Domestic Energy Displays: An Empirical Investigation

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ABSTRACT

We conducted two studies to explore how domestic energy information displays relate to a consumer’s energy awareness and behavior. First, we investigated the impact of a simple energy feedback system, both stationary and portable versions, on household energy awareness and consumption. In analyzing the results of that study, we saw an opportunity to better define a consumer’s energy awareness and examine. Second, we investigated how energy awareness interacts with the level of spatial and temporal information in an energy display in a more controlled manner with fifty-nine participants in both the USA and South Korea. Our findings from these two studies reveal how properties of energy information displays (e.g., portability, spatial and temporal resolution) encourage investigation of energy consumption patterns in the home. Specifically: 1) Portability supports real-time investigation, at least initially, and encourages energy detective behaviors that can result in real reduction of consumption. 2) The sophistication of an individual’s understanding of home energy consumption is important to consider when deciding what kind of information will be most useful. Simpler displays helped self-identified low-awareness user conserve energy, but were not helpful for energy high-awareness users. 3) There is a simple and effective way to determine whether an individual has high-awareness or low-awareness. 4) High-awareness users prefer spatially diverse information, whereas low-awareness users prefer temporally diverse information. This has very concrete implications on the adoption of existing home energy displays as well as the design of future displays.

Introduction

The seminal Twin Rivers empirical study of energy consumption in 1970 demonstrated that human behavior plays a critical role in energy conservation (Socolow, 1978). Although energy reduction can be realized automatically through advanced technologies and public control, the Twin Rivers study showed that even in identical physical environments, variations among individuals could lead to increased consumption by as much as two-fold. According to a 2007 telephone survey of 10,000 consumers in ten European countries, 80% of consumers were worried about climate change (Logica, 2007). However, the report found a gap between the attitude and the behavior of consumers with respect to energy savings. Despite interest in energy savings, not enough information was available for consumers to take appropriate actions toward energy savings (Logica, 2007). This motivates a lot of the research in how domestic information systems can influence energy consumption behaviors (Holmes, 2007; L. T. McCalley & Midden, 2002; McCalley, 2006).

In this paper, we explore how mobile energy information displays relate to a consumer's energy awareness and behavior. Specifically, we report the results of a small field study that aimed to reveal how the mobility of a simple energy information display impacted behavior. In analyzing the results of that study, we saw an opportunity to better define a consumer's energy awareness and examine, in a more controlled manner, how that awareness interacts with the level of spatial and temporal information in a mobile energy display. We report a second, controlled study conducted in the USA and South Korea that examines this relationship between energy awareness and energy display information.

Our findings from these two studies reveal how properties of energy information displays (e.g., mobility, spatial and temporal resolution) encourage investigation of energy consumption patterns in the home. Specifically: 1) Portability supports real-time investigation, at least initially, and encourages energy detective behaviors that can result in real reduction of consumption. 2) The sophistication of an individual's understanding of home energy consumption is important to consider when deciding what kind of information will be most useful. Simpler displays helped self-identified low- awareness user conserve energy, but were not helpful for energy high-awareness users. 3) There is a simple and effective way to determine whether an individual has high-awareness or low- awareness. 4) High-awareness users prefer spatially diverse information, whereas low-awareness users prefer temporally diverse information. This has very concrete implications on the adoption of existing home energy displays as well as the design of future displays.

Related Work

Many researchers became interested in understanding what a role the technology plays in influencing the behaviors that impact domestic energy consumption (Fitzpatrick & Smith, 2009). To bridge the gap between the attitude and the behavior, many studies investigated providing some form of feedback to users so that they can control energy consumption and save energy. The definition of feedback is "the transmission of evaluative or corrective information about an action, event, or process to the original or controlling source" ("feedback - Definition from the Merriam-Webster Online Dictionary," 2009). Providing direct, continuous consumption feedback reduces household energy use more effectively than providing either generic information about energy conservation or periodic feedback in the form of a bill (Fischer, 2008). Two meta-reviews about energy feedback found that energy feedback may improve energy savings by up to 20% (Darby, 2006; Fischer, 2008). One meta-review described effective feedback as being real-time, clearly and simply presented, and customized (Fischer, 2008). Several commercial solutions for real-time domestic energy monitoring have become popular as diagnostic tools for appliances (e.g., The Energy Detective (TED), Wattson, Kill A Watt, and Watts Up?) and for collaboratively managing power use with the electric company (e.g., Landis+Gyr, http://www.landisgyr.com/).

Empirical studies have focused on appliance-level energy feedback systems, which provide real- time information about energy consumption (Ueno et al. 2006). While this approach has shown great promise, it assumes a world of distributed, intelligent appliances that may never be available or affordable to the masses. Fischer emphasizes that failure to meet technological preconditions has stunted the development of useful feedback systems (Fischer, 2008). Wood and Newborough suggested that a household-level display unit placed inside the home might offer the best value in terms of practicality and comprehensiveness (Wood & Newborough, 2007b). Many studies analyze real-time energy feedback displays. However, few studies and few commercial systems have explicitly explored a rationale for energy feedback design and the relationship between energy feedback and energy knowledge or energy awareness of a user. Research into environmental behavior change supports the notion that the technology component will encourage an individual to gain knowledge and maintain or change behaviors that lead to better energy management (Hungerford & Volk, 1990). In a discussion of environmental behavior change, Hines et al. mention, “It appears that intention to act is merely an artifact of a number of other variables acting in combination (e.g, cognitive knowledge, cognitive skills, and personality factors.) Before an individual can intentionally act on a particular environmental problem, that individual must be cognizant of the existence of an issue. Thus, knowledge of an issue appears to be a prerequisite to action. An individual must also possess knowledge of those courses of action which are available and which will be most effective in a given situation. Another critical component is skill in appropriately applying this knowledge to a given issue.” (Hines et al. 1987) Thus, the design of energy feedback systems might rely on individual cognitive knowledge, cognitive skills, or personality factor. However, it is not clear how individual factors, specifically individual energy awareness, affect the design of energy feedback systems.

Our studies complement these previous studies by investigating individual energy awareness and information sets on energy feedback systems. Our studies produced two primary contributions: our empirical approach gathered information about the user experience of simple mobile energy feedback systems, and our second experiment can inform other researchers who intend to build similar mobile energy feedback systems.

The First Study: An Exploratory of Simple Energy Display Use

We present the results from the initial study where we deployed our simple energy feedback system across eight households for three weeks. The purpose of the first study is to investigate how a simple energy feedback system affected self-reported energy awareness and consumption. The second goal was to develop a qualitative understanding of the experience that each participant had using the portable or stationary energy feedback system. Our findings are 1) an indication that users may not fully use the portability of a device after initial survey period, after which users tend to use the feedback display as a stationary device and 2) simple “whole home” feedback devices may provide more usable information to self-reported low-awareness users, while this may not be true for the high-awareness user.

Prototype Overview

We developed portable and stationary versions of an energy feedback system to display a bar graph of the real-time energy consumption information received wirelessly from the power breaker of a house. The stationary device is plugged into a household outlet, while the portable device is battery operated so that it can be carried anywhere in the home.

The energy feedback system shows a simple representation of current energy use as a single bar graph implemented with four light-emitting diode (LED) lights. The system can display consumption between 0 and 4,096 Watts (W), representing typical appliance power levels (“Electric Power Annual Data Tables,” 2009). Each of the four LEDs has 256 levels of brightness, in which one level of brightness represents 4W of power. If total usage exceeds the maximum range of the display (4,096W), the entire LED bar begins to blink. The measuring device was attached to the home power breaker using an AC current transformer.

Method

We describe the three-week deployment of the stationary and portable energy feedback systems in eight households (two households have two participants who each had a portable energy feedback system). We recruited ten participants representing eight households in a large metropolitan city and the surrounding suburbs. The demographics of our participants and the households they represent are average age 32 (2 Females). Five participants were randomly selected to receive stationary energy feedback systems (placed in a location of their choice) and five were given portable energy feedback systems. After the three-week deployment, participants were compensated with a $20 gift card to a retail store.

Discussion and Design Implications of the First Study

Portability supports investigation, up to a point. Wood and Newborough suggested that providing a portable energy feedback system may encourage users to use it “as a diagnostic tool” for high-consumption (Wood & Newborough, 2007a). Though the portable energy feedback systems in our study better supported household-wide activity, we found that users experimented with both stationary and portable energy feedback systems to discover high-consumption devices. We also found that after the initial survey of the home, the portable energy feedback systems were used like stationary ones. Thus, a hybrid approach of portable energy feedback systems that can dock to stationary bases may be promising (e.g., a magnetic portable energy feedback system attaching to the refrigerator becomes a stationary energy feedback system).

Energy awareness impacts energy savings. Interestingly, the energy reduction of self-identified “low energy awareness” individuals was higher than “high energy awareness” individuals. It is appropriate to question our method of determining the level of energy awareness. We simply asked individuals to rate themselves on a scale of 1 (don’t know very well) to 7 (know very well) what they considered their level of understanding of energy consumption at their house. There is a body of research that supports a link between initial awareness or knowledge of a concept (such as energy consumption) and behavior modification coupled with feedback (Abrahamse et al. 2005; Wilson & Dowlatabadi, 2007). The preliminary results of this initial field study suggest we should explore a more hypothesis-driven and controlled study to determine if such a simple self-reporting scale can effectively differentiate a novice (lower energy awareness) from an expert (higher energy awareness). If we can, then the results of this field study suggest a novice would only require relatively simple energy feedback to impact a positive behavior change, but an expert would require more detailed information.

In order to conduct such a study, we must clarify the concept of energy awareness. In general, energy awareness involves understanding: 1) how much energy we use, both directly and indirectly; 2) what we actually use energy for; 3) where the energy comes from; 4) what side effects result from our use of energy; and 5) what we can do to reduce energy consumption (Wilson & Dowlatabadi, 2007). Domestic energy feedback systems designed to promote conservation do not need users to gain a broad awareness of energy consumption. The more parochial goal of the feedback system is to save energy in the user’s own home. Thus, our specific concerns about energy awareness reduce to understanding the various items that consume energy (e.g., HVAC, lighting, refrigerator) and the relative ranking of those items based on energy consumption. The challenge we explore in our second study is whether we can develop a reliable, yet simple way to classify energy awareness into two meaningful categories of novice and expert.

The Second Study 2: Energy Awareness and Information

When considering some commercial domestic energy displays, we can differentiate them based on the type of spatial and temporal information they reveal. Spatially, information can range from appliance-specific to whole-house aggregate, with intermediate levels, such as room-based. Temporal presentation can range from current, or real-time, information to historical aggregation of past consumption or predictions of future information. Table 1 shows how four different commercial products vary along those spatial and temporal dimensions.

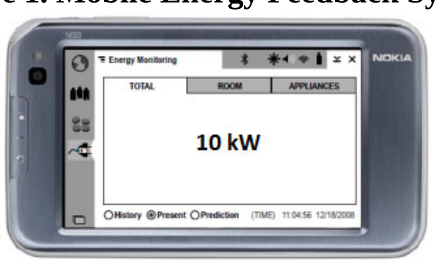
Table 1. Spatial and Temporal Information Provided by Current Commercial Energy Feedback Systems

		Total	Room	Appliance
Wattson: †				
Kill A Watt: ‡	Current	○, †		•, ‡
Watts Up?: •	History	○, †		•, ‡
TED: ○	Prediction	○		•

The purpose of this second study is to explore the relationship between self-reported energy awareness and the value of different temporal and spatial information. We begin with two hypotheses:

- Hypothesis 1) An individual who self-reports a low energy awareness, an energy novice, will perform worse on both spatial and temporal energy consumption tasks when compared to an energy expert, who self-reports a high energy awareness.
- Hypothesis 2) A self-reported energy novice will show different preferences for spatial and temporal energy feedback as compared against a self-reported energy expert.

Figure 1. Mobile Energy Feedback System



We designed a mobile energy feedback system, shown in Figure 1, which could be configured to reveal different levels of spatial and temporal energy feedback. We implemented the energy display on a touch-screen Nokia N810 Internet pad, which has a 4.13” WVGA (800 by 480 pixel) display. This includes three spatial (total, room-level, and appliance-level) and three temporal (history, present, and prediction) information levels. The prototype mobile energy feedback system has numeric and graphical representations, but we used only numeric representations to exclude the effect of representation in this study.

Method

Participants. We recruited 59 participants over the age of 18 from two different countries. We recruited two pools of participants: 36 participants in South Korea and 23 participants in the USA. All participants were students, researchers, family members or acquaintances of the research team. The ages of participants ranged from 25 to 57 years old. Participants included 22 females and 14 males with an average age of 32.4 years in South Korea, 12 females and 11 males with an average age of 28.5 years in the USA. 21 out of 36 in South Korea and 18 out of 23 in the USA were responsible for paying the energy bill in their home. Participants were not compensated.

Experimental environment. In both experimental environments (the USA and South Korea), we configured a laboratory to model a typical household. We populated the laboratory with different appliances that might be found in a typical home, and labeled physical regions as Kitchen, Bedroom, or Living Room since these are just label as common spatial divisions in the home. The kitchen contained a desktop computer and an LCD monitor. The living room contained a standing lamp and an LCD television, and the bedroom contained a cellular phone plugged into a charger.

Live energy consumption data was gathered from "Watts Up?" power meters plugged into each appliance and connected to a laptop computer via USB. The laptop ran a server that filtered, aggregated, and transmitted the data to the mobile device via a wireless network.

Procedure. Participants were initially told that the study was about a general mobile energy feedback design. Our experiments usually took 40-80 minutes per participant, and were separated into three stages.

Assessing energy awareness. We began with a series of questions aimed at assessing energy awareness. Participants were asked to rate what they considered their level of understanding of energy consumption in their home, using the same 7-point Likert scale as was done in Study 1 described above.

Participants then completed an Energy IQ test that included seven questions excerpted from the NEETF (The National Environmental Education & Training Foundation, 2002). We also asked participants to select which of the following three groups best described them:

- Group 1 (Simple awareness): knowing that a topic exists and is important but unfamiliar with its complexities and little relationship to personal change or action.
- Group 2 (Personal conduct knowledge): understanding of a class of environmental subjects that are simply and easily grasped, such as energy shortages, water shortages, and solid waste disposal problems, that lend themselves to changes in personal conduct but that do not require detailed comprehension.
- Group 3 (Environmental Literacy): the outcome of a sound program of environmental education through which the learner progresses from deep knowledge, to skill, to actual field application. These group definitions were taken from another NEETF report (Coyle, 2005).

Finally, participants were shown the experimental home lab setup and asked to: 1) rank each appliance in the experimental setup according to their estimation about energy consumption from greatest to least consumption when each appliance is turned on; 2) rank each room according to their estimation about energy consumption when each appliance is turned on; and 3) estimate total energy consumption at the present time, assuming every appliance was turned on. This ranking exercise was repeated at then end of the experiment to compare against this initial baseline performance.

Benchmark tasks. Participants were grouped by the research team into two categories. The first category, energy novices, were those who classified themselves as having "Simple Awareness," based on the NEETF definition given above (N=28). The second category, energy experts (N=27), was those who classified themselves as having either "Personal conduct knowledge" or "Environmental literacy." Novices and experts were then randomly assigned to one of three interface groups (low, medium, and high information), which had different combinations of spatial and temporal information available, as described in Table 2.

Table 2. Information Groups

Low Info: †
Medium Info: ‡
High Info: •

	Total	Room	Appliance
Current	†,‡,•	‡,•	•
History	‡,•	‡,•	•
Prediction	•	•	•

Participants were given nine tasks to complete via our mobile energy feedback system. They could interact with the appliances to observe real-time feedback. We describe in the results section how we scored the performance on these benchmark tasks (e.g. Please find out the bedroom's estimated electricity consumption for following 31days)

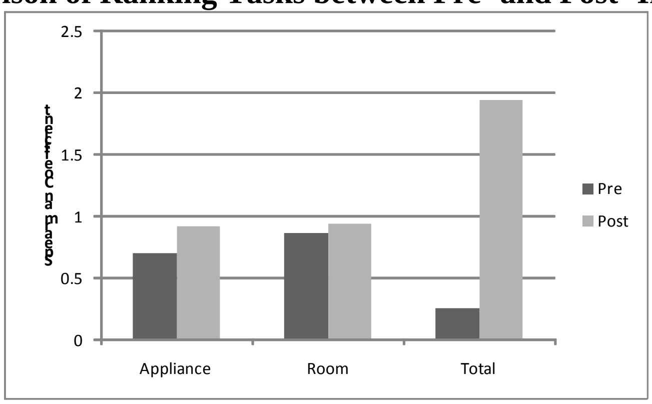
Post-interaction survey. This survey was designed to assess the user's reaction to the mobile energy feedback system, with a focus on preference of the spatial and temporal data presentations and their reactions to sharing energy consumption with others. The survey included closed-format questions with written, open-ended follow-ups questions, where appropriate.

Results

Assessment of awareness. We used three different assessment methods for the energy awareness level concerning energy consumption. The 7-point self-reported Likert scale awareness showed a mean rating of 3.44, with std. dev. = 1.424 (N = 55). The self-classification into awareness groups resulted in a Novice group of 28 and an Expert group of 27 (18 as Personal conduct knowledge, 9 as Environmental literacy). The mean score on the Energy IQ test was 2.64, with a std. dev. = 1.365 in South Korea, and 2.05, with a std. dev. = 1.046 in the USA (max score = 7). We excluded four participants who had problems with the mobile feedback system for our analysis. We calculated Pearson correlation coefficients. The Energy IQ test was not correlated to the other two assessments, so we will ignore that data for the rest of this analysis and discussion. The reason of uncorrelation is that the IQ test is about general knowledge not about specific knowledge regarding home. Thus, for future work, we should look at specific questions regarding home environmental issues. The self-reported Likert scale and the self-selected Novice/Expert classification showed significant correlation across all 55 participants (ρ = .490 p < .001). However, when we calculated the coefficients by each country, self-reported Likert scale and self-selected groups were still correlated in the USA (ρ = .752, p < .001), but not in South Korea. Thus, we might use self-reported Likert scale or self-selected groups to assess the prior condition of energy awareness and to provide customized information groups in the USA. We believe that the localization of questions used for group determination rather than literal translation may have yielded an improved result.

Pre- and post-exercise ranking tasks. We calculated the Spearman Rank Order Correlation Coefficients (yielding a value ranging from -1 to 1) for the appliance and room ranking tasks (Spearman, 1987). We compared the Spearman coefficients for the two times the ranking tasks were performed by each participant. A third measure was the score on total consumption task. When participants calculated the total consumption for the experimental house setup, they received a score of 2. If they attempted to calculate the total consumption, but did not come up with the right value, they received a score of 1. Participants who did not attempt to calculate the total consumption received a score of 0.

Figure 2. Comparison of Ranking Tasks between Pre- and Post- Interaction Survey

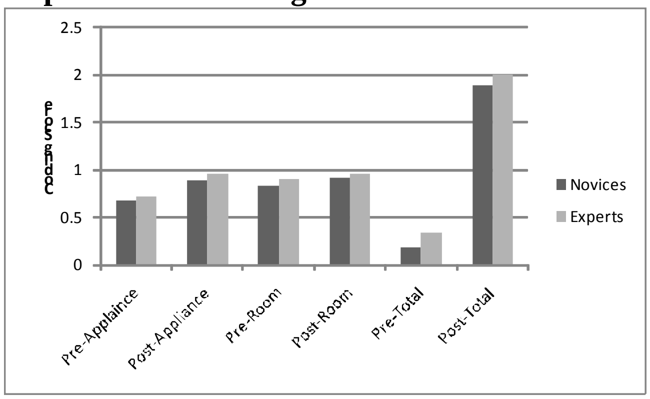


To compare the performance for each participant on the two times they performed these three ranking tasks, we conducted paired-samples t-tests (Figure 2). The performance of the ranking task for appliances ($t(54) = -5.807$, $p < .001$) and total consumption ($t(54) = -24.855$, $p < .001$) showed significant improvement after exposure to the energy feedback device, across all conditions. However, ranking rooms ($t(54) = -1.781$, $p = 0.081$) was not significantly improved. We attribute this result to the accuracy of participants' room-level rankings at all stages of the experiment.

We then divided the performance of the ranking tasks into assigned information groups. With low information and medium information (Table 2), only total consumption performance was significantly improved ($t(14) = -16.837$, $p < .001$ and $t(19) = -10.466$ $p <. 001$). On the other hand, both appliance and total consumption ranking performance were significantly improved with high information ($t(19) = -6.161$, $p < .001$, $t(19) = -27.606$, $p < .001$). Thus, providing room level information did not improve the understanding of energy consumption of rooms since participants already knew the relationship among rooms. However, if more appliances were present, the results may have differed.

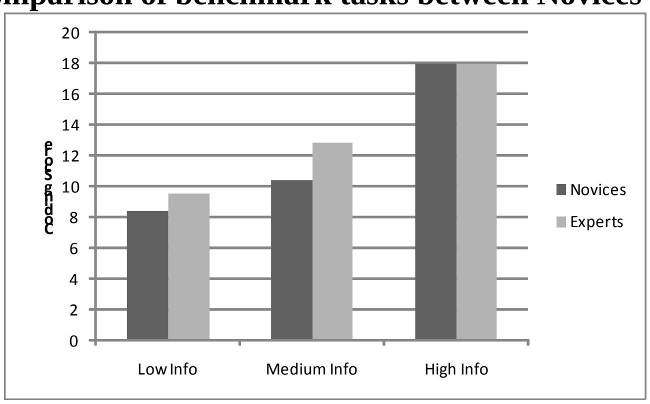
Ranking tasks in group selection. We also compared the results between Novices (N = 28) and Experts (N=27) (Figure 3). For ranking tasks performed before exposure to the mobile feedback system, Experts tended to have a higher score than Novices in the room ranking ($t(53) = -1.438$, $p = .157$), and the estimation of total consumption ($t(53) = -1.314$ $p = .195$). However, no significant difference exists in the appliance ranking ($t(53) = -.726$ $p = .472$). After using the mobile feedback system, Experts still tended to have higher scores than Novices in the appliance ranking ($t(53) = -1.545$ $p = .130$) and the estimation of total consumption ($t(53) = -1.337$ $p = .187$).

Figure 3. Comparison of Ranking Tasks between Novices and Experts



Group selection affect the performance of benchmark tasks. When participants completed any of the 9 benchmark tasks with the correct answer, we coded a 2. When participants attempted a benchmark task but ended up with the wrong answer, we coded a 1. When participants did not have any answer on a task, we coded a 0. We then summed across all nine tasks to derive a total score on the benchmark task section of the study.

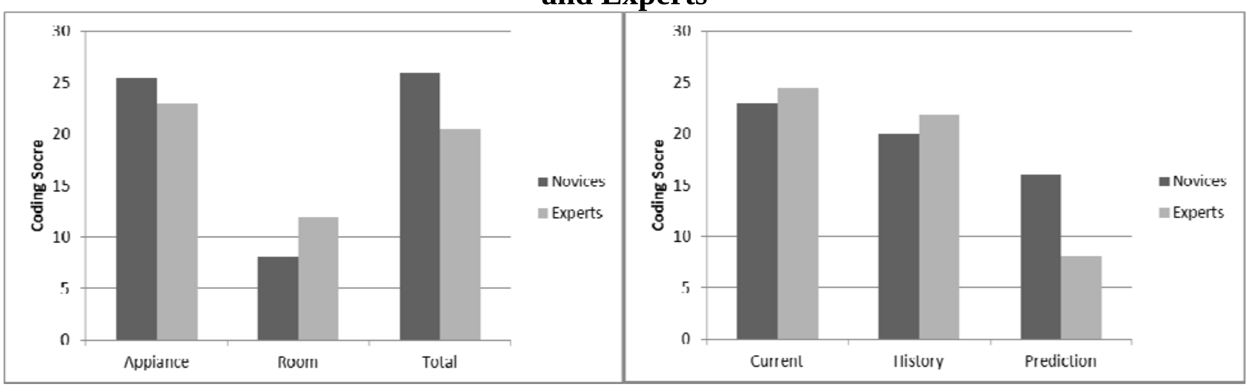
Figure 4. Comparison of benchmark tasks between Novices and Experts



We used an independent samples t-test to compare the performance on benchmark tasks between Novices and Experts for the different interface conditions (Figure 4). The difference in performance was significant in medium information between Novices and Experts ($t(18) = -2.773$, $p < .01$). The difference in performance was not significant in low information between Novices and Experts ($t(13) = -.681$, $p = .508$). With high information interface, we observed a ceiling effect for tasks completion because all groups could easily access all information by just clicking the buttons on the mobile energy feedback system. In other words, every benchmark task was directly answerable by information accessible in the high information interface, and every participant found that information.

Preference of information set. We provided 9 different information conditions, based on three spatial and three temporal levels. We asked each participant to assign "Useful" (10), "Not useful" (-10), and "Don't know" (0) to each of nine information sets, based on their limited experience with the benchmark tasks. Overall, participants preferred whole household and appliance-level information over room-level information ($F(2, 162) = 14.536$ $p < .001$) because participants probably know the relationship among rooms, and current or historical information over future predictions ($F(2, 162) = 9.137$ $p < .001$) because they did not trust prediction algorithms. However, we found significant difference of spatial preference in Novices ($F(2,81) = 11.271$, $p <. 001$), but no significant difference for Experts ($F(2,78) = 4.003$ $p = .022$) (Figure 5). This results show Novices might prefer appliance and room-level information, but Experts might need all information in terms of spatial information.

Figure 5. Comparison of Preference of Spatial and Temporal Information between Novices and Experts



When we examined the preference of temporal information sets in Novices, we found no significant difference between options (Figure 5). For Experts, however, prediction was significantly less preferred compared to historical and current information ($F(2,78) = 6.624$, $p < .001$). Experts indicated a lack of trust in the prediction algorithm to calculate projected energy consumption.

Design Implications

The results on the ranking tasks (both before and after exposure to the energy feedback display) and the benchmark tasks are very important for our study. What they indicate is that those who classified themselves as Experts actually performed better than those who classified themselves as Novice. In other words, the Experts really were more proficient at doing these ranking exercises. The simple act of self-identifying into one of three groups as defined by NEETF is enough to determine whether we should treat someone as a novice or expert with respect to energy consumption awareness in their own home. For the 7-point Likert scale, a self-rating of 1 or 2 would be classified as a Novice and 3 or higher as an Expert.

Why did experts perform better than novices? Our observations showed that experts tended to look at additional information than what we provided. For example, they looked at information tags attached to the appliances to rank and calculate energy consumption. No one in the Novices group checked these tags, which are not obviously displayed.

We are looking back to our hypothesis:

- Hypothesis 1) Knowing that a simple self-classification is sufficient to identify energy novices from experts, our results supported our first hypothesis on performance. The only exception was with the ceiling effect in the high information interface, where our benchmark tasks were not complicated enough to show any distinction.
- Hypothesis 2) Our results show that novices tended to prefer appliance and total-level temporal information over room-level information, whereas experts tended to prefer current and history information over prediction in terms of spatial information. There are two design implications to extract from this. First, if we look at Table 1 for commercial energy displays, energy novices will prefer the TED and Watts Up? devices because of their ability to show predictions of consumption. Experts will likely not be swayed by those features of prediction.

More interestingly is when we consider the transition from novice to expert, as one becomes more familiar with personal energy consumption patterns. As our first field study suggests, novices will benefit from simple energy feedback, and experts will need more information in order to benefit. More detailed spatial information and historical and current utilization is desired, but not prediction. Our results are inconclusive with respect to the intermediate spatial resolution, most likely because we did not present a realistic room-level task.

Conclusion

We present the results of two studies of the use of domestic energy feedback systems. For the initial exploratory field study, portable and stationary versions of an energy feedback system were developed to display a bar graph of the real-time energy consumption information and then were deployed for three weeks in eight households. We found that mobility enhances awareness of energy consumption for an initial exploratory period and results in energy saving behavior for self-proclaimed energy novices. In the second study, which is hypothesis-driven controlled study, the relationship between self-reported energy awareness and the value of different temporal and spatial information was explored via designing mobile energy feedback system, which could be configured to reveal different levels of spatial and temporal energy feedback. The proposed system includes three spatial (total, room-level, and appliance-level) and three temporal (history, present, and prediction) information levels with numeric representations. Our first hypothesis is that an energy novice, who self-reports low energy awareness, would perform worse on both spatial and temporal energy consumption tasks. Our experiment based on the first hypothesis reveals that knowing a simple self-classification is sufficient to identify energy novices from experts. The second hypothesis is that a self-reported energy novice will show different preferences for spatial and temporal energy feedback. From the experiment for the second hypothesis, it turns out that novices tended to prefer appliance and total-level temporal information over room-level information, whereas experts tended to prefer current and history information over prediction in terms of spatial information. Therefore, our second study established a simple mechanism for allowing an individual to self-identify as an energy expert or novice with respect to their home energy consumption knowledge. This simple classification can now be used to determine what kind of temporal and spatial information is appropriate for an individual.

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