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the effects of feedback through ambient lighting on energy consumption behavior

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Persuasive Technology Enlightenment: The Effects of Feedback Through Ambient Lighting on Energy Consumption Behavior

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Preface

With this thesis, I complete my studies in Human Technology Interaction at the Technical University of Eindhoven. Writing this thesis has proven to be a valuable learning experience, giving me insight into my field of interest and myself as a researcher.

I hope reading this thesis gives new insights and makes people curious to explore the subject more. I owe gratitude to my supervisors; dr. Jaap Ham and prof.dr. Cees Midden, from the Technical University of Eindhoven, for their advice and guidance throughout my graduation period. I would also like to thank Martin Bosman from the Technical University of Eindhoven for his technical assistance. Special thanks go out to my friends and family for their trust and moral support.

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Content

Abstract

Earlier research has investigated ambient lighting as a feedback mechanism aimed at influencing energy consumption behavior. This ambient persuasive technology is defined by Ham, Maan, Merkus, & Midden (2009) as “generic technologies that can be integrated unobtrusively into the environment and exert an influence on people without the need for their focal attention”. Ham et al. (2009) compared lighting feedback to numerical feedback and found that lighting caused a 21% reduction in energy use implying stronger persuasive effects, and suffered less from an added cognitive load task indicating easier processing. We argue these results stem from three main advantages lighting has over most other feedback mechanisms, namely; (1) it shows relative energy consumption at a glance, (2) it communicates a norm through the use of colors, and (3) it is easier to perceive. Current research aimed to replicate findings by Ham et al. (2009) and further investigate lighting’s advantages, by adding a third form of feedback indicating *relative* consumption without making use of colors or light. We found no differences in energy and time use between different forms of feedback. The adding of a cognitive load task resulted in *lower* average energy use scores, contradicting expectations. No interaction effect of cognitive load and type of feedback on energy consumption or time used in the experiments was found. Constraining time during the experiments had no effect on energy use. Effects of load on time used were found, replicating findings from Ham et al. (2009). Reasons for these findings are provided and implications for future research are discussed.

The Effects of Feedback Through Ambient Lighting on Energy Consumption Behavior

From the quest for the perpetual mobile to experiments with nuclear fusion, mankind's desire for energy seems to be as consistent as it is persistent throughout history. Our world and its inhabitants drive on energy and we seem to increasingly utilize it, even to the extent that our consumption behavior threatens to surpass our harvesting capabilities. Since the energy crisis in the 1970s, the fear for possible depletion of fossil fuels has initiated the demand for conservation research. Pollution, the emission of greenhouse gasses and threats to biodiversity have become a hot topic of debate for over some time now and are currently fueling most of this research. Ever since the Kyoto Protocol in 1997, countries across the world have committed themselves to the reduction of greenhouse gasses. Even though climate change skepticism receives worldwide media attention (for example the controversy concerning the Climatic Research Unit in 2009), the scientific consensus that human activity induces global warming still remains mostly unchallenged (Intergovernmental Panel on Climate Change, 2007). Apart from the discussion on the impact that greenhouse gasses have on global warming, reducing energy consumption facilitates economical benefits that stem from efficiency, which arte oftentimes prioritized above ecological consequences.

In this report we will further investigate technological methods capable of influencing people in their interaction with energy consuming devices, more specifically; technology meant to persuade energy consumers to reduce their consumption behavior during human-technology interaction. Earlier research by Ham, Maan, Merkus, &

Midden (2009) has already investigated this persuasive technology with positive results. However, some comments can be made on this research which we will aim to clarify in current research by replicating the research from Ham et al. (2009) with minor adjustments and some additional efforts.

Technology’s Role in Energy Consumption Behavior

With current public interest in global warming issues, influencing energy consumption behavior has become a popular area of research, as consumers constitute to a large portion of energy use around the world. The U.S. Department of Energy shows that 39% of total energy consumption can be attributed to residential & commercial use, with residential use being responsible for 21% of total energy consumption in the United States of America (Intermediate Energy Info Book 2009-2010). It seems crucial to control human use of technical systems in a residential setting, as it is the source of a significant amount of energy consumption. A lot of progress has been made in reducing energy use in residential settings by reducing energy loss, but also by increasing energy consuming appliances’ efficiency. But even though appliances have increased heavily in their efficiency and consumers are stimulated to purchase energy efficient appliances by for example the use of energy efficiency ratings, the US Department of Energy (2005) shows that emissions related to electricity use has risen since 1990 by 2.4% each year and those related to gas use have increased by 0.9% annually. Abrahamse, Steg, Vlek & Rothengatter (2005) state that reasons for this increase can be macro-level factors such as technological development, economic growth, demographic factors, institutional factors and cultural developments (the TEDIC factors). These factors shape the micro-factors; individual factors such as motivational factors, abilities and opportunities (MAO variables). There is an important interplay between macro-level (for example technical innovations) and micro-level (for example knowledge of efficient use of technological innovations) factors, since they are unavoidably interwoven. In the midst of this, technology plays a crucial role, even though modern research oftentimes sets technology apart from human behavior and resource conservation. Midden, Kaiser & McCalley (2007) focus on the relationship of humans and the roles technology plays in the consumption of natural resources. They give an overview of what they believe to be technology's four most critical roles in the relationship between humans and their consumption behavior. According to their research, technology might serve as: (1) an intermediary, (2) an amplifier, (3) a determinant, and (4) a promoter, in a manner illustrated in Figure 1. As an *intermediary*, technology stands between the behavior carried out by an individual and the amount of natural resources used in reaching that individuals goal. A person's affluence determines the technology they are able to afford. How, when and where they use this technology determines the environmental impact this individual has when their actions lead to a desired outcome. For example, a person commuting by car consumes more energy than if he or she were to travel by bike. As an *amplifier*, technology shapes the goals people try to reach; it enhances, extends, or amplifies its user's goal attainment. Technology requires consumption of natural resources, both in the original production as in its utilization. Augmented technology oftentimes means more overall energy use, even when this technology is more energy efficient. This effect is described as the rebound effect. Berkhout, Muskens, & Veldhuijsen (2000) describe the rebound effect as the effect that amplified consumption dissolves efficiency gains; people are known to overuse appliances they know to be energy efficient, resulting in the fact that the use of energy-efficient appliances does not always reduce overall energy consumption. It seems that the overall amount of time and money spend on, for example, travel is more or less constant. Faster, more efficient cars do not necessarily decrease fuel consumption, as it also increases people's mobility and ability to travel long distances. As a *determinant*, technology shapes behavior without requiring recognition or awareness by its user. For instance, in areas where more trash receptacles are placed, the likelihood of people littering is decreased, independent of people's tidiness. Furthermore, technology as a determinant motivationally stimulates action simultaneously by providing obstruction or facilitation and by making use of a certain device more or less appealing. Finally, as a *promoter*, technology can be specifically designed to promote behavioral choices leading to the conservation of natural resources. It is aimed at influencing motives and persuades energy consumers to lessen their consumption.

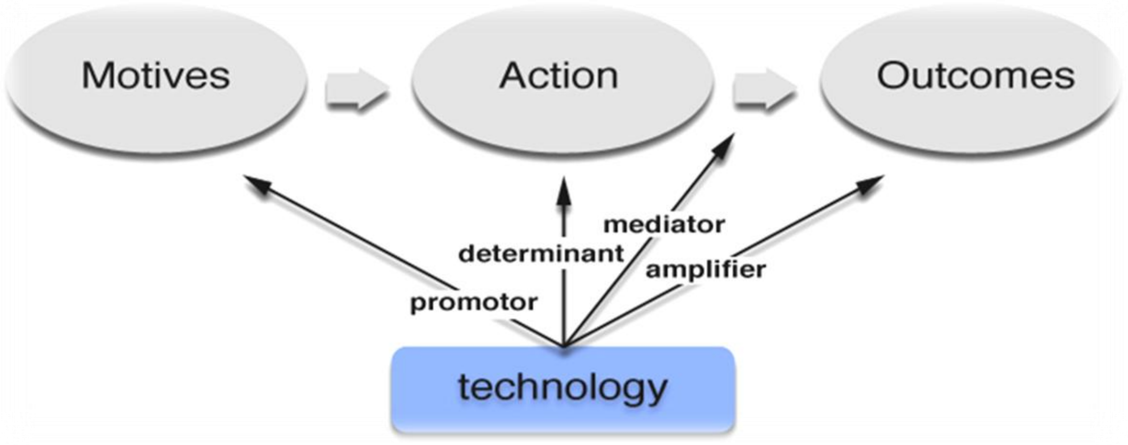


Figure 1: Technology's role in consumption behavior. This figure illustrates the four most critical roles of technology in the relationship between humans and their consumption behavior, according to Midden et al. (2007).

Persuasive Technology

Technology as a promoter of conservation behavior has a high degree of variety and applicability. As complex as it is to reduce overall energy consumption behavior in residential and commercial settings, the interaction between user and system offers important opportunities for technologies persuasive capabilities and its ability to influence consumption behavior. Technology aimed at influencing peoples motives or actions, the latter non-coercive and non-deceptive, can be labeled ‘persuasive technology’. A persuasive computing technology is a computing system, device or application intentionally designed to change a person’s attitudes or behavior in a predetermined way (Fogg, 2003). Essentially any interactive intelligent system designed to intentionally change people’s attitudes or behavior falls within the scope of persuasive technology. Persuasive technology has wide domain applicability and makes use of known strategies like for example positive feedback, personalization and monitoring (Fogg, 2003). A large variety of intervening techniques aimed at influencing behavior have been tested, with varying results (see Darby, 2006 for an overview). Abrahamse et al. (2005) differentiate between antecedent interventions (interventions aimed at influencing underlying behavioral determinants like knowledge to influence behavior) and consequence strategies (for example influencing behavior through the presence of positive or negative consequences). Even though antecedent interventions like mass media campaigns have shown some effect in increasing attitudes or knowledge, a problem lies in the fact that this information does not reach all energy consumers, especially printed media, as not all people read newspapers and printed information is relatively difficult to process. This media tends to only reach the elite and not the masses, resulting in a so called knowledge gap between well- and less-well educated people (Tichenor, Donohue, & Olien, 1970). Television ads do create high exposure, they however seem to lack ability to raise knowledge or motivate people to read more detailed information (Weenig & Midden, 1997). Traditional media has had limited effect in the endeavor of promoting environmental awareness, consequently, accomplishing behavioral change will need more than a raise in consumers' awareness. Technology can be used by intervening in human-system interactions, instigating behavioral change.

The overall tendency shows that for interventions to cause significant energy reduction there needs to be a strong linkage between specific actions and energy outcomes (for example Abrahamse et al., 2005; Midden et al., 2007). Feedback can be used to incite this connection between action and consequence. For feedback to obtain the right amount of linkage with behavior it needs to be of high frequency and specific to consumption behavior. Even though effectiveness of different forms of feedback is often hard to compare due to lack of knowledge about long-term results, providing people with direct tailored knowledge on their consumption behavior has already shown its importance in a wide range of research concerning conservation of natural resources (Darby, 2006). Feedback provides households with information on their energy use so they can associate certain outcomes with their behavior. This form of feedback is preferably given immediately after the behavior occurs with as high a frequency as possible to instigate habit forming (Geller, 2002). Sauer, Schmeink & Wastell (2007) state that proximal information (physically close to the center of the user's attention), is more effective than distal information. The need for proximal information that is given immediately after use of an appliance calls for the design of system embedded feedback which is integrated within the system and is permanently available, immediate and has a high degree of specify. By intervening in the user-system interaction the quality of feedback could improve substantially (McCalley & Midden, 2002). Contemporary technology offers this opportunity; electronic means can provide feedback more quickly and frequently than for example written feedback in the form of monthly energy bills. Moreover, electronic feedback can be given at any given location, for example the living room or the kitchen, making it easier to process than reading meters and bills. Furthermore, electronic feedback allows for the use of multiple standards, reference points and units, where written feedback forms are limited and uniform in the information they can provide. Add to this the efficiency of automation and the fact that electronic feedback can be source-specific to different uses, appliances or persons, and the advantages of smart, electronic feedback prove to be substantial.

Future Developments of Persuasive Technology

In some research, electronic feedback is used as interactive feedback, expanding the potential of feedback mechanisms further more as they enable two-way interaction between user and system. Research by McCalley & Midden (2002) demonstrated that immediate product-integrated factual feedback combined with interactive setting of conservation goals leads up to an 18% reduction in energy usage in a washing machine programming task, as opposed to no feedback conditions. Their intelligent feedback system allows for more precise targeting of tasks and for personalization. They expand feedback from specific appliances to specific tasks as well, combined with refined goal-setting procedures significant conservation becomes a fact.

Not only verbal communication is utilized by persuasive technology, as in some forms it is extended to sensory information like sounds and colors. A design by Kappel & Gretchenig (2009) implemented LED lights in a shower head wherein the number of LEDs illuminated indicated the amount of water used during the current showering session. Their shower water meter generated an average saving of 10 liters of water per showering session after a three week test period. There is a range of research aimed at testing different devices which are labeled persuasive technology, for example Martinez & Geltz (2005) who used their ‘Energy Orb’ to indicate time-of-use tariff on energy use. The Energy Orb is a sphere that changes color dependent on the current tariff and flashes before a critical peak. Results indicate that the energy orb is effective in persuading people to save energy and reduce energy consumption in advance of a critical peak in tariff. Gustafsson & Gyllenswärd (2005) used a technique to visualize electrical current flowing through the cable of an electrical power strip. Their ‘Power-Aware Cord’ glowed brighter when higher current flowed through it. It contributed to a better understanding of energy consumption, making consumers question their energy saving behavior (Gustafsson & Gyllenswärd, 2005). Gyllenswärd, Gustafsson & Bang (2006) built a radiator from light bulbs which they call ‘the Element’. As with the Power-Aware Cord, the Element visualizes energy consumption by changing intensity and brightness of the bulbs. The effects of the Element on energy consumption have not been tested thus far. Currently there are already commercially available forms of persuasive technology. A well known example of this technology is the Wattson of DIY Kyoto; a device that indicates residential energy consumption in numbers through a display on the device, and also by using lighting on the bottom of the device, which changes color dependant on current energy use. It glows from cold blue for no electricity to bright red for high usage.

Lighting as ambient persuasive technology

When looking at many of the above described persuasive technologies, lighting is a technique that is used frequently (LED lights in the Shower Water Meter indicating water flow, the Energy Orb which is a glowing sphere that changes color indicating current tariff, the Power Awareness Cord and also the Element that change intensity and brightness of light to indicate energy use and the Wattson which also uses lighting on the bottom to indicate current energy consumption). Research by Ham et al. (2009) suggests lighting offers advantages over numerical feedback given in numbers as it is used mostly in earlier research (see Darby, 2006 for an overview). They propose that lighting can serve as Ambient Persuasive Technology, they define this technology as follows: “generic technologies that can be integrated unobtrusively into the environment and exert an influence on people without the need for their focal attention” (Ham et al, 2009, p. 6). These sorts of systems can inform users at an intuitive level with little demand for cognitive effort. Intelligent systems as described above will no longer need to be located in home computers or special boxes but can be subtly integrated in the living environment. We believe lighting to have three main advantages over more commonly used forms of feedback like numerical feedback: (1) it is able to show relative consumption at a glance, (2) the use of color can indicate a norm, and (3) it needs no focal attention to be effective.

Relative Consumption Visible at a Glance

Many feedback mechanisms that have been tested make use of numerical displays indicating energy use. In many day-to-day situations however, people might lack the cognitive capacity to process relatively complex information (see for example Bargh, 1997). Ambient persuasive technology in the form of lighting communicates an evaluation; it places the consumption behavior in context by indicating whether certain consumption is considered high or low. For instance; in the research by Ham et al. (2009), feedback on energy consumption through lighting gradually changed color from green light indicating low energy use, to white light indicating average energy use to red light indicating high energy use. Participants had to operate a thermostat as to set room temperatures for hypothetical rooms, during which energy consumption scores varied as temperatures were changed. Numerical feedback only communicated the amount of energy used at the moment, it did not immediately indicate whether this amount is high or low, it required the user to cognitively process the information and then decide whether the amount is high or low. In the study by Ham et al. (2009), upper and lower energy use boundaries were given in numbers alongside the amount of current energy that was used by participants in the numerical feedback condition. This creates an opportunity for participants to place the numerical feedback in context. However, they still had to process the numerical feedback number, scale it within the upper and lower boundaries and decide whether current use was relatively high or low. Given the fact that Ham et al. (2009) used different energy scenario’s as a within subject factor, participants had to go through this scaling process for every new scenario. In the lighting situation the feedback provided is always scaled and the color of the light indicated energy use relative to the upper and lower energy usage boundaries involved in that specific scenario, so a certain color consistently indicates a certain relative use of energy throughout the different scenario’s. Lighting feedback has this scaling information in it naturally and the color of the light is always scaled so it indicates use relative to the upper and lower boundaries for a specific scenario.

This property of relative consumption at a glance is however not unique to lighting feedback, as scaled information can be communicated by a variety of feedback mechanisms, for example in more detailed electronic displays or even more old fashioned mechanical meters . One could use different forms of indicators that present relative amount in proportion to upper and lower boundaries, analog speedometers for example. We do believe however this property is of great importance because it abates cognitive processing and thus is easier to perceive and process.

Norm Communicated by Color

Another advantage of lighting feedback is the fact that green and red are well-learned concepts that generalize easily to meaningful information about energy conservation. This could also add to the ease of understanding the lighting feedback as opposed to factual feedback, even when factual feedback has some evaluative meaning to it. At the moment light begins to change to red, consumers can derive from this the message that current settings are considered ‘bad’ and they have to reduce consumption behavior to reach a ‘good’ state indicated by green light. This good and bad evaluation can also be triggered by goal setting as was done by Ham et al. (2009) by advising to use as little energy as possible whilst maintaining comfortable room temperatures. In this manner, ambient technology automatically activates a norm on sight, whereas factual feedback needs cognitive processing.

No Need for Focal Attention

Another advantage of ambient persuasive technology in the form of lighting feedback might be that lighting does not necessarily require focal attention. The perceptual ease of lighting feedback allows for it to be placed outside the periphery of consumers without losing its persuasive power (Nijënstein, 2009). Lighting feedback does not require perceptual focusing whereas factual feedback does. Nijënstein (2009) states that ambient persuasive technology can change attitudes and behaviors without the need for conscious attention, as consciousness and attention is found to be separate from each other in human processes (Koch & Tsuchiya, 2006). In research by Ham, Midden and Beute (2009), subliminal persuasive technology is used; participants received brief pictures of smiling or frowning faces for only 22ms so they could not be consciously aware of the feedback. Subliminal feedback resulted in lower energy use than no feedback. This strengthens the suggestion put forward by Nijënstein (2009) that unconsciously, feedback can be registered in the periphery of the visual field. Advantages of this could be that lighting feedback can be placed unobtrusively in the surroundings of a human-system interaction. Nijënstein (2009) compared frontal lighting, peripheral lighting and factual feedback with each other. Results suggest again that both lighting feedback situations are more effective than factual feedback, in part replicating results from Ham et al. (2009).

Lighting Feedback Tested in an Experimental Setting

Ham et al. (2009) have investigated the influence of interactive feedback through lighting on energy conservation behavior. In an experimental setting they have tested the use of lighting as a means of feedback to indicate absolute levels of energy consumption compared to a more widely used form of feedback, where levels of energy consumption are given in numbers representing Watts. They used a lamp that changed color gradually dependent on energy consumption, with red light indicating high energy consumption and green light indicating low energy consumption. During an energy conservation task participants had to program a simulated thermostat which was made visible on a computer screen and received feedback on the energy use that accompanied their thermostat settings by the lamp. This lamp was placed on the desk where participants were sitting, in such a manner that the light from the lamp was projected on the wall behind the desk, and was easily visible for participants. In the numerical feedback condition, the amount of energy that was currently used was made visible on the same screen as the thermostat was shown on, by a number representing energy use in Watts. Two additional numbers were added, indicating high and low consumption.

Participants in the lighting condition had significantly lower energy consumption scores (*M* = 544 Watt, *SD* = 208) than participants in the numerical feedback condition (*M* = 692 Watt, *SD* = 202), *F*(1, 53) = 7.16, *p* = .01, which is a lowering of energy consumption by 21% compared to the factual feedback condition. Also, participants in the numerical feedback condition needed more time to program the thermostat (*M* = 39 s., *SE* = 2.0) than participants in the lighting feedback condition (*M* = 33 s., *SE* = 2.0), *F*(1, 53) = 5.53, *p* = .038. These results indicate that lighting feedback has greater persuasive power than numerical feedback. As an extra manipulation, half of the participants had to perform an additional number recognition task while operating the thermostat. Participants heard random numbers ranging from one to thirty read out aloud through headphones and had to press the space bar each time they heard an odd number, as to create cognitive load on participants. Participants under load, on average, needed more time to program the thermostat (*M* = 41 s., *SE* = 2.0) than participants that were not under load (*M* = 31 s., *SE* = 2.0), *F*(1, 53) = 13.40, *p* = .001. Results by Ham et al. (2009) also suggest that the additional load task interfered with processing factual feedback, but not with processing lighting feedback. Participants in the numerical feedback condition needed more time to program the thermostat under load (*M* = 55 s., *SD* = 15) than without cognitive load (*M* = 39 s., *SD* = 7), *F*(1, 40) = 6.52, *p* = .019, whereas this difference was not found for participants who received lighting feedback, *F* < 1. These results indicate that lighting feedback is easier to process as added cognitive load interferes with numerical feedback whereas it does not interfere with lighting feedback.

Notable findings

We have described what we believe to be the most important advantages of lighting feedback over other more common types of feedback like numerical feedback. These are the relative consumption that is visible at a glance, the norm that is communicated through color and the easy of perception. When tested in an experimental setting, these advantages lead to significant effects both in persuasive power as in ease of processing. There are however some notable findings in the research by Ham et al. (2009). Firstly, there was no main effect of cognitive load on energy consumption, although there was an effect of cognitive load on time needed to program the thermostat. Ham et al. (2009) expected participants in the numerical feedback condition under cognitive load to use more energy than participants in the lighting condition not under cognitive load. This was not the case. A reason for this could be the experimental setup;

there were no time constraints used in the experiment. Participants in the numerical feedback condition under cognitive load could, and actually did, use more time to program the thermostat than participants in the lighting feedback condition not under cognitive load. One could argue that participants used this extra time to process the numerical feedback and if not given this opportunity, their goal attainment could suffer, resulting in less conservation behavior and thus higher energy consumption scores. Secondly, Ham at al. (2009) investigated factual and lighting feedback in their research by adding a cognitive load task to their experiment. Participants heard numbers (one to thirty) read out aloud on headphones and had to press the space bar when hearing an odd number. The results indicated that for participants in the numerical feedback, the cognitive load task slowed down processing speed where this was not the case in the lighting feedback condition. It could be argued that the *numerical* cognitive load task interfered with the processing of factual feedback, which was also numerical, but not with the lighting feedback. Therefore, the effect of the cognitive load task on the time needed to program the thermostat could be the result of an overlap in numerical processing, which leads us to our current research.

Current Research

In the current research, the effects of ambient feedback in the form of lighting on energy consumption behavior are investigated and compared to the effects of numerical feedback. We set up an experiment in which participants had the opportunity to conserve energy in a series of tasks and received feedback on their energy consumption during these tasks. We used an experimental setup comparable to that which was used in the experiment by Ham et al. (2009); lighting feedback was compared to a more commonly used form of feedback given in numbers. Lighting feedback was given by a lamp that changed color dependant on energy use, with green light indicating low use and red light indicating high use. In the numerical feedback condition, feedback consisted of only one number (representing energy consumption in Watts). On the same screen that indicated numerical feedback, two additional numbers were presented, indicating low and high consumption. This was done to create more comparability between lighting feedback and numerical feedback, as the former also conveyed this information (relative consumption was made visible by color saturation and distinction across the borders of hue categories; red and green). We proposed in our theory that lighting has three important advantages over more commonly used forms of feedback like numerical feedback. One of these properties, the fact that lighting shows relative consumption scores at a glance, is however not unique to lighting and can also be communicated though other forms of feedback, even electronic feedback on a display. We added a third form of feedback which possesses this property of relative consumption visible at a glance, but does not profit from communicated norms or peripheral perception like ambient lighting does. This was done by using a slider; an indicator bar scrolling up and down between lower and upper extremes of energy use, dependent on current thermostat settings and thus energy consumption. We expected that lighting feedback has more persuasive power (leading to lower energy consumption and less time needed to program the thermostat) than slider feedback, which in turn has more persuasive power than numerical feedback. In addition, we expected that lighting feedback would be easiest to process and numerical feedback to be hardest to process. To test this we added an additional task as to manipulate cognitive load. Half of the participants performed this task and we expected participants in the lighting feedback condition to be least hindered (leading to lower energy consumption) by this task than and participants in the numerical feedback condition to be hindered most.

We also investigated whether the lack of a time constraint in the research by Ham et al. (2009) could have been a reason that no effect of cognitive load was found. We used cut-off points in time and checked the effects on interaction between cognitive load and energy use. We refrained from using a time constraint during the experiment because we feared this might cause participants to haste and deviate from their main goals to first set room temperatures to a comfortable setting and second use as little energy as possible while doing so. A time constraint could cause stress in participants which could have interfere with the results. By registering energy use on a timely base we could later on investigated energy settings on desired moments in time. We measured the precise times at which participants made changes to their thermostat settings, and registered their settings at certain preset timeslots (every 10 seconds). This made it possible for us to check energy use at for instance 30 or 40 seconds, which were roughly the mean times participants used in earlier research by Ham et al. (2009) for respectively no cognitive load and cognitive load conditions. We expected there would be an interaction effect between cognitive load en type of feedback for dependant variables energy consumption and time needed to program the thermostat.

By using a different load task, one that did not make use of numbers, we hoped to confirm earlier findings by Ham et al. (2009) and repudiate possible confounding effects of load task and main task. We expected the load task to interfere with the feedback in the same manner as it did in the research by Ham et al. (2009); the load task placed load on the cognitive processing of participants which would result in longer trial times and higher energy use. We expected participants under cognitive load to use more energy than participants not under cognitive load. Furthermore, we expected participants under cognitive load to use more time to reach their final temperature settings than participants not under cognitive load.

Method

Participants

A total of 90 participants participated in the experiment. Most of the participants were university students. Fifty seven participants were male and 33 participants were female. Participants were given €5,- as a compensation for their participation during 30 minutes.

Design

The study was conducted as a 3 (feedback type: light vs. factual vs. slider) by 2 (cognitive load: load vs. no load) by 10 (task number 1-10) between subjects design. Participants were randomly assigned to one of the six conditions.

Materials and Procedure

On arrival participants were welcomed by the experiment leader and requested to take a seat in front of the computer. The experiment leader then started the software program and set the participant number and condition, after which he left the room. The thermostat program was set up to mimic the Chronotherm Vision by HoneyWell (http://www.honeywellbv.nl), which is a central heating interface common in Dutch households (Figure 2). This program was also used to gather information about participants' energy consumption behavior while they set desired temperatures for six virtual rooms; the living room, kitchen, bathroom, toilet, hall and bed room.

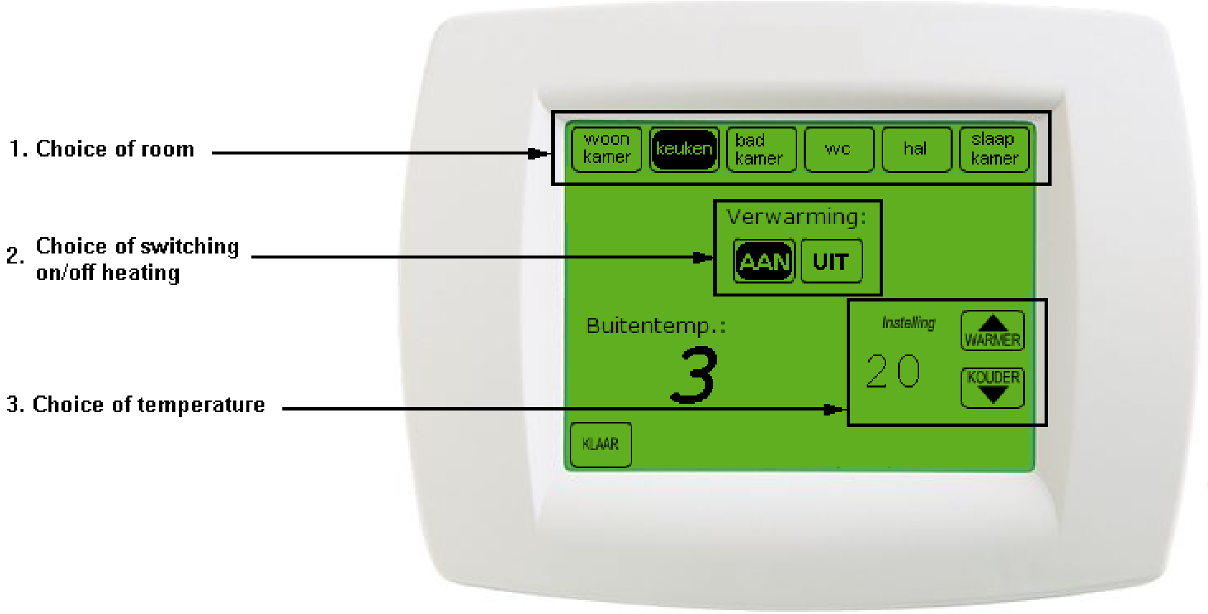


Figure 2: Thermostat interface. Picture of the thermostat interface as was used in the experiments.

First participants were presented a short introduction about the experiment and an explanation on how to program the thermostat. After that, two goals were triggered, namely:

1. Make sure to set a comfortable room temperature
2. Make sure to use as little energy as possible

Reasons for these goals are first to make participants aware of the trade-off between comfort and energy conservation, and did not just simply set all room temperatures extremely low to conserve energy, but to keep temperatures at levels they felt to be comfortable in rooms they believed comfort was of importance, all of this while using as little energy as possible.

Next participants were presented instructions about the type of feedback participants received, either factual or lighting or via the slider. *Numerical feedback* was the same as the one used in the research by Ham et al. (2009) (see Figure 3). First two numbers were given, one which represent high energy use and below that, one that represents low energy use. In the example shown in figure 3: High energy use: 2.328 Watt, Low energy use: 1.011 Watt. Than below these two numbers current energy use was given, in our example: Your energy use is 1.307,49 Watt.

Hoog energieverbruik: 2.328 Watt
Laag energieverbruik: 1.011 Watt

Uw energieverbruik is 1.307,49 Watt

Figure 3: Numerical feedback. Picture of numerical feedback display as was used in the experiments.

Lighting feedback was also the same as it was used in the research by Ham et al. (2009). A lamp that gradually changes color dependant on energy use was placed in near proximity of the thermostat monitor (see Figure 4). Low energy was given by bright saturated green and started becoming less saturated and turned light green to white as energy use increased to a middle point where the light was completely white. From there it went via an orange color to complete saturated red at maximum energy use.

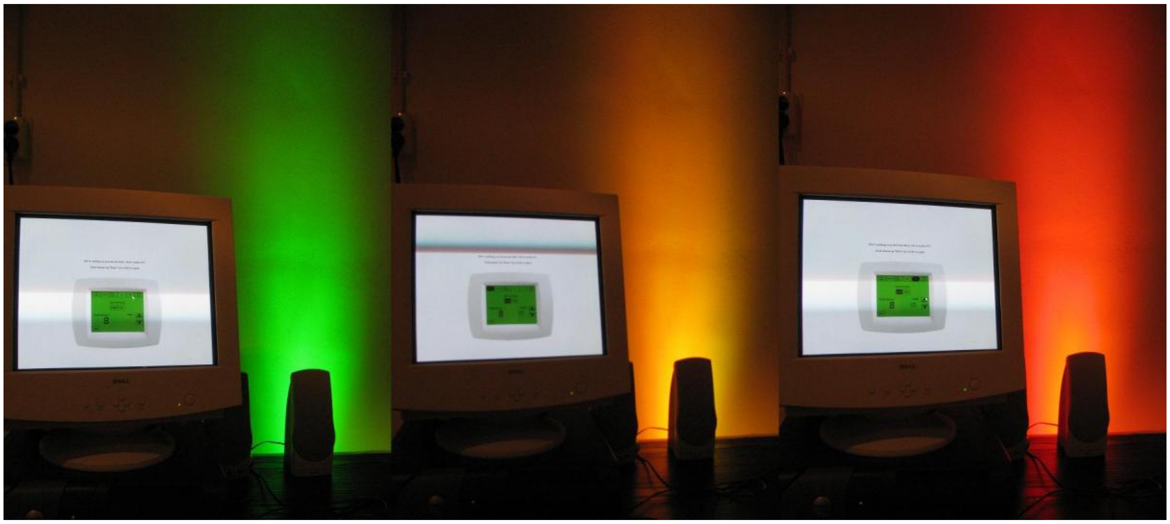


Figure 4: Lighting feedback. Picture of lighting feedback setup as was used during the experiments.

A new form of feedback that was added was the *slider feedback* (see Figure 5). The slider feedback placed energy use on a scale that could be easily viewed and thus made relative consumption visible at a glance. No numbers were added to the scale, only ‘High energy use’ at the top of the scale and ‘Low energy use’ at the bottom. It relieved participants of some of the cognitive load that is involved in the process of scaling and evaluating the numerical feedback. It did not have properties of the norm that is communicated by colors like red and green and it also requires focal attention.

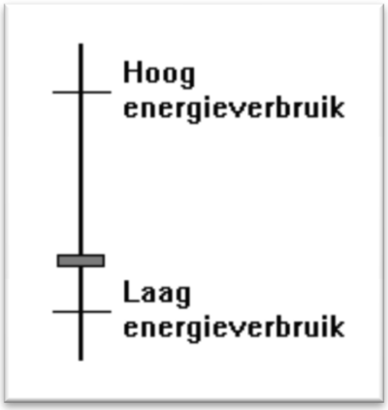
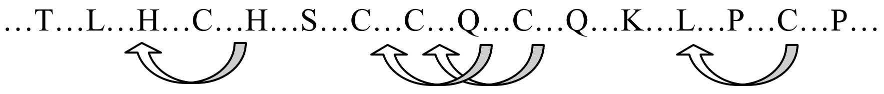


Figure 5: Slider feedback. Picture of slider feedback display as was used in the experiments.

Two practice trials followed the feedback instructions. The practice trails were similar to the experimental trails; participants were presented a scenario of the following sort “It is evening and you are at home, the outside temperature is 3^{o}C” , and they had to set the temperatures for the different rooms to a comfortable level while consuming as little energy as possible. Thereafter, people in the cognitive load condition were instructed on how to perform the memory task during the experiment, for which they also had some practice trails. The load task was a 2-back task as is commonly used in other research. Participants were presented a sequence of random letters read out aloud on headphones; their task was to indicate when the current letter read out matched the one from two steps ago by pressing the space bar. For example in this 2-back task:


…T…L…H…C…H…S…C…C…Q…C…Q…K…L…P…C…P…

Following this, ten scenarios were used for the experiment, with outside temperatures ranging from -5^{o}C to 19^{o}C and varying daily periods (see Appendix: scenarios for an overview of the ten scenarios that were used in the experiment). For every scenario a different upper and lower energy use boundary was calculated, these were used in the feedback (in Watts in the numerical feedback situation, as the respectively upper en lower part of the slider in the slider situation and as respectively saturated green and saturated red in the lighting situation). Roughly, when all rooms were heated at 22^{o}C, this indicated the upper boundary. When the thermostat was turned off in all rooms this represented the lower boundary, or in some scenarios with low outside temperatures the lower boundary was given by minimal heating settings. Appendix 1 shows the calculation of these reference values in more detail. A complete list of the scenarios can be found in Appendix 2.

After the 10 trails a number of questionnaires were presented to the participants. Participants answered various questions asking whether participants felt good or bad during the experiment, whether the feedback was boring or interesting, clear or unclear, to what agree the feedback influenced their behavior, and to what degree participants felt hampered by the cognitive load task in operating the control unit. Participants answered questionnaires on a 7-point Likert scale.

After the questionnaires, participants were debriefed, rewarded for their efforts and thanked for their participation. The experiment took 20 to 30 minutes.

Results

In the load task, participants had to press the space bar when they heard a letter that was the same as the letter they heard two back in the series. When doing so, the outcome could be one of four cases: a hit (they should have pressed the space bar and they did), a miss (they should have pressed the space bar and they did not), a false alarm (they should not have pressed the space bar but they did) and a correct rejection (they should not have pressed the space bar and they did not). Correct responses were a hit and a correct rejection, incorrect responses were a miss and a false alarm. A manipulation check of our load task indicates that 74,9% of all responses were correct, that is 22,8% were hits and 52,1% were correct rejections. Average load task performance scores are presented in Table 1.

Table 1

Avarage Load Task Performance Scores

	Response		
Stimulus	True	False	Total
True	Hit	Miss	
	(22,8%)	(22,4%)	(45,2%)
False	False Alarm	Correct Rejection	
	(2,7%)	(52,1%)	(54,8%)

Note. Score percentages are presented between brackets. *N* = 90.

Participants scoring less than two thirds of all trials correct on the load task were excluded from analysis. For the final analysis 85 participants were included, and 5 participants were excluded for load task scores lower than 66%, we thus excluded about 6% of the participants.

There were no significant differences between Energy Use scores in between different feedback forms, *F* < 1. Mean Energy Consumption scores are presented in table 2. We expected that participants receiving lighting feedback would use the least energy and participants receiving numerical feedback the most. This was not the case. We also checked average energy consumption scores at pre-set cutoff points in time. Analyzing the data at preset cutoff points of 30 and 40 seconds resulted in no significant interaction effects, *F*'s < 1.

Table 2

Mean Energy Consumption Scores (kWh) (and Standard Deviations) by Feedback Type and Cognitive Load

	Feedback Type		
Description	Numerical	Slider	Lighting
No Load	586	625	579
	(96)	(205)	(185)
Load	587	536	418
	(233)	(239)	(154)

Note. Standard deviations are presented between brackets; *N* = 85.

Furthermore, no significant differences between Time Use scores in between different feedback forms were found, $F < 1$. Mean time scores are presented in Table 3. We expected that participants that received lighting feedback would use the least time and participants that received numerical feedback the most. This was also not the case.

Table 3

Mean Time Used Scores (s) (and Standard Deviations) by Feedback Type and Cognitive Load

	Feedback Type		
Description	Numerical	Slider	Lighting
No Load	30,89	30,64	32,08
	(8,79)	(11,75)	(13,41)
Load	37,58	35,23	38,03
	(10,19)	(12,76)	(9,40)

Note. Standard deviations are presented between brackets; $N = 85$.

Average Energy Consumption scores were submitted to a 3 (feedback type: lighting vs. numerical vs. slider) x 2 (load: load vs. no load) x 10 (task number 1-10) Manova, in which task number was manipulated within participants. In contrast to expectations, no interaction effect between load en type of feedback for the dependant variable Energy Use was found, $F(2, 79) = 1.24$, $p = 0.294$. Again we tested for Energy Use at the preset cutoff points in time of 30 and 40 seconds and found no effects of Type of Feedback, $F < 1$. In Figure 6 the effects of load on energy consumption are illustrated.

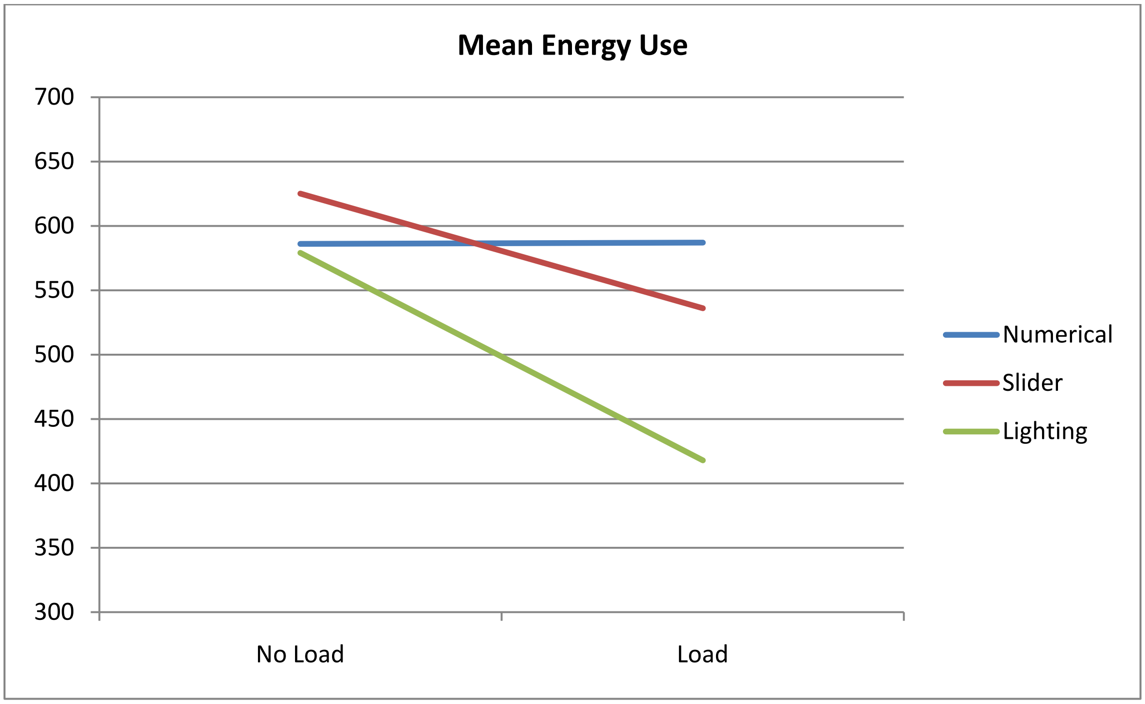


Figure 6: Mean energy use scores. Graph illustrating mean energy scores for different forms of feedback and the effect that added cognitive load has on these scores.

Average Time Used scores were also submitted to a 3 (feedback type: lighting vs. numerical vs. slider) x 2 (load: load vs. no load) x 10 (task number. 1-10) Manova, in which task number was manipulated within participants. We expected that there is an interaction effect between load en type of feedback for the dependant variable Time Use, this interaction effect was not found, *F*(2, 79) = 0,065, *p* = 0,937.

We also expected that participants under load would use more energy than participants not under load. There seems to be a marginally significant effect of load on Energy Use. Participants in the load condition (*M* = 514, *SD* = 222) used less energy than participants in the no load condition (*M* = 596, *SD* = 165), *F*(1, 79) = 3,89, *p* = 0,052. Mean energy scores for load conditions are illustrated in Figure 7, left chart. This effect is in the opposite direction of what we predicted, which we will further explain in the discussion.

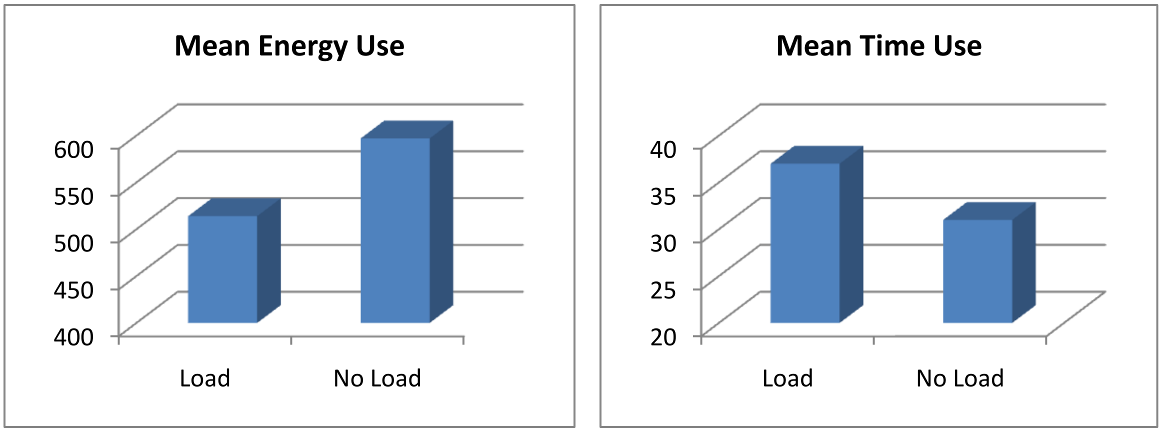


Figure 7: Mean energy and time charts for load manipulation. Left chart illustrates mean energy scores for Load and No Load condition, right chart illustrates Time scores for these same conditions.

In confirmation of our expectations, which were that participants under load use more time than participants under no load, participants under load used more time (*M* = 36,90, *SD* = 10,75) than participants under no load (*M* = 31,22, *SD* = 11,22), indicated by a main effect on time, *F*(1, 79) = 5,490, *p* = 0,022. Mean time scores for load conditions are illustrated in Figure 7, right chart.

Conclusion & discussion

In this study we focused on feedback mechanisms intervening in human-technology interaction to stimulate energy efficient behavior when operating a simulated thermostat by using different forms of interactive feedback to inform participants on their current energy use during this interaction. The use of feedback through ambient persuasive technology has proven to be effective in earlier research by Ham et al. (2009), and we described in our research three main reasons we feel to be responsible for the effectiveness of lighting feedback as opposed to antecedent feedback mechanisms like numerical feedback. We aimed to gain more insight into the validity of these reasons. Also, research by Ham et al. (2009) had some notable findings. We attempted to replicate their research, clarify some uncertainty in their findings and add some thought or our own. We used a lamp that gradually changed color dependent on energy use as a feedback mechanism and compared it to numerical feedback and feedback given on a slider. The latter with the intention to further investigate some advantageous properties of lighting. In a laboratory setting participants had to operate a thermostat to set room temperatures in such a manner that they were comfortable and used as little energy as possible. Energy and time data was recorded.

Expectations

Expectations were that lighting would have more persuasive power than the slider feedback, which in turn was expected to have more persuasive power than numerical feedback. This could be measured by higher energy consumption and longer times to program the thermostat as persuasive power decreases. We also expected that lighting feedback was easiest to process and numerical feedback the hardest. This could be measured by an increase in energy use and time needed in cognitive load conditions as opposed to no cognitive load conditions for numerical feedback, a smaller difference between load conditions in the slider feedback condition, and the smallest difference between load conditions in the lighting feedback condition.

Type of Feedback

In research by Ham et al. (2009), participants used less energy when receiving feedback through ambient lighting as opposed to numerical feedback. Also, participants on average needed more time to program the thermostat control unit in the numerical feedback condition than they did in the lighting feedback condition. We failed to replicate these findings to the extent that we did not find significant differences in energy use and time use between different forms of feedback in our research. The lack of this main effect indicates we were not able to confirm the persuasive power of lighting feedback to the extent that Ham et al. (2009) did. Reasons for this can be both as complicated as they are divers. It could be because of our experimental setup which we will further explain in the next paragraph.

Cognitive Load

We found a marginally significant effect of cognitive load on overall energy use, where participants under cognitive load used less energy than participants not under load. This is contrary of our expectations, as we expected participants under load to use more energy as they would have less cognitive capacity to progress the feedback. This could result in a deviation away from the goal to use as little energy as possible and get the participants to be more selfish to the extent that they would set higher room temperatures.

A first explanation for our reverse effect is that the load task was more difficult than we anticipated, and participants abandoned both goals (set comfortable room temperatures and use as little energy possible while doing so) and to put all their effort in the load task performance, and hopefully adjust some thermostat settings while doing so, but without too much thinking because all their cognitive power was focused on the load task. When we look at the performance data from the cognitive load task, we see participants performed reasonably well on the task. In 74.9% of all cases participants pressed the space bar when they should have. A large portion of this percentage can be ascribed to correct rejection which is not pressing the space bar in case of no signal. Even if a participant did not press the space bar at all, they would still score this percentage of correct rejections. However, when we look at all the times participant did press the space bar, they pressed right in 89.4% scoring a hit, and were wrong in 11.6% of the time scoring a false alarm. We conclude from that, that participants performed well on the load task. Feedback from participants after the experiments suggests the load task had high cognitive load, and many participants indicated they focused primarily on performing the load task and not so much on setting the thermostat. When we look at the experimental setup and keep in mind the difficulty of the load task, our results might be explained. The experiment was designed in such a manner that starting conditions for heating settings were ‘off’. Participants could adjust the heating from zero upwards to a desired temperature, and this process might be hampered by the large cognitive load resulting in lower energy scores. A recommendation for future research is to vary the initial startup temperatures of the thermostat randomly in such a manner that in about half the cases the starting conditions for heating settings are maximal (for example 30 degrees centigrade).

In these cases participant will have to adjust thermostat settings from maximum heating setting downwards to a desired temperature. By doing this bottom and ceiling effect could even each other out and the real effect of load on goal priority could become more visible.

There was a significant effect of load on time used to program the thermostat, as was in the research by Ham et al. (2009). It seems obvious that the reason for this is that participants needed the extra time to process the load task. This proves our load task was indeed chosen correctly.

Interaction: Type of Feedback and Cognitive Load

We did not find an interaction effect of Cognitive Load on Type of Feedback for either Energy Use or Time Used. In the experiment by Ham et al. (2009) this effect did occur, and criticism to this effect was that the load task consisted of numbers as did the factual feedback. Therefore load interfered with factual feedback and did not interfere with lighting feedback. In our experiment we took a load task that consisted of letters, so it did not interfere with the numerical feedback in the factual feedback situation. A closer look at some theory might shed more light on this effect. According to Cognitive Load Theory (Sweller, 1988), an increase in cognitive load stems from an increase of information processed by the working memory. This becomes especially profound when people are performing complex tasks like programming the thermostat in our experiment. Since feedback will be processed by working memory, feedback increases cognitive load, at least to some extent. Baddeley's model of working memory (Baddeley, 2007) describes the fundamental components of the working memory. It discriminates between an executive function as a supervisory system and two domain-specific subsystems, the phonological loop (PL), which deals with phonological information (audio), and the visuospatial sketchpad (VSSP), which deals with visual information (imagery and location). According to this model, a certain amount of phonological information or visual information brings about a certain load on the subsystems' memory span, which is more or less equal to the load on working memory when both types of information are combined (Baddeley & Della Sala, 1996). In other words, PL and VSSP can work in parallel.

One could thus argue that not all increase in load on the working memory is equal. The amount of load certain information has on the working memory is dependent on the category of this information (PL vs. VSSP). It is important to make this distinction clear, but also to understand what types of information are considered phonological and visual. When words, letters, numbers, etc. are presented visually, they can be silently articulated and thus remembered as auditory information through the PL. It thus seems that both numerical and literal information provide phonological load, whether they are presented visually or auditory. Following this train of thought we can see that factual feedback given in numbers placed load on the PL. What about the perception of color? Ikeda & Osaka (2006) investigated brain activity in people remembering colors in a 2-back task. They conclude that colors across the border of hue categories, defined by basic color names, strongly activate the left inferior frontal gyrus of the brain. This is the area responsible for auditory working memory. Since our feedback is given in two distinct colors (red and green), we conclude that the lighting feedback will have a strong effect on the PL. However, there is also a distinction of colors within the borders of hue categories;

differences in color saturation. These activate the right hemisphere, indicating VSSP processing. Thus, both factual feedback and lighting feedback will have an effect on the PL, but lighting feedback has a smaller effect on the PL combined with a small effect on the VSSP. Looking at the thermostat programming task, one can see that it mostly consists of number processing and setting temperatures (numerical). Most load on working memory during this task will be on the PL. Since the main task places great load on the PL, both feedback mechanisms place some load on the PL, and the load task placed load on the PL, the increased programming time in the lighting situation could be the result of lighting feedback in itself providing less load than the factual feedback. For future research, it could be of interest to use a cognitive load task that places load on the VSSP, this could be something like a navigational task.

Another possible explanation might be found in automated vs. controlled processes theory. This theory implies that automated processes are lower order perceptual processes that occur without conscious thinking. Controlled processes occur deliberate and conscious; they are higher order inferential processes that require cognitive reasoning. Gilbert, Pelham, & Krull (1988) argue that adding a cognitive load task will interfere with controlled processes but not with automated processes. When people are under high cognitive load, processing of controlled information suffers. According to this theory, factual feedback processing suffers under high cognitive load and lighting feedback processing does not suffer under high cognitive load, since lighting feedback can be processed without conscious awareness (Nijënstijn, 2009). Above described are two theoretical explanations for the effect of the load task.

Final Thoughts

Conserving energy is of global interest and viewed upon from multiple perspectives throughout the research community. During our research we have seen an integration of psychological and technological means to arrive at new ways to profit from technology's ability to promote conservation behavior. Current and future technology allows for new and promising ways to intervene in user-system interaction, which prove to be highly efficient, as was shown in for example research by Ham et al. (2009). With current research we aimed to gain more insight into the workings of ambient persuasive technology and its effectiveness. We also hoped to contribute to this field of research. We feel we did so, even though many of our expectations were not found in the results. Shedding some light on persuasive technology was our main goal, future research might enlighten it some more.

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Appendix: Scenarios

Table

Different scenarios that were used during the experiments.

Scenario number	Description
Practice	It is evening and you are at home. It is 3°C outside.
Practice	It is afternoon and you are not at home. It is 20°C outside.
1	It is in the morning and you are at home. The outside temperature is -5 °C.
2	It is in the morning and you are at home. The outside temperature is 15 °C.
3	It is in the afternoon and you are not at home. The outside temperature is 8 °C.
4	It is Sunday in the afternoon and you are at home. The outside temperature is 19 °C.
5	It is in the afternoon and you are not at home. The outside temperature is 18 °C.
6	It is in the evening and you are at home. The outside temperature is 6 °C.
7	It is in the evening and you are at home. The outside temperature is 17 °C.
8	It is in the evening and you are given a party at your place this evening.
9	It is at night and you are in bed. The outside temperature is -1 °C.
10	It is at night and you are in bed. The outside temperature is 14 °C.

Note. The experiment was in Dutch, the descriptions are translated into English for the purpose of this paper.