the side effects of taking part?

We do not anticipate any negative effects – you will be answering questions on a standard computer screen. However, if you feel unwell during the course of the task, please inform the researcher. You will be able to stop at any time if you feel you are experiencing any strain.

Will my taking part in this study be kept confidential?

Data Protection Act 1998: all information that is collected about you and all your answers will be maintained confidential by the University of Bath, and remain anonymous in all cases. All information gathered will be used only for research.

What will happen to the information/data provided after the study?

All data collected will be given a unique code number. This means that no information collected will have your details or any other means of identifying you personally. A computer file with all data will be kept, but this will not identify you in any way, i.e. it will be anonymous.

What will happen to the results of the research study?

The results of the study will be published and used as part of Teresa Chiang's Ph.D. research project. No individual would be identified in any publication.

Contact for further information

Teresa Chiang
Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY
Tel: [not shown], e-mail: [not shown]

Alternatively, you may contact Teresa's doctoral supervisors:

Dr. Sukumar Natarajan
Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY
Tel: [not shown], e-mail: [not shown]

Dr. Ian Walker
Department of Psychology, University of Bath, Bath BA2 7AY
Tel: [not shown], e-mail: [not shown]

Please note that you will be given a copy of the information sheet and a signed consent form to keep.

****

7.2. Appendix B – Pilot study tabulated results

7.2.1. Display design type

Table 7.1. Accuracy rates and response times of design types

	Numerical		Analogue		Ambient	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Accuracy rate (%)						
Correct	76.5	11.8	81.9	10.8	78.4	11.0
Incorrect	8.6	5.0	8.3	5.0	11.2	6.8
Not answered	14.9	9.8	9.8	8.1	10.4	7.5
Response time (ms)						
Mean	2446.4	167.4	2364.0	169.0	2393.1	148.7
Correct	2340.1	138.7	2288.3	143.0	2314.4	142.4
Incorrect	2585.4	236.3	2446.2	203.0	2443.8	216.9

Table 7.2. Mean differences of accuracy rate and response time of design types

	Mean difference	***p***
Correct answer (%)		
Numerical-Analogue	-5.4	.000
Numerical-Ambient	-1.9	.720
Analogue-Ambient	3.5	.059
Incorrect answer (%)		
Numerical-Analogue	0.3	1.000
Numerical-Ambient	-2.6	.108
Analogue-Ambient	-2.9	.035
Non-response (%)		
Numerical-Analogue	5.1	.000
Numerical-Ambient	4.5	.000
Analogue-Ambient	-0.6	1.000
Response time (ms)		
Numerical-Analogue	82.4	.000
Numerical-Ambient	53.3	.001
Analogue-Ambient	-29.1	.060

7.2.2. Colour of display component

Table 7.3. Accuracy rates and response times of colour types

	Red		Blue		Yellow	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Accuracy rate (%)						
Correct	81.8	11.6	79.7	11.6	79.9	11.2
Incorrect	7.0	5.7	10.3	8.6	8.8	8.2
Not answered	11.2	9.8	10.0	8.9	11.3	9.5
Response time (ms)						
Mean	2322.0	183.7	2381.8	195.9	2441.3	185.3
Correct	2229.1	158.4	2308.2	190.7	2355.8	183.2
Incorrect	2456.1	361.5	2482.5	373.7	2615.7	297.3

	Green		Orange		Grey	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Accuracy rate (%)						
Correct	80.2	13.8	79.2	14.1	78.0	11.7
Incorrect	8.7	7.5	10.9	8.9	10.4	6.4
Not answered	11.1	10.6	9.9	9.6	11.6	10.0
Response time (ms)						
Mean	2378.9	169.3	2407.9	164.9	2376.4	165.9
Correct	2310.1	148.1	2330.4	152.7	2280.6	163.3
Incorrect	2344.5	364.2	2528.9	226.8	2458.6	304.0

Table 7.4. Mean differences of response time of colour types

Colour	Mean difference (ms)	*p*
Red-Blue	-59.8	.053
Red-Yellow	-119.3	.000
Red-Green	-56.9	.036
Red-Orange	-85.9	.000
Red-Grey	-54.4	.056
Blue-Yellow	-59.5	.166
Blue-Green	2.9	1.000
Blue-Orange	-26.1	1.000
Blue-Grey	5.4	1.000
Yellow-Green	62.4	.103
Yellow-Orange	33.4	1.000
Yellow-Grey	64.9	.005

Colour	Mean difference (ms)	*p*
Green-Orange	-29.0	1.000
Green-Grey	2.5	1.000
Orange-Grey	31.5	1.000

7.2.3. Character size of display component

Table 7.5. Accuracy rates and response times of character sizes

	Large		Medium		Small	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Accuracy rate (%)						
Correct	82.4	12.7	70.7	15.2	80.0	13.2
Incorrect	7.5	7.2	15.9	10.6	8.1	7.4
Not answered	10.1	9.7	13.4	11.3	11.9	12.0
Response time (ms)						
Mean	2336.2	170.9	2435.1	197.2	2337.2	170.4
Correct	2249.7	146.4	2347.0	188.3	2218.6	170.9
Incorrect	2453.8	307.8	2466.1	403.0	2527.2	321.4

Table 7.6. Mean differences of accuracy rate and response time of character sizes

	Mean difference	*p*
Correct answer (%)		
Large-Medium	11.8	.000
Large-Small	2.5	.688
Medium-Small	-9.3	.002
Incorrect answer (%)		
Large-Medium	-8.5	000
Large-Small	-0.6	1.000
Medium-Small	7.5	.000
Non-response (%)		
Large-Medium	-3.2	.280
Large-Small	-1.8	.810
Medium-Small	1.4	1.000
Response time (ms)		
Large-Medium	-98.8	.000
Large-Small	-1.0	1.000
Medium-Small	97.9	.002

7.2.4. Location of display component

Table 7.7. Accuracy rates and response times of locations

	Top left		Top right		Bottom left		Bottom right	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Accuracy rate (%)								
Correct	80.7	11. 6	78.1	14.5	75.7	13.7	75.6	16.9
Incorrect	9.2	7.8	8.9	7.7	10.4	7.9	8.1	7.9
Not answered	10.1	10.1	13.1	12.0	13.9	10.4	16.3	12.0
Response time (ms)								
Mean	2358.0	193.0	2506.5	170.9	2442.6	175.7	2557.8	182.5
Correct	2273.1	180.2	2434.6	160.8	2341.5	156.0	2470.8	167.0
Incorrect	2487.7	358.6	2535.4	343.6	2496.4	311.8	2623.0	306.0

Table 7.8. Mean differences of accuracy rate and response time of locations

	Mean difference	*p*
Correct answer (%)		
Top left-Top right	2.6	.121
Top left-Bottom left	4.9	.016
Top left-Bottom right	5.1	.010
Top right-Bottom left	2.4	.290
Top right-Bottom right	2.5	.225
Bottom left-Bottom right	0.1	.949
Incorrect answer (%)		
Top left-Top right	0.4	1.000
Top left-Bottom left	-1.2	1.000
Top left-Bottom right	1.1	1.000
Top right-Bottom left	-1.6	1.000

	Mean difference	*p*
Top right-Bottom right	0.8	1.000
Bottom left-Bottom right	0.3	.585
Non-response (%)		
Top left-Top right	-3.0	.101
Top left-Bottom left	-3.8	.014
Top left-Bottom right	-6.2	.001
Top right-Bottom left	-0.8	.646
Top right-Bottom right	-3.3	.052
Bottom left-Bottom right	-2.4	.119
Response time (ms)		
Top left-Top right	-148.6	.000
Top left-Bottom left	-84.7	.003
Top left-Bottom right	-199.8	.000
Top right-Bottom left	63.9	.039
Top right-Bottom right	-51.2	.032
Bottom left-Bottom right	-115.1	.000

7.3. Appendix C – Experiment 1 tabulated results

7.3.1. Display design type

Table 7.9. Accuracy rates and response times of design types

	Numerical		Analogue		Ambient	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Accuracy rate (%)	95.7	4.5	81.7	10.8	92.0	8.4
Response time (ms)	2505.4	1013.8	3615.3	1462.0	3177.2	1209.4

Table 7.10. Mean differences of accuracy rate and response time of design types

	Mean difference	*p*
Accuracy rate (%)		
Numerical-Analogue	14	.000
Numerical-Ambient	3.7	.017
Analogue-Ambient	-10.3	.000
Response time (ms)		
Numerical-Analogue	-1109.9	.000
Numerical-Ambient	-671.8	.001
Analogue-Ambient	438.2	.132

7.3.2. Colour of display component

Table 7.11. Accuracy rates and response times of black-on-white and coloured displays

	Black-on-white		Coloured	
	Mean	**SD**	**Mean**	**SD**
Accuracy rate (%)	89.1	6.3	90.5	7.8
Response time (ms)	3127.7	1109.0	3017.3	1048.4

Table 7.12 . Accuracy rates and response times of Design type x Colour

	Numerical		Analogue		Ambient	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Accuracy rate (%)						
Black-on-white	95.3	5.8	80.7	13.2	91.4	8.3
Colour	96.1	5.2	82.8	13.3	92.7	12.0
Response time (ms)						
Black-on-white	2538.3	1048.7	3521.9	1450.4	3373.4	1453.0
Colour	2473.8	1042.6	3690.2	1593.7	2978.6	1148.7

Table 7.13. Mean differences of response time of Design type x Colour

Black/white-Colour	**Mean difference (ms)**	***p***
Numerical	64.6	.289
Analogue	-168.4	.345
Ambient	394.8	.012

7.3.3. Location of display component

Table 7.14. Accuracy rates and response times of locations of manipulated display components

	Left		Left-centre		Centre	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Accuracy rate (%)	91.7	7.6	90.8	7.5	87.3	12.2
Response time (ms)	3012.9	1123.2	3139.5	1138.4	3010.6	1354.5

	Right-centre		Right	
	Mean	**SD**	**Mean**	**SD**
Accuracy rate (%)	89.3	8.4	89.0	9.7
Response time (ms)	3129.5	1080.7	3101.3	1008.6

7.3.4. Range of display component

Table 7.15. Accuracy rates and response times of ranges of manipulated display components

	Reduction		Increase	
	Mean	**SD**	**Mean**	**SD**
Accuracy rate (%)	89.9	7.2	89.7	6.2
Response time (ms)	3047.0	1000.5	3100.3	1161.6

7.4. Appendix D – Experiment 1 comparative study results

7.4.1. Background and aim

This appendix presents a comparative study to Experiment 1, examining the effects of energy expenses, education and income levels on display design types, colours of display components and participant preference.

An attempt was made to recruit participants from the general public with as a wide range of socio-economic backgrounds as possible. However, a majority of the participants in Experiment 1 had undertaken higher education or above, which suggested that they were mostly in the middle income class or higher, who were, therefore, not fully representative of the population at large[25]. The notion was derived based on 1993-2010 data that people with higher education qualifications, on average, earn more than those educated to around the GCSE or equivalent level (ONS, 2011). Energy spending tends to be positively correlated with income (ONS, 2012a) – the higher a household's income, the higher its energy use – but not proportionally, while the risk of fuel poverty[26] rises as household income falls (DCLG, 2014). In relative terms, poorer households spend larger portions of their incomes on energy use than richer households, in addition to dependent factors such as the location, dwelling type and its levels of insulation, the efficiency of the heating mechanism, and household composition (Druckman and Jackson, 2008; Wyatt, 2013; ONS, 2014c).

Although the aim of the research developed in this thesis was not to examine the implications of improved feedback techniques on fuel poor households, it is

[25] Between 2011 and 2012, when this follow-up experiment was conducted, the national middle 20% were those with a lower bound on gross household income between £22,776 and £28,184 (ONS, 2014b).

[26] A UK household is considered to be in fuel poverty if it needs to spend more than 10% of its income on fuel to afford adequate energy services, such as maintaining a satisfactory heating regime (usually 21°C for the main living area, and 18°C for other occupied rooms), and spending on heating water, appliance usage, lights and cooking (DECC, 2012b). In 2011, there were 4.5 million households in the UK in fuel poverty, representing approximately 7% of overall population; in Bath and North East Somerset, between 10 and 14% of all households were experiencing fuel poverty (BANES, 2012).

still an important line of investigation that could provide a more comprehensive understanding of user response to the design of feedback techniques resulting in a significant impact on reducing energy use. The working hypothesis was that participants' education, income and energy spending would affect their performance on the computerised tasks.

7.4.2. Participants

The present experiment used the same experimental design as in Experiment 1 (see Section 4.3.1) and was carried out on a group of participants who reported to spend at least 10% of their household income on energy use. Two of their socio-economic indices, namely education and income levels, were also taken into account (Table 7.16). These participants were recruited through snowball sampling from local communities and consisted of 40 volunteers (18 male, 22 female) aged between 22 and 63 years (mean = 40.1, SD = 10.3).

Table 7.16. Socio-economic backgrounds of participants

Highest qualification attained[7a]	n	Household income band[7b] (£)	n	Expenditure on energy (% of total household income)	n
Other	5	<10,000	3	10-12	30
GCSEs or equiv.	16	10,000-11,999	2	13-15	7
A Level or equiv.	5	12,000-13,999	6	16+	3
Higher education	8	14,000-15,999	7		
Degree or equiv.	6	16,000-17,999	9		
		18,000-19,999	8		
		20,000-21,999	5		

[7a] Groupings according to ONS (2012b). In 2011, 88.5% of the 40 million adults aged between 16 and 64 years old in the UK had received some form of education: 23.3% had GCSEs, 21.8% A Level or equivalent, 9.3% higher education, 23.8% degree or equivalent, and 10.5% other qualifications (ONS, 2012b).
[7b] Total household income from all sources before tax and other deductions.

Snowball sampling is a form of opportunity sample. The researcher finds a small group of people who are relevant to the research topic and uses them to establish contacts with others in the same group. Although this method does not give a representative sample of the population, because it is not a random sample (Bryman, 2012), it was a feasible approach for the present study to find participants who were willing to discuss about their socio-economic backgrounds.

7.4.3. Results

Results in Table 7.17, Table 7.18 and Table 7.19 showed that participants' education, income and expenditure on energy did not affect their abilities to spot changes in energy information shown on the computer-simulated energy displays.

Table 7.17. Interaction effect of education on accuracy and response time

	F	**Df**	**Error df**	***p***
Accuracy rate				
Design type	.522	6.509	56.951	.803
Colour	.364	4	35	.832
Location	1.041	16	140	.418
Range	1.314	4	35	.284
Response time				
Design type	.641	8	70	.741
Colour	.770	4	35	.552
Location	.631	16	140	.855
Range	.813	4	35	.525

Table 7.18. Interaction effect of income on accuracy and response time

	F	**Df**	**Error df**	***p***
Accuracy rate				
Design type	.845	10.151	55.827	.590
Colour	.933	6	33	.485
Location	1.166	19.194	105.569	.300
Range	.954	6	33	.471
Response time				
Design type	.773	12	66	.676
Colour	.791	6	33	.583
Location	1.070	24	132	.387
Range	.915	6	33	.496

Table 7.19. Interaction effect of energy expenditure on accuracy and response time

	F	Df	Error df	*p*
Accuracy rate				
Design type	.672	3.324	61.503	.587
Colour	.237	2	37	.790
Location	1.194	8	148	.306
Range	1.242	2	37	.301
Response time				
Design type	1.638	4	74	.174
Colour	.940	2	37	.400
Location	.538	8	148	.827
Range	.133	2	37	.876

However, the three display designs differed in accuracy ($F(1.678,65.460) = 29.531$, $p < .001$) and in response time ($F(2,78) = 10.917$, $p < .001$). Results showed a similar performance pattern as in Experiment 1 – the numerical design was associated with the highest accuracy rate (93.2% versus 77.9% for analogue and 86.7% for ambient); the analogue design, again, had the slowest response time (3380 ms versus 2768 ms for numerical and 3161 ms for ambient).

Mean accuracy rates for black-on-white and coloured displays were almost identical (86.3% for black-on-white and 85.6% for coloured displays) ($F(1,39) = .510$, $p = .479$). Unlike Experiment 1, there was no Design x Colour interaction nor difference in response time between black-on-white and coloured displays (3113 ms for black-on-white and 3046 ms for coloured) ($F(1,39) = 1.163$, $p = .287$).

An analysis on the effect of display range was carried out. Again, results showed no difference between a reduction and an increase in consumption value in accuracy rate (86% for reduction and 85.8% for increase) ($F(1,39) = .022$, $p = .882$) and response time (3097 ms for reduction and 3071 ms for increase) ($F(1,39) = .013$, $p = .908$).

Although Experiment 1 did not find a difference in accuracy, the present experiment showed that accuracy rate of the analogue design was affected by the difference in location shown by a Design x Location interaction (F(5.740,223.855) = 2.497, p = .025), in which accuracy was generally higher for the display components located towards the left side of the screen than to the right side (Figure 7.1). The locations also differed in response time (F(4,156) = 6.290, p < .001). Figure 7.2 shows that the display components positioned towards the left generally had shorter response time than those on the right.

Multivariate analysis of variance was conducted to determine the effects of display design, colour, range and location of the display component on accuracy and response time between the present experiment and Experiment 1. The comparison results in Table 7.20 showed that all task performances did not differ between the two experiments.

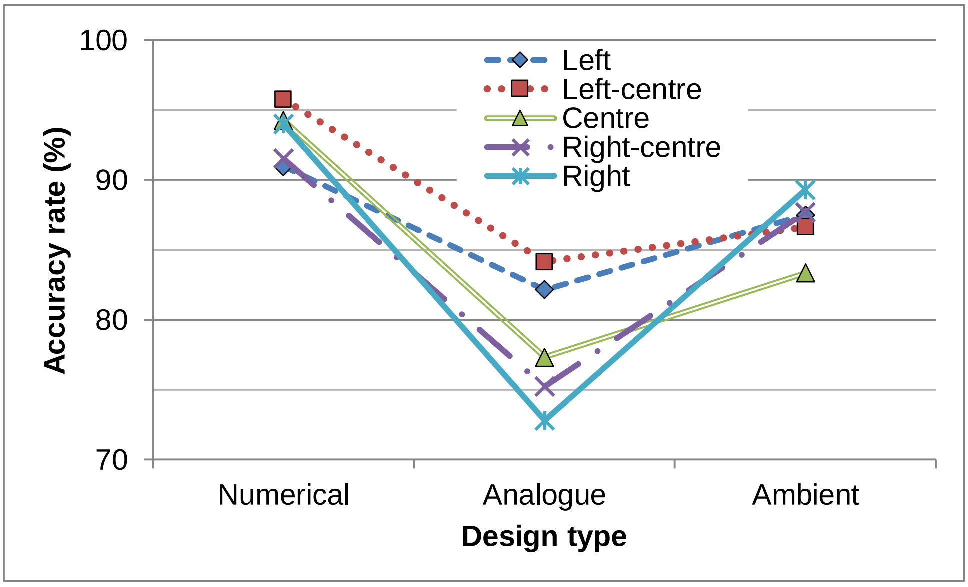


Figure 7.1. Mean accuracy rate of Design x Location interaction of manipulated display components

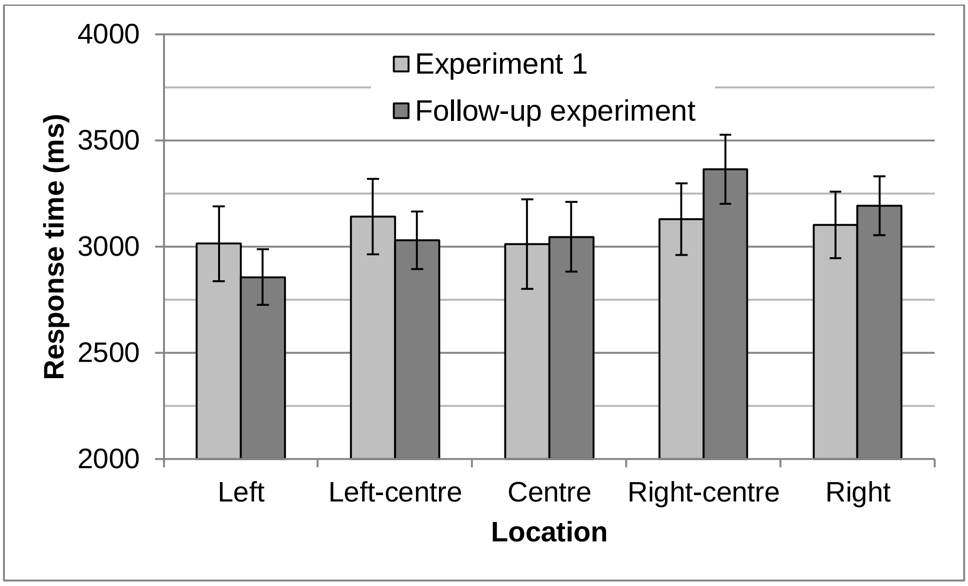


Figure 7.2. Mean response times of locations of manipulated display components compared with Experiment 1

Table 7.20. Results of comparing task performance with Experiment 1

	F	**Df**	**Error df**	***p***	**Wilks' λ[7c]**
Accuracy rate					
Design type	2.382	3	77	.076	.915
Colour	2.801	2	78	.067	.933
Location	1.694	5	75	.146	.899
Range	2.542	2	78	.085	.939
Response time					
Design type	2.421	3	77	.072	.914
Colour	.123	2	78	.885	.997
Location	1.576	5	75	.177	.105
Range	.284	2	78	.753	.993

[7c] Wilks' lambda is used in MANOVA to show the overall significance, ranging between 0 and 1. If the value of Wilks' lambda is small, the between-groups dispersion is large, and so the null hypothesis is rejected.

7.4.4. Conclusion

The study showed that participants' abilities to detect changes in information presented on displays were not affected by the qualifications they had attained, or how much money they earned or spent on energy use at home. There was also a similarity in the results emerging from the present experiment and Experiment 1 – the numerical design led to superior performance on accuracy and response time compared with the analogue design using dials and the ambient design using emotional faces; and coloured displays produced no advantage in achieving better performance than black-on-white displays. Further, no significant difference was found in the performance results between the two experiments, suggesting that socio-economic factors such as the ones investigated in this study have little influence on people's performance on computerised tasks like in these experiments.

The experiment grouped participants based on their education, household income and expenditure on energy services. As a consequence, sample sizes were small and unequal within each subgroup, which resulted in unevenly weighted means in the analysis. Similar work with a larger sample size should be useful to address this limitation. Work could also explore displaying "live" energy information to fuel poor and non-fuel poor households to study the influence of displays on their consumption behaviour in a real-world setting.

7.5. Appendix E – Chapter 5 pre-field study

This appendix details the proposed work of a trial study that was designed, but not deployed, before the main field-based experiments were implemented.

7.5.1. Background and aim

Twenty-five plug-in energy monitors, The Ploggs[27] (Energy Optimizers Ltd, 2009) (Figure 7.3) were provided by the Department of Computer Science at the University of Bath, and presented an opportunity for collaborative work. The intent was to conduct a pilot study in one of the university buildings before trialling the system on a larger scale in the local households.

Figure 7.3. The Ploggs

The aim of the study was to develop a display design prototype for the main field-based experiments that would investigate how energy information shown

[27] The Plogg is developed as a combined electricity meter plug and data logger. It logs power usage of the appliance plugged into it and transmits data wirelessly through an ethernet gateway. The logged data are accessible via any Bluetooth-enabled devices or the ethernet access point (EAP) (Energy Optimizers Ltd, 2009). The EAP allows remote access (which is applicable to this study), such as from a computer, to a network of Ploggs using ZigBee wireless technology carried by The Ploggs. More than one EAP can be connected via the internet (Telegesis, 2009).

on a display device can influence energy-use behaviour. The present study would use The Ploggs to measure electricity consumption at the appliance level.

7.5.2. Participants

The study would take place in an on-campus residence for postgraduate students at the University of Bath and measure electricity consumption in the communal kitchens. Each kitchen group consisted of eight students. Before the experiment was scheduled to start, request for participation would be sent to the students via e-mail, the aim of the study would also be stated. The students would be informed of a monetary reward of £25 worth of shopping vouchers that would be given to each member of the group that showed the lowest electricity consumption by the end of the study. Three experimental groups would then be selected from the volunteered kitchens to test three types of display design. Between three and five of the remaining non-participating kitchens would be used as controls based on the similarity in where they were located in the building and their floor layout to the experimental kitchens.

7.5.3. Materials

The student residence chosen for running the experiment has a 17-inch colour LCD computer monitor in each kitchen. The monitor screen would make an ideal output medium for The Ploggs to display instantaneous energy information to the students. Measuring electricity consumption in the kitchens would give the experimenter direct access to The Ploggs, and the model specifications of the electrical appliances in the kitchens were similar or identical.

Each kitchen is equipped with the following appliances:

- 1x Toaster
- 1x Kettle
- 1x Microwave oven
- 1x Electric hob and oven
- 2x Refrigerator freezer

- 1x Wall-mounted computer monitor with internet connection through the university's network

Only the toaster, the kettle and the microwave oven can be independently plugged in and unplugged from the mains supply socket, so between these appliances, electricity consumption would be captured using The Ploggs. Figure 7.4 shows the concept flowchart of how The Ploggs would be set up.

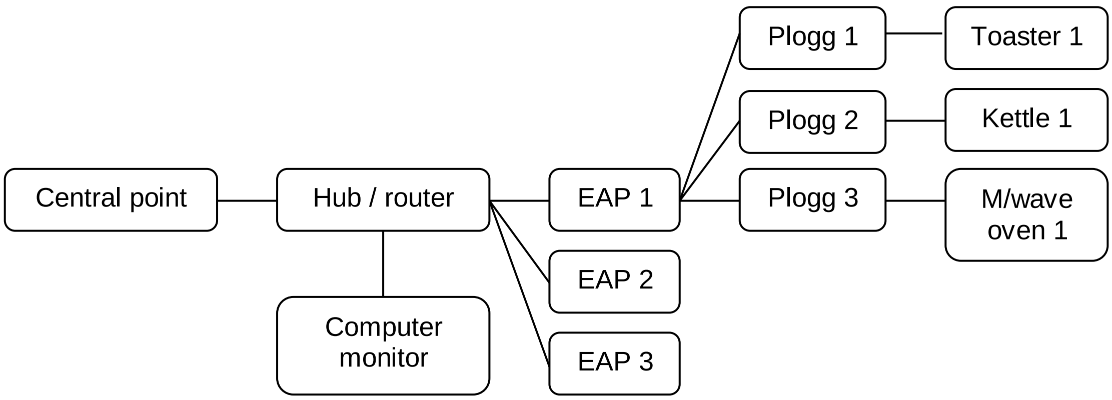


Figure 7.4. Plogg networking

Three display types with designs similar to those tested in the laboratory experiments were to be used to represent energy information: numerical design, analogue dials design and ambient faces design. Each design would be displayed to the students for one week before changing to the next one (see Table 7.21). All six possible orders of the three display designs would be tested (hence six experimental weeks).

Table 7.21. Display designs on weekly rotations

	Group 1	Group 2	Group 3
Week 1	Baseline week 1		
Week 2	Baseline Week 2 End of Week 2: Induction session		
Week 3	Numerical	Analogue	Ambient
Week 4	Analogue	Ambient	Numerical
Week 5	Ambient	Numerical	Analogue

	Group 1	Group 2	Group 3
Week 6	Analogue	Numerical	Ambient
Week 7	Numerical	Ambient	Analogue
Week 8	Ambient	Analogue	Numerical
Week 9	Discussion session		

Figure 7.5 shows an initial display design for The Ploggs that had been tested in the kitchen of the Department of Computer Science. Details of building the sensing and software architecture of the experiment were still to be finalised with the help from them at the time of writing this proposal.

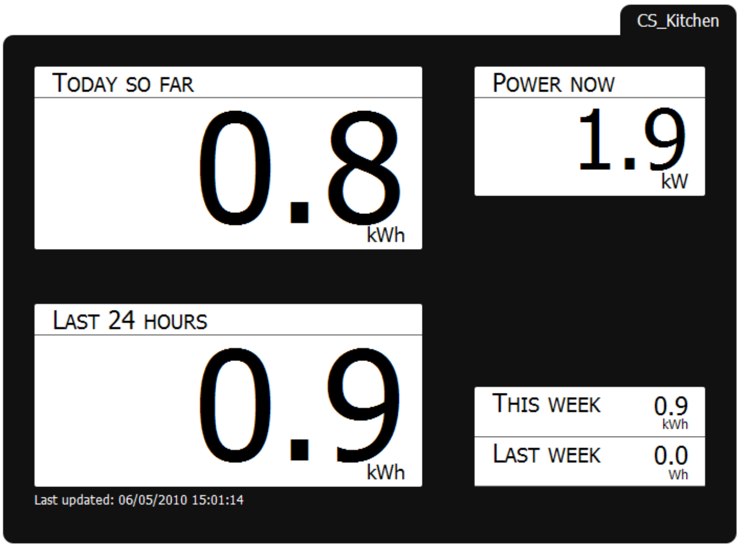


Figure 7.5. Preliminary numerical display design for The Ploggs

There were some practical design requirements to be considered:

1. A “heartbeat” monitoring application is needed to detect any malfunction of the software or the hardware (e.g. The Plogg device is missing, damaged, disconnected).
2. The display must be preset as the main interface on the computer monitor, and be able to switch back automatically after a time period has lapsed (e.g. 10 minutes) if other programmes have become inactive, such as a web browser. This is to ensure that, in the instances when the students leave the computer and do not close the programmes they have finished using, the display continues to present energy information

whenever the students are not using the computer. Further, the monitor must be switched on all the time and cannot go into “sleep” or “screen saver” mode or be logged off when the computer is in an inactive state.

3. The type of information shown on the display can be presented either in power unit (Wk or kWh) per hour, per day, per week or per cooking event, or in ranking order to compare a group’s consumption with its own past consumption or with other groups at the time the data are updated.

7.5.4. Experimental design

The study period was estimated to be nine weeks long (Table 7.21). Two weeks prior to the start of the experiment would be used as the baseline period. Neither the control nor experimental groups would be told about when the baseline period was. These baseline data would be used to show participants how they had used electricity in the kitchen since the experiment had started. In the second week of the baseline period, the students would be introduced to the study. A status survey would also be conducted at this time to record the current status of the electrical appliances and the mains supply sockets in the kitchens.

After the experiment was completed, the experimental groups would be interviewed for their feedback on the display design. They would also be asked to talk about their experiences of being able to see their electricity consumption shown on a display, and about their preferences for the displays by designing their own.

The control and experimental groups would be asked to complete pre- and post-study questionnaires (see Section 7.6, the post-study questionnaire was modified for Experiment 2; the original version designed for this study only included Parts A and B) on their basic information, their attitudes on the environment and energy use, and their current (pre-study) and recent (post-study) energy use activities.

The core interview questions were:

1. Awareness: did taking part in the study make you think more about energy consumption in general?
2. Cognition: did you try to change the way you used energy in the kitchen? If yes,
    a. Motivation: what were the main reasons for the change?
    b. Control: what actions did you take to make the change?
3. Learning: was there anything you wished to know more about, for example, the impact of your action might have on the environment, how you could take your action further?
4. Relevance, customization: which display feature (component) did you find most useful, and which was least useful?
5. Display design:
    a. Would you like to see the display in colour?
    b. Which type of display design did you like the most, and the least?
    c. Which type of display design would you prefer to have at home?

The interviews were to be semi-structured, so that discussion could stem from the core questions and the questionnaires.

7.5.5. Limitations

The study proposed to use a small sample to measure electricity consumption of three kitchens due to lack of confidence in the deployment of The Ploggs[28]. Consequently, results may not show the consumption trend or a significant change in participants' behaviour.

The display designs were to be shown to the students over a six-week period; however, the last three weeks would repeat the same designs, only in a different order. Therefore, participants might become less interested in the

[28] Author's note: the proposal of this study was made when the opportunity of collaborative work with the Department of Computer Science was presented, before the laboratory-based pilot study was carried out. Therefore, the author had little experience in designing experiments, much less working on field experiments.

displays during those weeks, and results could be affected. The design of the experiment would be improved if the number of the experimental groups were increased to six to test the six orders, and if each of the three designs were displayed to the students for two weeks or longer to reduce the potential influence of the Hawthorne effect[29].

The study was to take place in a university residence environment, which limits the experiments to being undertaken during term times only, when the building is occupied by the same group of students, and puts a constraint on post-study monitoring. However, this should not be so problematic if the goal is to study the students' behaviour during the experimental period.

The study would make use of the computer monitors in the kitchens as live energy displays with a temporary log-in username and password. Students who wished to use the computer in the kitchen to access their remote desktop would have to log in using their own usernames. This might pose a problem for the display to continue, unless the students remembered to log back using the temporary username when they were finished with their work. Although the students might reduce or stop using the computer during the experimental period, a better solution (budget and resources permitting) would be to have a display device dedicated to the study.

The study was not carried out mainly due to technical difficulties. During the time when The Ploggs were tested in the Department of Computer Science, it was found that more than two thirds of the 25 devices were defective. The idea of replacing The Ploggs with other commercial energy monitors was rejected as there was no clear way to gain full access to the logged data from the product companies, who did not wish to share their ownership of data. Further, the design of the sensor framework was not completed in time for the experiment to start at the beginning of an earliest possible teaching term. As a result, the study was put on hold.

[29] The Hawthorne effect refers to the phenomenon in which human subjects of a study alter their behaviour due to their awareness of being studied.

7.6. Appendix F – Construction of the pre-study and post-study questionnaires for Experiment 2

The pre-study questionnaire was designed to explore the level of awareness that the students had regarding the environment, consumerism and energy consumption. The questions were derived and modified based on research on environmental attitudes and ecological behaviour (e.g. Kaiser *et al*., 1999, 2007; Kotchen and Reiling, 2000).

7.6.1. Pre-study questionnaire

The questionnaire was completed by the control and experimental groups.

Department of Architecture & Civil Engineering
Department of Psychology
Department of Computer Science
Department of Estates
Accommodation and Hospitality Services

UNIVERSITY OF BATH

Domestic Energy Consumption and the Design of Energy Displays

Pre-study survey

A little about the survey

The intent of this questionnaire is to gather your individual thoughts on energy consumption, specifically in the context of domestic environment, and your current energy use activities. The information that you provide will be valuable for improving the existing understanding of the social, environmental and economic aspects of user behaviour and energy-saving interventions.

The questionnaire should take you approximately 5 minutes to complete, and will be used as part of Teresa Chiang's research on the subject of 'Domestic Energy Consumption and the Design of Energy Displays' in collaboration with the Departments of Architecture & Civil Engineering, Psychology, Computer Science, Estates, and Accommodation and Hospitality Services at the University of Bath.

Under Data Protection Act 1998, the information that you provide will be maintained as confidential by the University of Bath. All information gathered is confidential and will be used only for research. Nobody will be able to identify you or use the information against you.

By completing this survey, you agree to take part in this research project and give permission for the researcher to use the information that you provide in subsequent papers and general publications.

****

A little about yourself Kitchen group number: ________

Age:		
Gender	☐ Male	☐ Female
Level of study	☐ UG	☐ PG
Are you colour blind?	☐ Yes	☐ No
Method of accommodation payment:	☐ Self-funded / family	☐ Sponsored
	☐ Student loan	☐ Other________

****

A. Your attitude on the environment, consumerism and energy consumption

Listed below are 10 statements on the environment, consumerism and energy consumption. Please indicate your extent of agreement by using the following scale. There are no "right" or "wrong" answers.

	Strongly disagree	Mildly disagree	Neutral	Mildly agree	Strongly agree
1. I prefer online shopping	☐	☐	☐	☐	☐
2. I learn / read about environmental issues in the media (TV, newspapers, magazines, books, online, etc.)	☐	☐	☐	☐	☐
3. I take bags with me when I go shopping	☐	☐	☐	☐	☐
4. Climate change and its effects on the environment are mainly caused by human activities	☐	☐	☐	☐	☐
5. I switch off the lights when I am not in the study bedroom, even if I am just eating in the kitchen	☐	☐	☐	☐	☐
6. The threat of environmental					

	Strongly disagree	Mildly disagree	Neutral	Mildly agree	Strongly agree
problems has been greatly exaggerated	☐	☐	☐	☐	☐
7. For scribbling or making notes, I take paper that is already used on one side	☐	☐	☐	☐	☐
8. I turn off / down the radiator in my room when I go out	☐	☐	☐	☐	☐
9. I would make efforts to reduce my energy consumption if I knew it would bring on a 10% reduction in my accommodation fees	☐	☐	☐	☐	☐
10. I look for certified organic foods whenever possible when I shop	☐	☐	☐	☐	☐

B. Your current energy use activities – part ONE

For each statement below, please put a cross (X) in front of all the appliances that are applicable to you, and rate how often you use them by circling the number between 1 and 5, 1 is Almost never*, 5 is* Always*.*

In an average week, I use the following appliances to…

	Almost never				Always
1. Make a toast / sandwich:					
☐ Toaster	1	2	3	4	5
☐ Oven / grill	1	2	3	4	5
☐ Microwave oven	1	2	3	4	5
☐ A pan on the hob	1	2	3	4	5
☐ Other____________________	1	2	3	4	5
2. Cook (from raw ingredients):					
☐ Microwave oven	1	2	3	4	5
☐ Hob	1	2	3	4	5
☐ Oven / grill	1	2	3	4	5
☐ Other____________________	1	2	3	4	5
3. Boil water for a cup of hot drink:					
☐ Kettle	1	2	3	4	5
a. By filling the kettle with roughly the amount of water I need	1	2	3	4	5
b. By filling up the kettle with more than the amount of water I need	1	2	3	4	5

	Almost never				Always
now to save for later					
☐ Microwave oven	1	2	3	4	5
☐ A pot on the hob	1	2	3	4	5
☐ Other___________________	1	2	3	4	5
4. Re-heat food / ready meals:					
☐ Microwave oven	1	2	3	4	5
☐ Hob	1	2	3	4	5
☐ Oven / grill	1	2	3	4	5
☐ Other___________________	1	2	3	4	5

B. Your current energy use activities – part TWO

Please put a cross (X) in front of all the statements below that are applicable to you, and circle the number between 1 and 5 that best applies to you, 1 is Almost never*, 5 is* Always*.*

	Almost never				Always
5. When I wish to defrost frozen food:					
☐ I will use the microwave oven	1	2	3	4	5
☐ I will use warm water	1	2	3	4	5
☐ I will leave it in room temperature	1	2	3	4	5
☐ I will leave it in the refrigerator overnight	1	2	3	4	5
☐ Other___________________	1	2	3	4	5
☐ I do not defrost frozen food	1	2	3	4	5
6. When the refrigerator is generally full, half full, empty or when I'm away on holiday:					
☐ I will adjust the temperature control knob	1	2	3	4	5
☐ I do not adjust the temperature control	1	2	3	4	5
7. When I use the hob to cook and/or bring to boil:					
☐ I will put the lid on	1	2	3	4	5
a. Pot	1	2	3	4	5
b. Pan	1	2	3	4	5
c. Wok	1	2	3	4	5
d. Other___________________	1	2	3	4	5
☐ I do not put the lid on	1	2	3	4	5
8. When I wish to have a cup of hot drink, and there is enough amount of cold water left in the kettle:					
☐ I will reheat the water	1	2	3	4	5
a. In the kettle	1	2	3	4	5
b. In the microwave oven	1	2	3	4	5

	Almost never				Always
c. In a pot on the hob	1	2	3	4	5
☐ I will dispose of it and fill up with fresh water	1	2	3	4	5
9. When I finish using an appliance (e.g. toaster, kettle, microwave oven, hob):					
☐ I will switch off the power on the appliance / leave it as is	1	2	3	4	5
☐ I will switch off the main power on the wall	1	2	3	4	5
10. I put food into the refrigerator / freezer when it is still warm	1	2	3	4	5
11. When I leave my study bedroom and go to the kitchen to cook or eat:					
☐ I will switch off the lights in my room	1	2	3	4	5
☐ I will leave my laptop on standby	1	2	3	4	5

****

Please feel free to leave comments relating to the survey.

____

____

Thank you for taking time to complete this survey.

****

7.6.2. Post-study questionnaire

The questionnaire was designed for the control kitchens to complete parts A and B on their recent energy use activities. The experimental kitchens needed to answer all the questions.

Department of Architecture & Civil Engineering
Department of Psychology
Department of Computer Science
Department of Estates
Accommodation and Hospitality Services

UNIVERSITY OF BATH

Domestic Energy Consumption and the Design of Energy Displays

Post-study survey

A little about the survey

The aim of this questionnaire is to collect your feedback on the design of the energy display and your recent energy use activities in the past six weeks.

Under Data Protection Act 1998, the information or data that you provide will be maintained as confidential by the University of Bath. All information gathered is confidential and will be used only for research. All information, including personal information, will not be revealed to anyone. Nobody will be able to identify you or use the information against you.

By completing this survey, you agree to give permission for the researcher to use the information that you provide in subsequent papers and general publications.

****

Kitchen group number: ________

A. Your recent energy use activities

Please put a cross (X) in front of all the statements below that are applicable to you, and circle the number between 1 and 5 that best applies to you, 1 is Almost never*, 5 is* Always*.*

During the past 6 weeks…

	Almost never				Always
1. When I wished to defrost frozen food:					
☐ I would use the microwave oven	1	2	3	4	5
☐ I would use warm water	1	2	3	4	5
☐ I would leave it in room temperature	1	2	3	4	5
☐ I would leave it in the refrigerator overnight	1	2	3	4	5
☐ Other____________________	1	2	3	4	5
☐ I did not defrost frozen food	1	2	3	4	5
2. When the refrigerator was generally full, half full, empty, or when I was away on holiday:					
☐ I would adjust the temperature control knob	1	2	3	4	5
☐ I did not adjust the temperature control	1	2	3	4	5

	Almost never				Always
3. When I used the hob to cook:					
☐ I would put the lid on	1	2	3	4	5
a. Pot	1	2	3	4	5
b. Pan	1	2	3	4	5
c. Wok	1	2	3	4	5
d. Other___________________	1	2	3	4	5
☐ I did not put the lid on	1	2	3	4	5
4. When I wished to have a cup of hot drink, and there was enough amount of cold water left in the kettle:					
☐ I would reheat the water	1	2	3	4	5
a. In the kettle	1	2	3	4	5
b. In the microwave oven	1	2	3	4	5
c. In a pot on the hob	1	2	3	4	5
☐ I would dispose of it and fill up with fresh water	1	2	3	4	5
5. When I finished using an appliance (e.g. toaster, kettle, microwave oven, hob)					
☐ I would switch off the power on the appliance / leave it as is	1	2	3	4	5
☐ I would switch off the main power on the wall	1	2	3	4	5
6. I put food into the refrigerator / freezer when it was still warm	1	2	3	4	5
7. When I wished to re-heat food / ready meals:					
☐ I would use the microwave oven	1	2	3	4	5
☐ I would use the hob	1	2	3	4	5
☐ I would use the oven / grill	1	2	3	4	5
☐ Other___________________	1	2	3	4	5
8. When I left my study bedroom and went to the kitchen to cook or eat:					
☐ I would switch off the lights in my room	1	2	3	4	5
☐ I would leave my laptop on standby	1	2	3	4	5

B. Your feedback on the study

Listed below are statements on your thoughts about the study. Please indicate your extent of agreement by using the following scale.

	Strongly disagree	Mildly disagree	Neutral	Mildly agree	Strongly agree
1. The study has made me think					

	Strongly disagree	Mildly disagree	Neutral	Mildly agree	Strongly agree
more about my everyday energy consumption	☐	☐	☐	☐	☐
2. I have tried to reduce my energy use in my study bedroom	☐	☐	☐	☐	☐
3. I have tried to reduce my energy use in the kitchen	☐	☐	☐	☐	☐
4. I have told my friends about the study	☐	☐	☐	☐	☐
5. The study has made me want to know more about energy consumption of different appliances (in the study bedroom / kitchen)	☐	☐	☐	☐	☐
6. The study has made me want to know more about where and how I can reduce my energy use	☐	☐	☐	☐	☐
7. I am curious about how other groups have done in the study	☐	☐	☐	☐	☐

C. Your feedback on the display design – part ONE

Please answer the following questions about the design of the displays. Please put a cross (X) in the box that best applies to you.

	Easy to understand	Difficult to understand	Useful	Useless	Nice to have	Irritating to look at
1. How did you find the colour coding of the energy information shown on the display?	☐	☐	☐	☐	☐	☐
2. How did you find the following features on the display?						
a. Today so far	☐	☐	☐	☐	☐	☐
b. Last 24 hours	☐	☐	☐	☐	☐	☐
c. Power now	☐	☐	☐	☐	☐	☐
d. This week (average)	☐	☐	☐	☐	☐	☐

	Easy to understand	Difficult to understand	Useful	Useless	Nice to have	Irritating to look at
e. Last week (average)	☐	☐	☐	☐	☐	☐
f. Ranking out of 6 groups	☐	☐	☐	☐	☐	☐

C. Your feedback on the display design – part TWO

Please answer all the questions.

3. How did you find the energy information represented by the 6 display features?
   Enough / Too much / Too little (*please circle)*
4. What other type(s) of energy information would you like to see on the display?
   ____
5. Would you like to have more control of what you can see on the display?
   Yes / No (*please circle*)
6. If yes, please name them (e.g. by adding or removing certain display feature(s), mixing different design types for different information, etc.)
   ____
7. In the past 6 weeks, you have seen 3 display types using the following designs: numbers, dials, faces. Please indicate your preference for the design type in the order of **most** preferred to **least** preferred: ______________________________
8. For each design type, please state what you liked and disliked about the design:
   Numbers: ______________________________
   ____
   Dials: ______________________________
   ____
   Faces: ______________________________
   ____

****

Please feel free to leave comments relating to the survey.

____

____

Thank you for taking time to complete this survey.

****

7.7. Appendix G – Chapter 5 supplementary results

7.7.1. Experiment 2 energy consumption data

Table 7.22. Energy consumption data by display design type

	Mean daily consumption (kWh)	SD	Mean daily change compared with baseline[7d] (kWh)	Effect size (*d*)
Numerical	17.115	3.085	-1.157	0.371
Analogue (dials)	17.248	2.546	-1.025	0.360
Ambient (faces)	16.502	2.932	-1.770	0.582
Exp. baseline	18.272	3.153	-	-
Control (no displays)	28.835	4.854	-0.491	0.115
Control baseline	29.325	3.649	-	-

[7d] Negative value indicates a reduction in electricity consumption.

7.7.2. Experiment 2 preference survey results

Table 7.23. Survey of display design preferences

	Liked	**Neutral**	**Disliked**	
Display design type (%)				
Numerical	82.4	14.7	2.9	
Analogue	15.2	63.6	21.2	
Ambient	3.0	21.2	75.8	
	Understandable	**Useful**	**Useless**	**Disliked**
Display component (%)				
Today so far	67.6	70.6	11.8	14.7
Yesterday	64.7	58.8	20.6	11.8
This week average	58.8	55.9	32.4	14.7
Last week average	55.9	26.5	58.8	14.7
Group ranking	73.5	52.9	26.5	17.6
Colour coding (%)	85.3	55.9	-	38.2

7.7.3. Experiment 3 energy consumption data

Table 7.24 . Comparison of energy consumption between control and experimental groups

	Mean daily consumption (kWh)	SD	Mean daily change compared with baseline[7e] (kWh)	Effect size (*d*)
Experimental	16.030	3.851	-0.399	0.110
Exp. baseline	16.429	3.387	-	-
Control (no displays)	18.854	5.924	0.363	0.059
Control baseline	18.491	6.352	-	-

[7e] Negative value indicates a reduction in electricity consumption.

References

Abrahmase, W., Steg, L., Vlek, C., Rothengatter, T., 2005. A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology*, 25, pp.273-291.

Abrahamse, W., Steg, L., Vlek, C., Rothengatter, T., 2007. The effect of tailored information, goal setting, and tailored feedback on household energy use, energy-related behaviors, and behavioral antecedents. *Journal of Environmental Psychology*, 27, pp.265-276.

Abrahamse, W. and Steg, L., 2009. How do socio-demographic and psychological factors relate to household's direct and indirect energy use and savings? *Journal of Economic Psychology*, 30, pp.711-720.

AECOM, 2011. *Energy Demand Research Project: final analysis.* St. Albans: AECOM House.

Ajzen, I. and Fishbein, M., 1970. The prediction of behavior from attitudinal and normative variables, *Journal of Experimental Social Psychology*, 6(4), pp.466-487.

Alfano, G. and d'Ambrosio, F.R., 1991. Clothing: an essential individual adjustment factor for obtaining general thermal comfort. *Environment International*, 17, pp.205-209.

Allcott, H. and Mullainathan, S., 2010. Behavior and energy policy. *Science*, 327, pp.1204-1205.

Allen, D. and Janda, K., 2006. The effects of households characteristics and energy use consciousness on the effectiveness of real-time energy use feedback: a pilot study. *2006 ACEEE Summer Study Proceedings*.

AmbientDevices, 2010. *Energy orb*. Available from http://ambientdevices.com/products/what-is-ambient

Anderson, W. and White, V., 2009. *Exploring consumer preferences for home energy display functionality. Report to the Energy Saving Trust*. Bristol: Centre for Sustainable Energy.

Arvola, A., Uutela, a., Antilla, U., 1993. Billing feedback as a means to encourage household electricity conservation: a field experiment in Helsinki, Finland. *1993 ECEEE Summer Study Proceedings*, panel 3, pp.11-21.

ASHRAE Standard 55-2013. 2013. *Thermal environmental conditions for human occupancy.* Atlanta: America Society of Heating, Refrigerating and Air-Conditioning Engineers.

Baguley, T., 2012. S*erious stats*. Basingstoke: Palgrave Macmillan.

Bahaj, A.S. and James, P.A.B., 2007. Urban energy generation: the added value of photovoltaics in social housing. *Renewable and Sustainable Energy Reviews*, 11, pp.2121-2136.

Bandura, A., 1977. *Social Learning Theory*. London: Prentice Hall.

BANES, 2012. *Fuel poverty*. Available from http://www.bathnes.gov.uk/services/your-council-and-democracy/local-research-and-statistics

Barmack, J.E. and Sinaiko, H.W., 1966. *Human factors problems in computer-generated graphic displays*. Institute for Defense Analyses, Research and Engineering Support Division.

Barr, S., Gilg, A.W., Ford, N., 2005. The household energy gap: examining the divide between habitual-and purchase related conservation behaviours. *Energy Policy*, 33(11), pp.1425-1444.

Becker, L.J., 1978. Joint effect of feedback and goal setting on performance: a field study of residential energy conservation. *Journal of Applied Psychology*, 63, pp.428-433.

Becker, L.J. and Seligman, C., 1978. Reducing air conditioning waste by signalling it is cool outside. *Personality and Social Psychology Bulletin*, 4(3), pp.412-415.

Becker, L.J., Seligman, C., Fazio, R.H., Darly, J.M., 1981. Relating attitudes to residential energy use. *Environment and Behavior*, 13, pp.590-609.

Bertoldi, P., Aebischer, B., Edlington, C., Hershberg, C., Lebot, B., Lin, J., Marker, T., Meier, A., Nakagami, H., Shibata, Y., Siderius, H.P., Webber, C., 2002. *Standby power use: how big is the problem? What policies and technical solutions can address it?* Lawrence Berkeley National Laboratory, California.

Bittle, R.G., Valesano, R.M., Thaler, G.M., 1979-1980. The effects of daily feedback on residential electricity usage as a function of usage level and type of feedback information. *Journal of Environmental Systems*, 9, pp.275-287.

Blackler, A. and Popovic, V., 2003. The nature of intuitive use of products: an experimental approach. *Design Studies*, 24, pp.491-506.

Boardman, B., 2007. Examining the carbon agenda via the 40% house scenario. *Building Research and Information*, 35, pp.363-378.

Boddy, J., Neumann, T., Jennings, S., Morrow, B., Alderson, P., Rees,P., Gibson, W., 2010. *The research ethics guidebook: a resource for social scientists*. The Institute of Education, University of London. Available from http://www.ethicsguidebook.ac.uk/Compensation-rewards-or-incentives-89

Bonino, D., Corno, F., De Russis, L., 2012. Home energy consumption feedback: a user survey, *Energy and Buildings*, 47, pp.383-393.

Börner, D., Kalz, M., Specht, M., 2013. Beyond the channel: a literature review on ambient displays for learning. *Computers and Education*, 60, pp.426-435.

Boynton, R.M. and Kambe, N., 1980. Chromatic difference steps of moderate size measured along theoretically critical axes. *Color Research and Application*, 5(1), pp.13-23.

Brandon, G. and Lewis, A., 1999. Reducing household energy consumption: a qualitative and quantitative field study. *Journal of Environmental Psychology*, 19, pp.75-85.

BRE, 2005. *Estimates of hot water consumption from the 1998 EFUS. Implications for the modelling of fuel poverty in England*. BRE Housing Centre.

Brewer, G.D. and Stern, P.C., eds., 2005. *Decision making for the environment: social and behavioural science research priorities*. National Research Council. Oxford: Oxford Publicity Partnership.

Brounen, D., Kok, N., Quigley, J.M., 2013. Energy literacy, awareness, and conservation behaviour of residential households. *Energy Economics*, 38, pp.42-51.

Bryman, A., 2012. Social research methods. 4th ed. Oxford: Oxford University Press.

Cambridge in Colour, 2014. *Tutorials: colour perception*. Available from http://www.cambridgeincolour.com/tutorials/color-perception.htm

Canham, M. and Hegarty, M., 2010. Effects of knowledge and display design on comprehension of complex graphics. *Learning and Instruction*, 20, pp.155-166.

Carrasco, M., McLean, T.L., Katz, S.M., Frieder, K.S., 1997. Feature asymmetries in visual search: effects of display duration, target eccentricity, orientation and spatial frequency. *Vision Research*, 38, pp.347-374.

Chia, A., Gazzard, G., Tong, L., Zhang, X., Sim, E-L, Fong, A., Saw, S.M., 2008. Red-green colour blindness in Singaporean children. *Clinical and Experimental Ophthalmology*, 36, pp.464-467.

Chiang, T., Natarajan, S., Walker, I., 2011. The user interface design of energy displays. *In*: T. Chiang and F. Moran, eds. *Proceedings of Buildings Don't Use Energy, People Do? Research on Reducing Energy Use and CO_2 Emissions in Existing Dwellings*, 28 June 2011, Bath. EDEn, University of Bath, pp.77-88.

Chiang, T., Natarajan, S., Walker, I., 2012. A laboratory test of the efficacy of energy display interface design. *Energy and Buildings*, 55, pp.471-480.

Chiang, T., Mevlevioglu, G., Natarajan, S., Padget, J.A., Walker, I., 2014. Inducing [sub]conscious energy behaviour through visually displayed energy information: a case study in university accommodation. *Energy and Buildings,* 70, pp.507-515.

Cialdini, R.B., Kallgren, C.A., Reno, R.R., 1991. A focus theory of normative conduct: a theoretical refinement and re-evaluation. *Advances in Experimental Social Psychology*, 24, pp.201-234.

Climate Change Act 2008. c. 27. London: The Stationery Office.

Cohen, J., 1988. *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Lawrence Erlbaum.

Colour blindness awareness, 2010a. *Causes of colour blindness.* Available from http://www.colourblindawareness.org/colour-blindness/causes-of-colour-blindness/

Colour blindness awareness, 2010b. *Colour blindness*. Available from http://www.colourblindawareness.org/colour-blindness/

Colour blindness awareness, 2010c. *Types of colour blindness*. Available from http://www.colourblindawareness.org/colour-blindness/types-of-colour-blindness/

Costanzo, M., Archer, D., Aronson, E., Pettigrew, T., 1986. Energy conservation behaviour: the difficult path from information to action. *American Psychologist*, 41(5), pp.521-528.

Cowan, N., 2001. The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *The Behavioural and Brain Sciences*, 24(1), pp.87-114.

CSE, 2013. *How much energy am I using?* Bristol: Centre for Sustainable Energy. Available from http://www.cse.org.uk/advice/advice-and-support/how-much-electricity-am-i-using

Cyr, D., Head, M., Larios, H., 2010. Colour appeal in website design within and across cultures: a multi-method evaluation. *International Journal of Human-Computer Studies*, 68, pp.1-21.

Dancey, C.P. and Reidy, J., 2011. Statistics without maths for psychology. 5th ed. Harlow: Prentice Hall.

Dara, N., 2012. *The effectiveness of behavioural interventions to reduce office energy consumption*. Dissertation (M.Sc). University of Bath.

Darby, S., 2000. Making it obvious: designing feedback into energy consumption. Proceedings of the 2nd *International Conference on Energy Efficiency in Household Appliances and Lighting*. Italian Association of Energy Economists / EC-SAVE programme.

Darby, S., 2006. *The effectiveness of feedback on energy consumption: a review for DEFRA of the literature on metering, billing and direct displays*. Environmental Change Institute, University of Oxford.

Darby, S., 2008a. Why, what, when, how, where and who? Developing UK policy on metering, billing and energy display devices. *2008 ACEEE Summer Study*, pp.70-81.

Darby, S. 2008b. Energy feedback in buildings: improving the infrastructure for demand reduction. *Building Research and Information*, 36, pp.499-508.

Darby, S., 2009. Literature review: real-time energy display functionality. Appendix 3 in W. Anderson and V. White, *Exploring consumer preferences for home energy display functionality. Report to the Energy Saving Trust*. Bristol: Centre for Sustainable Energy.

Darby, S., 2010. Smart metering: what potential for householder engagement? *Building Research and Information*, 38(5), pp.442-457.

DCLG, 2013. *English housing survey: households. Annual report on England's households, 2012-2013*. Available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/335751/EHS_Households_Report_2012-13.pdf

DECC, 2012a. *Smart metering implementation programme: smart metering equipment technical specifications*. London: The Stationery Office.

DECC, 2012b. *Fuel poverty statistics*. Available from http://www.decc.gov.uk/en/content/cms/statistics/fuelpov_stats/fuelpov_stats.aspx

DECC, 2014a. *Digest of United Kingdom energy statistics 2014*. London: The Stationery Office. Available from https://www.gov.uk/government/statistics/digest-of-united-kingdom-energy-statistics-dukes-2014-printed-version

DECC, 2014b. *2013 UK greenhouse gas emissions, provisional figures and 2012 UK greenhouse gas emissions final figures by fuel type and end-use.* London: The Stationery Office. Available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/295968/20140327_2013_UK_Greenhouse_Gas_Emissions_Provisional_Figures.pdf

DECC, 2014c. *Energy consumption in the United Kingdom*. Domestic data tables. Available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/375388/domestic.xls

DECC, 2014d. *Annual domestic energy bills*. Available from https://www.gov.uk/government/statistical-data-sets/annual-domestic-energy-price-statistics

DECC, 2014e. *Consumer prices index: fuel components.* Available from https://www.gov.uk/government/statistical-data-sets/monthly-domestic-energy-price-stastics

DECC, 2014f. *Power the nation 2: electricity use in homes, and how to reduce it*. Available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/325741/Powering_the_Nation_2_260614.pdf

DECC, 2014g. *Average variable unit costs and fixed costs for electricity for UK regions*. Available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/388144/qep_224.xls

DECC, 2014h. *Smart meter roll-out for the domestic and small and medium non-domestic sectors (GB)*. Available from https://www.gov.uk/government/publications/smart-meter-roll-out-for-the-domestic-and-small-and-medium-non-domestic-sectors-gb-impact-assessment

DECC, 2014i. *Seasonal variations in electricity demand*. Available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/295225/Seasonal_variations_in_electricity_demand.pdf

DEFRA. 2007. *UK energy efficiency action plan 2007.* London: The Stationery Office.

Dietz, T., Gardner, G.T., Gilligan, J., Stern, P.C., Vandenbergh, M.P., 2009. Household actions can provide a behavioral wedge to rapidly reduce U.S. carbon emissions. Proceedings of the *National Academy of Sciences of the U.S.A.*, 106(44), pp.18452-18456.

Druckman, A. and Jackson, T., 2008. Household energy consumption in the UK: a highly geographically and socio-economically disaggregated model. *Energy Policy*, 36, pp.3177-3192.

DTI, 2006. *The energy challenge: energy review report 2006*. CM 6887. London: The Stationery Office.

DTI, 2007. *Meeting the energy challenge: a White Paper on energy, May 2007*. CM7124. London: The Stationery Office.

Dünnhoff, E. and Duscha,M., 2008. Effiziente Beratungsbausteine zur Minderung des Stromverbrauchs in privaten Haushalten. Endbericht (Efficient building blocks for energy counselling aimed at reducing electricity consumption in private households. Final report). Heidelberg: Institut für Energie- und Umweltforschung.

Dupont, D.P., 2004. Do children mater? An examination of gender differences in environmental valuation. *Ecological Economics*, 49(3), pp.273-286.

Dwyer, W.O., Leeming, F.C., Cobern, M.K., Porter, B.E., Jackson, J.M., 1993. Critical review of behavioral interventions to preserve the environment. Research since 1980. *Environment and Behavior*, 25(3), pp.275-321.

Dye, M., 2001. *Qualitative methodologies*. Available from http://www.bris.ac.uk/Depts/DeafStudiesTeaching/dissert/Qualitative%20Methodologies.htm

Egan, C., 1999. Graphical displays and comparative energy information: what do people understand and prefer? *1999 ECEEE Summer Study Proceedings*, panel 2.

Ergonomics in Australia, 2010. *How to sit at a computer*. Available from http://www.ergonomics.com.au/pages/400_useful_info/420_how_to_sit.htm

Erhardt-Martinez, K., Donnelly, K.A., Laitner, J.A., 2010. *Advanced metering initiatives and residential feedback programs: a meta-review for household electricity-saving opportunities*. ACEEE report E105.

ESD, 2006. Energy End-Use Efficiency and Energy Services Directive 2006/32/EC.

EST, 2006. *Habits of a lifetime: European energy usage report*. Energy Saving Trust, UK.

EST, 2012. *Powering the nation: household electricity-using habits revealed*. Available from http://www.energysavingtrust.org.uk/sites/default/files/reports/PoweringthenationreportCO332.pdf

Faruqui, A., Sergici, S., Sharif, A., 2010. The impact of informational feedback on energy consumption: a survey of the experimental evidence. *Energy*, 35, pp.1598-1608.

Faul, F., Erdfelder, E., Buchner, A., Lang, A.-G., 2010. *G*Power: statistical power analyses for Windows and Mac*. Available from http://www.gpower.hhu.de/en.html

Festinger, L., 1954. A theory of social comparison processes. *Human Relations*, 7(2), pp.117-140.

Field, A.P., 2013. *Discovering statistics using IBM SPSS statistics: and sex and drugs and rock 'n' roll*. 4th ed. London: Sage.

Fischer, C., 2007. Influencing electricity consumption via consumer feedback: a review of experience. *2007 ECEEE Summer Study Proceedings*, pp.1873-1884.

Fischer, C., 2008. Feedback on household electricity consumption: a tool for saving energy? *Energy Efficiency*, 1, pp.79-104.

Fitzpatrick, G. and Smith, G., 2009. Technology-enabled feedback on domestic energy consumption: articulating a set of design concerns. *IEEE Pervasive Computing*, 8, pp.37-44.

Foster, B. and Mazur-Stommen,S., 2012. Results from recent real-time feedback studies. ACEEE report. Available from http://www.aceee.org/research-report/b122

Frankish, C., 2009. Literature review: design of domestic energy meters: a psychological perspective. Appendix 4 in W. Anderson and V. White, *Exploring consumer preferences for home energy display functionality. Report to the Energy Saving Trust*. Bristol: Centre for Sustainable Energy

Froehlich, J., 2009. Promoting energy-efficient behaviors in the home through feedback: the role of human-computer interaction. *HCIC 2009 Workshop*, 4-8 February 2009, Colorado. Available from ftp://ftp.cs.washington.edu/tr/2009/02/UW-CSE-09-02-01.pdf

Froehlich, J., Findlater, L., Landay, J., 2010. The design of eco-feedback technology. Proceedings of the 28th *International Conference on Human Factors in Computing Systems*, 10-15 April 2010, Atlanta. Available from http://dub.washington.edu/djangosite/media/papers/tmpssyQcm.pdf

Garaas, T.W. and Pomplun, M., 2008. Inspection time and visual-perceptual processing. *Vision Research*, 48, pp.523-537.

Gardner, G.T. and Stern, P.C., 2002. *Environmental problems and human behavior.* Boston: Pearson.

Gaspar, R. and Antunes, D., 2011. Energy efficiency and appliance purchases in Europe: consumer profiles and choice determinants. *Energy Policy*, 39, pp.7335-7346.

Geller, E.S., 2002. The challenge of increasing pro-environment behaviour. *In*: R.G. Bechtel and A. Chruchman, eds. *Handbook of environmental psychology.* New York: Wiley, pp.525-540.

Geller, E.S., Winett, R.A., Everett, P.B., 1982. *Preserving the environment: new strategies for behaviour change*. New York: Pergamon Press.

GEO, 2010. *Minim*. Available from http://www.greenenergyoptions.co.uk/our-products/energy-monitors/domestic-stand-alone-displays/minim

Giacomin, J. and Bertola, D., 2012. Human emotional response to energy visualisations. *International Journal of Industrial Ergonomics*, 42, pp.542-552.

Grant, R.W. and Sugarman, J., 2004. Ethics in human subjects research: do incentives matter? *Journal of Medicine and Philosophy*, 29(6), pp.717-738.

Grønhøj, A. and Thøgersen, J., 2011. Feedback on household electricity consumption: learning and social influence processes. *International Journal of Consumer Studies*, 35, pp.138-145.

Guerra Santin, O., Itard, L., Visscher, H., 2009. The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy and Buildings*, 41, pp.1223-1232.

Gummerman, K., 1975. Successive processing of colour and form from brief visual displays. *Perceptual and Motor Skills*, 40, pp.31-41.

Gustafsson, A and Bång, M., 2008. Evaluation of a pervasive game for domestic energy engagement among teenagers. Proceedings of the 2008 *International Conference on Advances in Computer Entertainment Technology*, 3-5 December 2008, Yokohama, pp.232-239. Available from http://soda.swedish-ict.se/3858/1/Power_Agent_CIE.pdf

Haakana, M., Sillanpää, L., Talsi, M., 1997. The effect of feedback and focused advice on household energy consumption. *1997 ECEEE Summer Study Proceedings* , panel 4.

Ham, J.R.C., Midden, C.J.H., Maan, S., Merkus, B., 2009. Persuasive lighting: the influence of feedback through lighting on energy conservation behavior. *Experiencing Light 2009 International Conference on the Effects of Light on Wellbeing*, 26-27 October 2009, Eindhoven, pp.122-128.

Hanna, A. and Remington, R., 1996. The representation of color and form in long-term memory. *Memory and Cognition*, 24, pp.322-330.

Hargreaves, T., Nye, M., Burgess, J., 2010. Making energy visible: a qualitative field study of how householders interact with feedback from smart energy monitors. *Energy Policy*, 38, pp.6111-6119.

Hargreaves, T., Nye, M., Burgess, J., 2013. Keeping energy visible? Exploring how householders interact with feedback from smart energy monitors in the longer term. *Energy Policy*, 52, pp.126-134.

Harkins, S. and Lowe, M., 2000. The effects of self-set goals on task performance. *Journal of Applied Psychology*, 30, pp.1-40.

Hayes, S.C. and Cone, J.D., 1977. Reducing residential electrical energy use: payments, information, and feedback. *Journal of Applied Behavior Analysis*, 10, pp.425-435.

Hayes, S.C. and Cone, J.D., 1981. Reduction of residential consumption of electricity through simple monthly feedback. *Journal of Applied Behavior Analysis*, 14, pp.81-88.

Henryson, J., Håkansson, T., Pyrko, J., 2000. Energy efficiency in buildings through information: Swedish perspective. *Energy Policy*, 28, pp.169-180.

Holah, M., 2006a. *Qualitative ad quantitative data*. Available from http://www.holah.karoo.net/quantitativequalitative.htm

Holah, M., 2006b. *Reliability*. Available from http://www.holah.karoo.net/reliability.htm

Holah, M., 2006c. *Advantages of laboratory* experiments. Available from http://www.holah.karoo.net/evaluationofexperiment.htm

Holland, S.P. and Mansur, E.T., 2008. Is real-time pricing green? The environmental impacts of electricity demand variance. *Review of Economics and Statistics*, 90, pp.550-561.

Holmes, T., 2007. Eco-visualization: combining art and technology to reduce energy consumption. *In*: B. Shneiderman, G. Fischer, E. Giaccardi, M. Eisenberg, eds. *Creativity and Cognition*, pp.153-162.

Holt, N. and Walker, I., 2009. Research with people: theory, plans and practicals. Basingstoke: Palgrave Macmillan.

Hopkins, W.G., 2000. *Quantitative research design*. Available from http://www.sportsci.org/jour/0001/wghdesign.html

Hori, S., Kondo, K., Nogata, D., Ben, H., 2013. The determinants of household energy-saving behaviour: survey and comparison in five major Asian cities. *Energy Policy*, 52, pp.354-362.

Huang, K., 2008. Effects of computer icons and figure/background area ratios and color combinations on visual search performance on an LCD monitor. *Displays*, 29, pp.237-242.

Huberty C.J. and Morris J.D., 1989. Multivariate analysis versus multiple univariate analyses. *Psychological Bulletin*, 105(2), pp.302-308.

Humar, I., Gradišar, M., Turk, T., 2008. The impact of color combinations on the legibility of a web page text presented on CRT displays. *International Journal of Industrial Ergonomics*, 38(11-12), pp.885-899.

Humar, I., Gradisar, M., Turk, T., Erjavec, J., 2014. The impact of color combinations on the legibility of text presented on LCDs. *Applied Ergonomics*, 45, pp.1510-1517.

Hutton, R.B., Mauser, G.A., Filiatrault, P., Ahtola, O.T., 1986. Effects of cost-related feedback on consumer knowledge and consumption behavior: a field experimental approach. *Journal of Consumer Research*, 13(3), pp.327-336.

Iyer, M., Kempton, W., Payne, C., 2006. Comparison groups on bills: automated, personalized energy information. *Energy and Buildings*, 38, pp.988-996.

Jackson, T., 2005. *Motivating sustainable consumption: a review of evidence on consumer behaviour and behavioural change. A report to the Sustainable Development Research Network*. Centre for Environmental Strategy, University of Surrey.

Jacucci, G., Spagnolli, A., Gamberini, L., Chalambalakis, A., Björksog, C., Bertoncini, M., Torstensson, C., Monti, P., 2009. Designing effective feedback of electricity consumption for mobile user interfaces. *PsychNology Journal*, 7(3), pp.265-289.

Jain, R.K., Taylor, J.E., Peschiera, G., 2012. Assessing eco-feedback interface usage and design to drive energy efficiency in buildings. *Energy and Buildings*, 48, pp.8-17.

Jain, R.K., Taylor, J.E., Culligan, P.J., 2013. Investigating the impact eco-feedback information representation has on building occupant energy consumption behavior and savings. *Energy and Buildings*, 64, pp.408-414.

Jerison, H.J. and Pickett, R.M., 1964. Vigilance: the importance of the elicited observing rate. *Science*, 143(3609), pp.970-971.

Jessa, M. and Burns, C.M., 2007. Visual sensitivities of dynamic graphical displays. *International Journal of Human-Computer Studies*, 65, pp.206-222.

Kaiser, F.G., Ranney, M., Hartig, T., Bowler, P.A., 1999. Ecological behaviour, environmental attitude, and feelings of responsibility for the environment. *European Psychology*, 4(2) pp.59-74.

Kaiser, F.G., Oerke, B., Bogner, F.X., 2007. Behavior-based environmental attitude: development of an instrument for adolescents. *Journal of Environmental Psychology*, 27(3), pp.242-251.

Karjalainen, S., 2011. Consumer preferences for feedback on household electricity consumption. *Energy and Buildings*, 43, pp.458-467.

Kaufmann, S., Künzel, K., Loock., M., 2013 Customer value of smart metering: explorative evidence from a choice-based conjoint study in Switzerland. *Energy Policy*, 53, pp.229-239.

Keller, T., Gerjets, P., Scheiter, K., Garsoffky, B., 2006. Information visualizations for knowledge acquisition: the impact of dimensionality and color coding. *Computers in Human Behavior*, 22, pp.43-65.

Kempton, W., Darley, J.M., Stern, P.C., 1992. Psychological research for the new energy problems: strategies and opportunities. *American Psychologist*, 47(10), pp.1213-1223.

Kliger, D. and Gilad, D., 2012. Red light, green light: color priming in financial decisions. *The Journal of Socio-Economics*, 31, pp.738-745.

Kluger, A.N. and DeNisi, A., 1996. Effects of feedback intervention on performance: a historical review, a meta-analysis, and a preliminary feedback intervention theory. *Psychological Bulletin*, 119, pp.254-284.

Kollmuss, A. and Agyeman, J., 2002. Mind the gap: why do people act environmentally and what are the barriers to pro-environmental behavior? *Environmental Education Research*, 8(3), pp.239-260.

Kotchen, M.J. and Reiling, S.D., 2000. Environmental attitudes, motivations, and contingent valuation of non-use values: a case study involving endangered species. *Ecological Economics*, 32(1), pp.93-107.

Krishnamurti, T., Davies, A.L., Wong-Parodi, G., Wang, J., Canfield, C., 2013. Creating an in-home display: experimental evidence and guidelines for design. *Applied Energy*, 108, pp.448-458.

Lally, P., van Jaarsveld, C.H.M., Potts, H.W.W., Wardle, J., 2010. How are habits formed: modelling habit formation in the real world. *European Journal of Social Psychology*, 40(6), pp.998-1009.

Langton, S.R.H., Law, A.S., Burton, A.M., Schweinberger, S.R., 2008. Attention capture by faces. *Cognition*, 107(1), pp.330-342.

Lin, C., 2005. Effects of screen luminance combination and text color on visual performance with TFT-LCD. *International Journal of Industrial Ergonomics*, 35, pp.229-235.

Lincoln, Y.S. and Guba, E.G., 1985. *Naturalistic inquiry*. London: Sage.

Ling, J. and van Schaik, P., 2002. The effect of text and background colour on visual search of web pages. *Displays*, 23, pp.223-230.

Lomas, K.J., 2010. Carbon reduction in existing buildings: a trans-disciplinary approach. Editorial in *Building Research and Information*, 38, pp.1-11.

Mansouri, I., Newborough, M., Probert, D., 1996. Energy consumption in UK households: impacts of domestic electrical appliances. *Applied Energy*, 54, pp.211-285.

Maréchal, K., 2010. Not irrational but habitual: the importance of “behavioural lock-in” in energy consumption. *Ecological Economics*, 69, pp.1104-1114.

Martiskaïnen, M., 2007. *Affecting consumer behaviour on energy demand. Final report to EdF Energy.* Science and Technology Policy Research, University of Sussex.

McCalley, L.T. and Midden, C.J.H., 2002. Energy conservation through product-integrated feedback: the roles of goal-setting and social orientation. *Journal of Economic Psychology*, 23, pp.589-603.

McClelland, L. and Cook, S.W., 1979. Energy conservation effects of continuous in-home feedback in all-electric homes. *Journal of Environmental Systems*, 9, pp.169-173.

McClelland, L. and Cook, S.W., 1980. Promoting energy conservation in master-metered apartments through group financial incentives. *Journal of Applied Psychology*, 10(1), pp.20-31.

McMakin, A.H., Malone, E.L., Lundgren, R.E., 2002. Motivating residents to conserve energy without financial incentives. *Environment and Behaviour*, 34, pp. 848-863.

Merton, R.K., Fiske, M., Kendal, P.L., 1956. *The focused interview: a manual of problems and procedures*. New York: Free Press.

Mettler-Meibom, B. and Wichmann, B., 1982. The influence of information and attitudes toward energy conservation on behaviour (translated by M. Stommel, Michigan State University). *In*: H. Schaefer, ed. *Einfluß des Verbraucherverhaltens auf den Energiebedarf privater Haushalte*. Berlin: Springer-Verlag.

Meyers, R.J., Williams, E.D., Matthews, H.S., 2010. Scoping the potential of monitoring and control technologies to reduce energy use in homes. *Energy and Buildings*, 42, pp.563-569.

Midden, C.J.H., Meter, J.E., Weenig, M.H., Zieverink, H.J.A., 1983. Using feedback, reinforcement and information to reduce energy consumption in households: a field-experiment. *Journal of Economic Psychology*, 3, pp.65-86.

Moser, S.C. and Dilling, L., 2004. Making climate hot: communicating the urgency and challenge of global climate change. *Environment*, 46, pp.32-46.

Noiwan, J. and Norcio, A.F., 2006. Cultural differences on attention and perceived usability: investigating color combinations of animated graphics. *International Journal of Human-Computer Studies*, 64, pp.103-122.

Nye, M., Burgess, J., 2008. *Promoting durable change in household waste and energy behaviour: a technical research report completed for the Department of Environment, Food and Rural Affairs*. University of East Anglia, Norwich.

O'Brien R.G. and Kaiser M.K., 1985. MANOVA method for analyzing repeated measures designs: an extensive primer. *Psychological Bulletin*, 97(2), pp.313-333.

OFGEM, 2010. *Previous schemes*. Office of gas and electricity markets. Available from http://www.ofgem.gov.uk/Sustainability/Environment/EnergyEff/PrevSchemes/

OFGEM, 2011. *Typical domestic energy consumption figures. Factsheet 96*. Office of gas and electricity markets. Available from http://www.ofgem.gov.uk/Media/FactSheets/Documents1/domestic%20energy%20consump%20fig%20FS.pdf

Ojanpää, H. and Näsänen, R., 2003. Effects of luminance and colour contrast on the search of information on display devices. *Displays*, 24, pp.167-178.

Okabe, M. and Ito, K., 2002. *Color universal design (CUD): how to make figures and presentations that are friendly to color-blind people*. Available from http://jfly.iam.u-tokyo.ac.jp/color/#redundant1

Ölander, F. and Thøgerson, J., 1995. Understanding consumer behaviour as a prerequisite for environmental protection. *Journal of Consumer Policy*, 18, pp.345-385.

Oltra, C., Boso, A., Espluga, J., Prades, A., 2013. A qualitative study of users' engagement with real-time feedback from in-house energy consumption displays. *Energy Policy*, 61, pp.788-792.

ONS, 2011. *Earnings by qualification in the UK*. Office for National Statistics. Available from http://www.ons.gov.uk/ons/dcp171776_229888.pdf

ONS, 2012a. *Detailed household expenditure by gross equivalised income decile group (OECD-modified scale), 2012, UK*. Office for National Statistics. Available from http://www.ons.gov.uk/ons/about-ons/business-transparency/freedom-of-information/what-can-i-request/published-ad-hoc-data/econ/january-2014/detailed-household-expenditure-by-gross-equivalised-income-decile-group--oecd-modified-scale---2012.xls

ONS, 2012b. *Qualification levels and human capital*. Office for National Statistics. Available from http://www.ons.gov.uk/ons/rel/wellbeing/measuring-national-well-being/education-and-skills/art-education-and-skills.html#tab-Qualification-levels-and-human-capital

ONS, 2013. *Region and country profiles: key statistics (based on 2011 census)*. Office for National Statistics. Available from http://www.ons.gov.uk/ons/rel/regional-trends/region-and-country-profiles/key-statistics--december-2013/regional-profiles---key-statistics--december-2013.xls

ONS, 2014a. *UK environmental accounts 2014*. Office for National Statistics. Available from http://www.ons.gov.uk/ons/dcp171778_369063.pdf

ONS, 2014b. *Gross household income by income decile group, 2012*. Office for National Statistics. Available from http://www.ons.gov.uk/ons/about-ons/business-transparency/freedom-of-information/what-can-i-request/published-ad-hoc-data/econ/january-2014/household-income-and-expenditure-by-income-decile-group---2012.xls

ONS, 2014c. *Full report: household energy spending in the UK, 2001-2012*. Office for National Statistics. Available from http://www.ons.gov.uk/ons/dcp171776_354637.pdf

Onzo, 2014. *Introducing the Onzo smart energy kit*. Available from http://www.electricity-monitor.com/wireless-energy-monitors-onzo-c-37_75.html

Parag, Y. and Darby, S., 2009. Consumer-supplier-government triangular relations: rethinking the UK policy path for carbon emissions reduction from the UK residential sector. *Energy Policy*, 37, pp.3984-3992.

Payne, C. (ctpayne@lbl.gov), 6 November 2013. *Energy and Buildings article on energy feedback*. E-mail to T.S.Chiang (t.s.chiang@bath.ac.uk).

Pearson, R. and van Schaik, P., 2003. The effects of spatial layout of and link colour in web pages on performance in a visual search task and an interactive search task. *International Journal of Human-Computer Studies*, 59, pp.327-353.

Peschiera, G., Taylor, J.E., Siegel, J.A., 2010. Response-relapse patterns of building occupant electricity consumption following exposure to personal, contextualized and occupant peer network utilization data. *Energy and Buildings*, 42, pp.1329-1336.

Petersen, J.E., Shunturov, V., Janda, K., Platt, G., Weinberger, K., 2006. Dormitory residents reduce electricity consumption when exposed to real-time visual feedback and incentives. *International Journal of Sustainability in Higher Education*, 8(1), pp.16-33.

Petkov, P., Köbler, F., Foth, M., Krcmar, H., 2011. Motivating domestic energy conservation through comparative, community-based feedback in mobile and social media. Proceedings of the 5th *International Conference on Communities and Technologies*, 29 June-2 July 2011, Brisbane, pp.21-30.

PhysOrg, 2010. *Spot the difference predicts model of human visual attention*. Available from
http://phys.org/news196361817.html

Pierce, J., Odom, W., Blevis, E., 2008. Energy aware dwelling: a critical survey of interaction design for eco-visualizations. *OZCHI*, 8-12 December 2008, Cairns QLD.

Poortinga, W., Steg, L., Vlek, C., 2004. Values, environmental concern, and environmental behaviour: a study into household energy use. *Environment and Behavior*, 36(1), pp.70-93.

Preece, J. and Keller, L., 1990. *Human computer interaction*. Hertfordshire: Prentice Hall International (UK).

Rensink, R.A., O'Regan, J.K., Clark, J.J., 1997. To see or not to see: the need for attention to perceive changes in scenes. *Psychological Science*, 8, pp.368-373.

Ro, T., Russell, C., Lavie, N., 2001. Changing faces: a detection advantage in the flicker paradigm. *Psychological Science*, 12(1), p.94.

Roberts, S. and Baker, W., 2003. *Towards effective energy information: improving consumer feedback on energy consumption*. Bristol: Centre for Sustainable Energy.

Roberts, S., Humphries, H., Hyldon, V., 2004. *Consumer preferences for improving energy consumption feedback. Report to Ofgem*. Bristol: Centre for Sustainable Energy.

Sardianou, E., 2007. Estimating energy conservation patterns of Greek households. *Energy Policy*, 35, pp.3778-3791.

Schultz, P.W., Nolan, J.M., Cialdini, R.B., Goldstein, N.J., Griskevicius, V., 2007. The constructive, destructive, and reconstructive power of social norms. *Psychological Science*, 18(5), pp.429-434.

Scott, F.L., Jones, C.R., Webb, T.L., 2014. What do people living in deprived communities in the UK think about household energy efficiency interventions? *Energy Policy*, 66, pp.335-349.

Seligman, C., Darly, J.M., Becker, L.J., 1978. Behavioral approaches to residential energy conservation. *Energy and Buildings*, 1, pp.325-337.

Sernhed, K., Pyrko, J., Abaravicius, J., 2003. Bill me this way! Customer preferences regarding electricity bills in Sweden. *2003 ECEEE Summer Study Proceedings*, panel 6, pp.1147-1150.

Sexton, R.J., Johnson, N.B., Konakayama, A., 1987. Consumer response to continuous-display electricity-use monitors in a time-of-use pricing experiment. *Journal of Consumer Research*, 14, pp.55-62.

Shenton, A.K., 2004. Strategies for ensuring trustworthiness in qualitative research projects. *Education for Information*, 22, pp.63-75.

Siero, F.W., Bakker, A.B., Dekker, G.B., van den Burg, M.T.C., 1996. Changing organizational energy consumption behaviour through comparative feedback. *Journal of Environmental Psychology*, 16, pp.235-246.

Slavin, R.E., Wodanski, J.S., Blackburn, B.L., 1981. A group contingency for electricity conservation in master-metered apartments. *Journal of Applied Behavior Analysis*, 14(3), pp.357-363.

Smith, S.L. and Mosier, J.N., 1986. *Guidelines for designing user interface software. ESD-TR-86-278.* Massachusetts: The MITRE Corporation. Available at
http://hcibib.org/sam/2.html

Smith, S.L. and Thomas, D.W., 1964. Color versus shape coding in information displays. *Journal of Applied Psychology*, 48, pp.137-146.

Socolow, R.H., 1978. The Twin Rivers program on energy conservation in housing: highlights and conclusions. *In*: R.H. Socolow, ed. *Saving energy in the home: Princeton's experiments at Twin Rivers*. Cambridge: Ballinger Publishing Company, pp.2-62.

Sonderegger, R.C., 1978. Movers and stayers: the residents contribution to variation across houses in energy consumption for space heating. *Energy and Buildings*, 1, pp.313-324.

Staats, H., Harland, P., Wilke, H.A.M., 2004. Effecting durable change: a team approach to improve environmental behaviour in the household. *Environment and Behavior*, 36(3), pp.341-367.

Staats, H.J., Wit, A.P., Midden, C.Y.H., 1996. Communicating the greenhouse effect to the public: evaluation of a mass media campaign from a social dilemma perspective. *Journal of Environmental Management*, 45, pp.189-203.

Stern, N.H., 2007. *The economics of climate change, the Stern review*. Cambridge: Cambridge University Press.

Stern, P.C. and Aronson, E., eds., 1984. Energy use: the human dimension. New York: The National Academic Press.

Straughan, R.D. and Roberts, J.A., 1999. Environmental segmentation alternatives: a look at green consumer behaviour in the new millennium. *Journal of Consumer Marketing*, 16(6), pp.558–575.

Summerfield, A.J., Lowe, R.J., Bruhns, H.R., Caeiro, J.A., Steadman, J.P., Oreszczyn, T., 2007. Milton Keynes Energy Park revisited: changes in internal temperatures and energy usage. *Energy and Buildings*, 39, pp.783-791.

Summerfield, A.J., Oreszczyn, T., Pathan, A., Hong, S., 2009. Occupant behaviour and energy use. *In*: D. Mumovic and M. Santamouris, eds. *A handbook of sustainable building design and engineering: an integrated approach to energy, health and operational performance*. London: Earthscan, pp.359-370.

Tajfel, H. and Turner, J., 1979. An integrative theory of inter-group conflict. *In*: W. Austin and S. Worchel, eds. *The Social Psychology of Intergroup Relations*. Monterey CA: Brooks/Cole, pp.33-47.

Tanaka, J. and Bunosky, L.,1993. Is the object recognition system really colorblind? Poster presented at the annual meeting of the Psychonomic Society, Washington DC.

Telegesis, 2009. *EAP-E and EAP-E-PA Ethernet access point: product manual*. Rev. 1.04. High Wycombe: Telegesis (UK) Ltd.

Theeuwes, J. and van der Stigchel, S., 2006. Faces capture attention: evidence from inhibition of return. *Visual Cognition*, 13(6), pp.657-665.

Thomas, G.O. and Walker, I., 2011. Travel survey 2010-2011. University of Bath.

Tourangeau, R. and Smith, T.W., 1996. Asking sensitive questions: the impact of data collection mode, question format and question context. *Public Opinion Quarterly*, 60, pp.275-304.

Treisman, A. 1986. Properties, parts and objects. Chapter 35 in: L.R. Boff, L. Kaufman, F.P. Thomas, eds. *Handbook of perception and human performance: cognitive processes and performance.* Vol.2. Oxford: Clarendon.

Trochim, W.M.K., 2006. *Qualitative validity*. Available from http://www.socialresearchmethods.net/kb/qualval.php

Ueno, T., Inada, R., Saeki, O., Tsuji, K., 2005. Effectiveness of displaying energy consumption data in residential houses: analysis on how the residents respond. *2005 ECEEE Summer Study Proceedings*, pp.1289-1299.

Ueno, T., Sano, F., Saeki, O., Tsuji, K., 2006. Effectiveness of an energy-consumption information system on energy savings in residential houses based on monitored data. *Applied Energy*, 83, pp.166-183.

Urban, J. and Ščasný, M., 2012. Exploring domestic energy-saving: the role of environmental concern and background variables. *Energy Policy*, 47, pp.69-80.

van den Broek, K. and Walker, I. (in prep.) Energy-consumption behaviours and attitudes in an on-campus university population.

van Houwelingen, J.H. and van Raaij, W.F., 1989. The effect of goal-setting and daily electronic feedback on in-home energy use. *Journal of Consumer Research*, 16, pp.98-105.

van Raaij, W.F. and Verhallen, T.M.M., 1983. A behavioral model of residential energy use. *Journal of Economic Psychology*, 3, pp.39-63.

van Schaik, P. and Ling, J., 2001. The effects of frame layout and differential background contrast on visual search performance in web pages. *Interacting with Computers*, 13, pp.513-525.

Vassileva, I., Odlare, M., Wallin, F., Dahlquist, E., 2012. The impact of consumers' feedback preferences on domestic electricity consumption. *Applied Energy*, 93, pp.575-582.

Vassileva, I., Dahlquist, E., Wallin, F., Campillo, J., 2013. Energy consumption feedback devices' impact evaluation on domestic energy use. *Applied Energy*, 106, pp.314-320.

Verhallen, T.M.M. and van Raaij, W.F., 1981. Household behaviour and the use of natural gas. *Journal of Consumer Research*, 8, pp.253-257.

Verma, M. and McOwan, P.W., 2010. A semi-automated approach to balancing of bottom-up salience for predicting change detection performance. *Journal of Vision*. 10(6), pp.1-17.

Verplanken, B. and Wood, W., 2006. Interventions to break and create consumer habits. *Journal of Public Policy and Marketing*, 25(1), pp.90-103.

Walker, I., 2007-2008. *Statistics for psychology: making sense of our world through analysis*. Available from http://staff.bath.ac.uk/pssiw/stats2/page2/page14/page14.html

Warm, J.S., 1984. *Sustained attention in human performance*, Chichester: Wiley.

Wilhite, H.A. and Ling, R., 1995. Measured energy savings from a more informative energy bill. *Energy and Buildings*, 22, pp.145-155.

Wilhite, H.A., Hoivik, A., Olsen, J.-G., 1999. Advances in the use of consumption feedback information in energy billing: the experiences of a Norwegian energy utility. *1999 ECEEE Summer Study Proceedings*, panel 3.

Winett, R.A., Kagel, J.H., Battalio, R.C., Winkler, R.C., 1978. Effects of monetary rebates, feedback, and information on residential electricity conservation. *Journal of Applied Psychology*, 63(1), pp.73-80.

Winett, R.A., Neale, M.S., Grier, G.C., 1979. The effects of self-monitoring and feedback on residential electricity consumption: winter. *Journal of Applied Behavior Analysis*, 12(2), pp.173-184.

Witherspoon, S., 1994. The greening of Britain: romance and rationality. *In*: R. Jowell, J. urtice, L. Brook, D. Ahrendt, A. Park, eds. *British social attitudes: the 11th report*. Aldershot: Dartmouth.

Wood, G. and Newborough, M., 2003. Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design. *Energy and Buildings*, 35, pp.821-841.

Wood, G. and Newborough, M., 2005. *Consumer preferences for energy-use information in the future home*. Report to TAHI.

Wood, G. and Newborough, M., 2007a. Energy-use information transfer for intelligent homes: enabling energy conservation with central and local displays. *Energy and Buildings*, 39, pp.495-503.

Wood, G. and Newborough, M., 2007b. influencing user behaviour with energy information display systems for intelligent homes. *International Journal of Energy Research*, 31, pp. 56-78.

WorkWithColor, 2013a. *The color wheel*. Available from http://www.workwithcolor.com/the-color-wheel-0666.htm

WorkWithColor, 2013b. *Color properties / Terminology*. Available from http://www.workwithcolor.com/color-properties-definitions-0101.htm

WorkWithColor, 2013c. *Color luminance*. Available from http://www.workwithcolor.com/color-luminance-2233.htm

Wu, J. and Yuan, Y., 2003. Improving searching and reading performance: the effect of highlighting and text color coding. *Information and Management*, 40, pp.617-637.

Wyatt, P., 2013. A dwelling-level investigation into the physical and socio-economic drivers of domestic energy consumption in England. *Energy Policy*, 60, pp.540-549.

Yohanis, Y.G., 2012. Domestic energy use and householders' energy behaviour. *Energy Policy*, 41, pp.654-665.

Yohanis, Y.G., Mondol, J.D., Wright, A., Norton, B., 2008. Real-life use in the UK: how occupancy and dwelling characteristics affect domestic electricity use. *Energy and Buildings*, 40, pp.1053-1059.

Zhao, T., Bell, L., Horner, M.W., Sulik, J., Zhang, J., 2012. Consumer responses towards home energy financial incentives: a survey-based study. *Energy Policy*, 47, pp.291-297.