

Living with an Intelligent Thermostat: Advanced Control for Heating and Cooling Systems

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ABSTRACT

In order to better understand the opportunities and challenges of an intelligent system in the home, we studied the lived experience of a thermostat, the Nest. The Nest utilizes machine learning, sensing, and networking technology, as well as eco-feedback features. To date, we have conducted six interviews and one diary study. Our findings show that improved interfaces through web and mobile applications changed the interactions between users and their home system. Intelligibility and accuracy of the machine learning and sensing technology influenced the way participants perceive and adapt to the system. The convenient control over the system combined with limitations of the technology may have prevented the desired energy savings. These findings assert that thoughtful, continuous involvement from users is critical to the desired system performance and the success of interventions to promote sustainable choices. We suggest that an intelligent system in the home requires improved intelligibility and a better way in which users can provide deliberate input to the system.

Categories and Subject Descriptors

H.5.m. Information interfaces and presentation (e.g., HCI):
Miscellaneous.

General Terms

Human Factors

Keywords

Thermostat, User Control, Energy Saving, Digital Home

1. INTRODUCTION

With advances in computing, networking and sensing technology, our everyday objects at home become more automated, connected, and intelligent. For digital home technology, the focus has been comfort, convenience and better user experience. Saving energy has become one of the goals for home appliances especially when 21% of the total energy consumed in the United States is used by home appliances [6]. With this increased awareness of energy consumption and need for upgrading existing product lines, many manufacturers have been interested in adding new energy saving functions to energy consuming devices [8].

In October 2011, a novel thermostat, the Nest [7], came out with advanced features, such as schedule learning, remote access, motion sensing and eco-feedback. The Nest gained the spotlight due to promises of convenience and energy savings. It is an

interesting example of advancement in digital technology for the home since there have been no major changes in the basic thermostatic controls in the past sixty years [8], and more than half of the home energy consumption in a typical home is used by heating and cooling systems [2].

In order to better understand how people co-adapt to “smart” digital home technology, we are studying households that have installed a Nest. We have no commercial interest in the Nest. We chose the Nest since it is an advanced thermostat with machine learning and sensing technology that people are installing in their homes. In this study, we are specifically interested in how “smart” technology, such as a Nest, can improve the user experience of temperature control and help users to save energy. To date, we have conducted six interviews and one diary study.

Our preliminary study results reveal how advanced features of the Nest impact the way people control their heating and cooling system. Generally, participants were satisfied with the ease of creating a schedule with the Nest and the ability to control the Nest remotely. However, our study of the Nest also demonstrates how the technology poses challenges to the successful adoption of digital technology in the home. Our key findings are as follows.

- Improved interfaces and remote access increase interactions.
- Lack of intelligibility and inaccuracy of machine learning and sensing technology pose challenges for users.
- New practices of user control emerge to deal with technology shortcomings.
- Nest users are generally uncertain about the Nest’s energy savings.

2. RELATED WORK

Increased interest in efficient energy consumption has prompted research investigating the use of home appliances as well as new designs to support energy savings in the home. Specifically research in the domain of home heating and cooling system has increased. Previous research found commonly available thermostats do not provide adequate support for people to operate their Heating, Ventilation, and Air Conditioning (HVAC) systems in the most efficient way possible [8]. People with a manual thermostat often forget to adjust temperature or keep it running to maintain a comfortable temperature upon arriving at home. Programmable thermostats allow users to automatically operate their HVAC system with a preset schedule. However, while 42% of households in the U.S. have programmable thermostats, only 56% of these are actually used on a regular basis [8]. Programmable thermostats are no longer considered energy saving appliances due to the lack of proper use [2]. One common reason is that the interfaces for programming them are very difficult to use [8]. As a result, a large number of houses are

heated or cooled while no one is home, resulting in wasted energy.

Eco-feedback systems have been proposed as a way to promote greater awareness of energy use, which will, it is thought, motivate people to save more energy. However, Strengers and Pierce et al. [9, 11] pointed out that obtaining information did not always cause people to take action or change behaviors. A promising approach to complement eco-feedback approaches and help people maintain an acceptable level of comfort while attaining greater energy efficiency is implementing machine learning and sensing technology to automate the operation of the system to some degree. "Smart" thermostats have been proposed that seek to learn occupants' preferences and adjust the temperature based on sensed conditions. Gupta et al. [4] used GPS data to predict the arrival time of a home's residents to adjust the thermostat to reach a pre-defined temperature on the person's arrival. Scott et al. [10] gathered occupancy data through RFID and motion sensors. They used that data to predict occupancy patterns and operate the thermostat accordingly. While these automation-based approaches promise to relieve the programming burden from users entirely, there are reasons to believe that the benefits of a fully automated approach will not be realized in a meaningful and straightforward manner. As systems get more complex, it might become more difficult for people to understand how those systems work, to detect errors, and to predict what the systems will do.

To better understand the lived experience an intelligent device in their home, we have studied households that have installed a Nest that utilizes machine learning, sensing, and networking technology to control home heating and cooling system.

3. THE NEST THERMOSTAT

The Nest thermostat programs itself based on the temperature setting changes users make. It also sets the temperature to a more energy-efficient level when its sensor does not detect movement, and can be remotely controlled through a device connected to a Wi-Fi network. The Nest has a sleek dial frame with a round display as shown in Figure 1. It does not have any buttons and users can rotate the outer ring of the round display to adjust the temperature or push the screen down to bring up a control menu. The Nest costs \$249 and provides advanced features as follows [7].

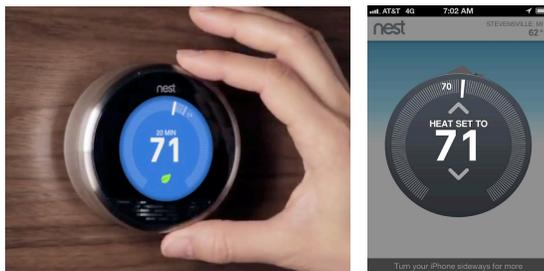


Figure 1. Nest thermostat display is shown on the left and a mobile application screenshot is shown on the right. Images are from the Nest website (left) and our participant (right).

- Auto-Schedule: The Nest automatically programs itself in about a week. It creates a schedule based on the temperature changes a user makes and continually adapts itself.

- Range Schedule: Users can program a temperature range for heating and cooling and Auto-Schedule will be paused.
- Remote Control: Users can control Nest on the website and through iPhone, iPad and Android apps.
- Auto-Away: About two hours after the Nest does not sense any movement, the Nest automatically adjusts the temperature set by its user in advance to avoid heating or cooling an empty home. The Auto-Away feature works with both Auto-Schedule and Range-Schedule.
- The Leaf: A green leaf icon appears when users turn the Nest to a temperature that is energy efficient, as shown Figure 1.
- Energy History (Figure 2): The 1.0 software version provides daily energy saving messages only on the physical device display. Starting with version 2.0 additional detailed history of when and how long the heating and cooling system ran can be viewed on the web and mobile applications.



Figure 2. Energy History 1.0 is shown on the left and Energy History 2.0 is on the right. Images are from the Nest website.

4. STUDY

We conducted an interview study with six participants from February to April 2012 and a one-month diary study with one participant from April to May 2012. The seven participants lived in California (2), Colorado (1), Massachusetts (1), Michigan (2), and Minnesota (1) in the United States. Six were male and one was female.

We recruited the six participants using various methods, including emails and private Facebook and Google+ messages to specific individuals who publicly posted their experiences with the Nest. We discuss below how selection may lead these participants to differ from a general audience for the Nest. Each participant was compensated \$20 for participating in one phone interview which lasted 45 minutes on average.

Five participants had purchased a Nest within a month after its announcement in October 2011, and three of them were programmers. Most participants considered themselves as early adopters and had one or more Apple products at home, such as an iPhone, iPad, or MacBook. Other demographic details of the participants are presented in Table 1.

For the diary study, we recruited one participant, P7, through personal contacts. This participant was compensated \$100 for participating in two phone interviews (at the start and end of the study) and a one-month diary study. This diary study started on the day she installed a Nest. We asked the participant to record her daily schedule of Nest adjustments and write down her and other house members' use of the Nest. For the diary tool, we used a free mobile application, Catch [1], which allows users to share pictures, text, and voice notes. We did not provide any prompts, but occasionally left comments on diary entries asking for an explanation or clarification.

Table 1. Participants Summary

ID (State)	Sex	Occupation	Adults (Kids)	Typical weekday schedule	Previous Thermostat Type and Scheduling	Days the Nest used at the time of interview
P1 (CA)	M	Sales manager	2(2)	He typically works at home for two weeks and travels for two weeks. His family stays at home.	He had a programmable thermostat. He had to adjust the temperature frequently, since he had a variable schedule.	73 days (12/2/11~02/13/12)
P2 (CA)	M	Retired software designer	2	He and his wife are usually both at home.	He had a programmable thermostat, but did not remember how it was scheduled.	74 days (12/02/11~02/14/12)
P3 (MN)	M	Designer and programmer	2	He primarily works at home from the lower level of the house, and his wife is home for about half the day.	He had a manual thermostat with a timer. His landlord set the schedule, which he believed was 58°F from 10 PM to 8 AM. He kept the temperature at 69°F most of the time.	88 days (11/20/11~02/16/12)
P4 (MA)	M	Entrepreneur and programmer	2	He travels often, but works from home when not traveling. His girlfriend has a regular 9 AM-5 PM job.	He had a programmable thermostat. He had kept the same schedule year round for the past four years.	47 days (12/31/11~02/15/12)
P5 (MI)	M	Programmer	2	He works from 8 AM to 6 PM weekdays. His wife is a professional photographer.	He had a programmable thermostat. His wife would have it on hold about four or five times during the week since she had a variable schedule.	33 days (01/26/12~02/27/12)
P6 (CO)	M	Professor	2(2)	Parents go to work 8:30 AM to 5:30 PM for 2-3 days a week. Children go to school at 8 AM and one comes back with a nanny around 12 PM and the other at 4 PM.	He had a programmable thermostat with Weekday, Saturday, Sunday and Special day scheduling options. He would frequently use the override when the house got too warm rather than reprogramming the thermostat.	Approximately 64 days (Late January~04/3/12)
P7* (MI)	F	Interaction designer	2(1)	Parents go to work 8:30 AM to 5:30 PM. Their child stays at the daycare while parents are at work.	She had a manual thermostat. It was always ON but she would often adjust the setting when leaving home, returning home, and going to bed.	33 days (04/17/12~05/20/12)

* P7 participated in a diary study with two interviews. Interviews were conducted on 4/16/12 and 5/20/12.

All interviews were audio-recorded and transcribed. The interviews, diary data, and participants' posts on their personal website were coded and analyzed using an iterative process of generating, refining, and probing the themes that emerged. Codes were initially drawn from research questions and then supplemented with those that emerged from the interviews. We coded the entire data set with codes related to the actual use of the Nest, participants' expectations and understanding of the Nest, benefits and issues participants had with the Nest, and interactions participants had with the Nest, as well as energy savings.

5. FINDINGS

Participants expressed that their motivation for purchasing a Nest was driven by their desire to try a "cool" device with new advanced functions and a nice style as well as to save energy. All participants mentioned energy savings as one of their motivation for getting a Nest. Participants explained that the possibility of saving money justified buying the Nest, but they were more impressed by the advanced features that the Nest offered, such as automatic scheduling, remote access, Auto-Away, and stylish appearance. But ultimately, they were motivated by the perception of Nest as "cool": "It's a cool device", "Yeah, that's cool. I wonder if it works", "I'm in technology business, so I'd like to know what's happening."

In the following sections, we describe how the Nest's specific advanced functions affect participants' ultimate experience and

successful achievement of their goal for convenience and energy savings.

5.1 Improved Interactions

Previously most participants found that programming their previous thermostat was complicated and difficult. P2 said that his previous thermostat was "probably the worst device [he has] ever had in the house." P3 became "frustrated too quickly" since he had to sit and push little buttons on a small LCD screen. All participants shared the opinion that creating schedules was "convenient" with the Nest. They were satisfied with the Nest since they could use the Auto-Schedule function to automatically create and update their heating and cooling schedule based on their temperature adjustments. Participants found the graphical interface made it especially easy and simple to monitor and edit the Nest schedule.

The expected benefit of remote access is enabling users to control their thermostats when they are away from home. Six participants used the Remote Control to adjust temperature or set the Nest to Away outside of the home. Interestingly, all participants found having the Remote Control convenient when they were at home.

"If I wake up and I'm freezing, I'll just grab the iPad next to the bed and crank up the heat. Then I haven't even gotten out of bed yet. Sometimes I'll just be sitting on the couch and rather than get up, I just grab the iPad [...] and turn it up or down." (P4)

The participants reported that having remote access made them interact more with their thermostat and become more aware of their heating and cooling system.

"It's kind of funny because I normally would never really care what the temperature in the house is. Now, just because I have an App on my phone and I can look it up [...] within a press of a button, I actually check." (P1)

"We definitely [didn't] interact with [his old thermostat] as much. The only time I had to think about it was when I had to replace the batteries. [...] I was certainly never worried about the schedule once it was programmed. [...] We definitely think about [the Nest] a lot more. [...] [The remote access] just makes it so easy." (P4)

P7 described her increased awareness as *"the level of extra connection to my home that I didn't have before."* It gave her feelings of increased control and a better understanding of her house.

5.2 Understanding an Intelligent Device in the Home

Despite improved interactions and increased ease of control, participants, regardless of their technical background, reported they did not fully understand how the Nest worked. Most of participants' partners were not impressed with the Nest and used it similar to their previous conventional thermostats.

5.2.1 Individual Differences in Adoption

All participants were excited about getting a Nest and curious about how it worked. P7 installed a Nest mobile application even before the Nest was delivered; however, not all household members shared the excitement or expectations. Four participants said their partners used the Nest the same way they did with their previous thermostat. They adjusted the temperature, but were not interested in other Nest functions. Three participants, P1, P4 and P5, mentioned their partner installed the Nest mobile application and used it to monitor or adjust the temperature.

P6's eight-year-old son enjoyed playing with the Nest and found the Energy History that informed users how much energy they saved. When his son walked by the Nest, he would wave in front of it to see what temperature it was. His son would climb up on a stool, and then he would press the dial going through different menus to check energy usage history. His son found the Nest attractive and became interested in adjusting the temperature:

"If it's cold in the house, he asks if he can be the one to turn it up. Or when we left the house the other day, he asked if he could be the one to set it on away." (P6)

Our participants self-identified as early adopters and were eager to try a 'cool' device, and thus, they were the main users and manipulators of the Nest in each household. Whether a person had a smart phone or not might also have impacted his or her adaptation. P7 said her husband still regarded the Nest as nothing more than a programmable thermostat. She considered not having a smart phone might be the reason and said, *"Actually, he hasn't seen all the stuff that I've seen on my app."* P1 also described his wife changed her attitude once she used the mobile application:

"My wife didn't like the idea (getting a Nest) at first. [...] She was a little bit reluctant. But once she realized how easy it is to (adjust temperature) [...], it was pretty simple to convince her and she did install her app on the phone. And now, she's all over it." (P1)

Next, we describe challenges our participants encountered due to the inaccuracy and precision of the machine learning and sensing technology.

5.2.2 Limitations of Machine Learning

We found that there were gaps between users' expectations of the Nest and the way it was actually designed. Our participants expected that the Nest would be smart enough to figure out the ideal schedule for the heating and cooling system to achieve comfort and save energy. As they observed how the Nest behaved, our participants developed different perceptions of how the Auto-Schedule learned their routines and temperature preferences.

While P1 said, *"I didn't believe in the learning process and it really does learn stuff,"* P6 said, *"I'm not clear at all whether that learning system is doing very much."*

For some participants, lack of understanding also led to disappointment. P7 said,

"The scheduling just seems to really just take the temperature that I was putting in, and then, just repeat it everyday of the week. I was never impressed with the scheduling. [...] It doesn't look smart. [...] Like one day, I decided I was cold and I wanted to increase the temperature, and then, it would change everyday to be like that." (P7)

In addition to the fact that all of our participants did not fully understand how the Nest's learning worked, there was another challenge our participants encountered due to the inaccuracy and precision of sensing technology.

5.2.3 Limitations of Sensing

In this section, we describe how participants experienced the inaccuracy of the Auto-Away. The Auto-Away is a feature that uses a motion sensor to detect whether people are at home and goes into away mode when no activity is recorded.

P5 and P6 recalled that the Nest went into Auto-Away mode while people were sleeping on the first day they installed it. The next day, the Nest figured it out somehow and so it did not set itself to Auto-Away during the night. Participants considered these adjustment period events minor unless the problems persisted.

P4 described his uncertainty about how the Auto-Away function worked, *"The Nest has got the Auto-Away thing. I'm not quite sure what the range of that is."* P3 had dogs and cats in his house and he thought Auto-Away worked about 25% of the time when people were gone because the Nest sensed the pets.

P7 switched to Range-Schedule mode and found the Auto-Away did not work. She misinterpreted that Auto-Away did not work with Range-Schedule. She wrote in her diary, *"Odd, maybe since we use range??"* She expressed her disappointment:

"One thing that I haven't been happy with is that, when using the range [...], [the Nest] wouldn't do an Auto-Away. That was a feature that I thought was lacking, because it should still know that we were not at home even though the range was set." (P7)

P2's Nest got stuck in Auto-Away mode and he eventually abandoned the Auto-Away function. P2 expressed his frustration:

"I could not figure out how to get back into 'At Home Mode'. [...] It might have been a bug in the software, but it wasn't very helpful. It was bad. [...] The Nest is doing its own [thing] and doesn't tell you what it is doing." (P2)

This discounted the benefit of the Nest, since P2 did not turn the temperature down when he left home.

While most of our participants—who largely fit the profile of "early adopters"—developed an understanding of how advanced features which utilized machine learning and motion sensing

worked, many of their co-inhabitants used the Nest like a conventional thermostat. This suggests that lay users who are not eager to learn or explore new technology may not adapt as successfully to certain types of intelligent digital home technology.

5.3 Emerging Practices of User Control

Our study allowed us not just to observe participants' reactions to features, but also to glimpse emerging strategies given the affordances of features. In particular, P3, P4 and P5, who were programmers quickly understood Nest's machine learning limitations and came up with workarounds. They changed the way they interacted with the Nest by intentionally giving limited input for the Nest to memorize intended adjustment and manually deleted temporary changes they made. Other participants set the Nest to Away mode manually since its sensing was not precise.

5.3.1 Give Proper Inputs to Guide Learning

P3 paid attention while the Nest was learning and he guided the Nest's Auto-Scheduler:

"After about a week, I looked at the schedule that it had memorized and it was crazy, it was all over the map. So, I erased the whole schedule and we started again. And at that point, basically, not more than three times a day." (P3)

P6 was the only participant who manually entered an initial schedule into his Nest. He described that his family members had not turned down the thermostat when they left the house in the past. He did not expect that they would quickly adopt a new habit of turning down the thermostat or be conscientious in programming the Nest. In order to avoid the Nest learning an undesirable schedule based on his family members' inputs, he decided to manually set an initial schedule for the Nest.

5.3.2 Revising the Schedule

P3, P4 and P5 observed how the Nest responded to their input and found that the Nest remembered too many detailed changes or inaccurately regarded a temporary event as a routine. After they realized that this happened, they started manually editing their schedule more often in order to make the Nest's schedule reasonable to them.

P5 ended up cleaning the schedule manually so the Nest would not make small, frequent temperature changes based on his and his wife's changes. P3's Nest schedule, shown in Figure 3, contained frequent temperature changes on certain days. P3 manually deleted a number of temperature settings from the schedule if he perceived the change to be a random adjustment.

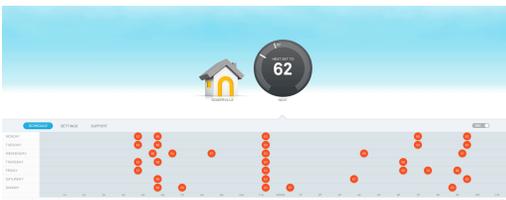


Figure 3. P3's Nest schedule learned multiple inputs

5.3.3 Doing it Manually

Due to the limitations of sensing accuracy, participants often manually set the Nest to Away mode. P3 had pets and his Nest detected the movement of them. Since he was not sure if the dogs would not stay still, he set the Nest to Away mode when he was gone. Several participants set the Nest to Away mode manually

when they left home since it would take two or three hours for the Nest to figure out if people were home. P5, P4's partner, and P7 set the Nest to Away while at work, if Auto-Away did not turn on. While P4 was working at his home, the house did not need heating. However, the Nest sensed when he came down stairs to drink water. P4's partner checked remotely from her work and set Away manually. P6 was the only participant who expressed a strong motivation to save the environment and he said he always set the Nest to Away before the Auto-Away turned on. He explained that the ability to control the thermostat easily made him realize how easy it was to save energy and therefore tried to save energy more frequently.

5.4 Uncertainty about Energy Savings

All participants expected the Nest to be helpful for energy savings. However, none of them was certain about whether the Nest *actually* saved energy. P1 said, "I will not say if it saved me any electricity at this point. I don't know." Even though P4 thought the Auto-Away was useful, he was not sure that there was a large benefit from it. P4 explained his doubt:

"In reality, it might be that I played with Nest so much, it cost me an extra 300 bucks. So, you can understand the hesitation I might have. But if they're able to put in your old schedule and your new schedule, I understand the difference would be worthwhile." (P4)

Participants made more changes to make the temperature comfortable at home, which they might have not bothered to do so with their previous thermostat. P1 said he would use the remote a lot of times when he was actually in the home because he was too lazy to get up. P2 and P7 pointed out that their Nest schedule seemed to run their heating system more than they would have expected.

"It seems like it stays warmer longer than what we would've done it if we left it purely manually. [...] Well, I think we've just been ignoring it and letting it run and expecting it to work" (P2)

"9 AM, felt too warm after shower, saw temp was up to 71, turned it down to 69, noticed the schedule now has mornings starting at 71!! That's a bit high for a usual temperature, even though we used it once on Monday [a day before], weird it just thinks that's what we want right away." (P7's diary entry)

Including P2 and P7, who explicitly expressed that they preferred comfort over energy savings, six participants did not change their behavior after getting a Nest. The Nest learning might have created a more inefficient schedule, since it learned participants' pattern of control and many participants made more adjustments for comfort. With the previous thermostat, they might have stayed with the less comfortable schedule they initially programmed without making capricious changes.

6. DISCUSSION

In this section, we describe some of the issues we found in our study and draw implications which would also be helpful for the design of the digital home.

6.1 Implications for Supporting User Control

Whitworth [12] stressed human control over the computer, pointing out the importance of user choice, and stating that the computer's poor understanding of the context changes outside its fixed parameters and unaccountability for what it does. While the Nest remembers past choices through its learning function, it is limited by not knowing the difference between what input needs to be remembered and what should be regarded as exceptions. If possible, intelligent systems need to remember how to handle both

regular routines that can be predicted and exceptional cases as well. The challenges of designing such a system are to provide mechanisms to let systems know what a human is doing and what their input would mean, so that the system can tell which input/pattern they should take into account, and also remember these exceptions and accommodate this better in the future.

Our findings also show that changes to the traditional thermostat interface provided by the Nest, such as schedule learning and motion sensing, both increased users' awareness of and improved interaction with their HVAC system. Although this improves the experience of thermostat control by making it much easier and convenient, it reveals that this might have lead people to pursue greater comfort which eventually consumes more energy rather than saves energy. In our study, only P6, who has strong motivation to save environment, turned the temperature down more often after getting a Nest. Energy History in the Nest's current format provided a simple report of previous energy consumption but it did not affect participants' behavior when they made adjustments with their mobile devices. Instead of retrospective analysis, we argue that a thermostat needs to provide explicit information about projected energy consumption resulting from temperature changes. Fogg [3] asserts the importance of timing in behavior changes. We believe that "*Kairos – the opportune moment to persuade*" [3] is a critical element for thermostat control in order to motivate or reinforce users' actions for better energy efficiency.

In order for people to accomplish the goal of saving more energy and developing good behaviors with the help of an intelligent system, humans need to be deliberate by giving proper input to a machine so that it can perform better.

6.2 Studying Early Adopters

Two limitations of our study are that most of our participants were early adopters and only one participant was female. However, we still observed that there were different levels of understandings and engagement among our participants and their partners. While our participants were eager to learn what was required to use and explore the technology, many other members of the household, who might not have gotten a Nest on their own, did not share same excitement. This helped us to better understand the importance of intelligibility of the digital home device in order for lay people to adapt without inefficient use or abandonment.

7. CONCLUSIONS AND FUTURE WORK

In this paper, we present a study of Nest users. We have shown that improved interfaces through web/mobile applications changed the interaction between users and their home system. We have also shown that intelligibility and inaccuracy of the system influences the way participants perceive and adapt to the system. Finally, convenient control over the system and limitations of the technology may have prevented the desired energy savings. These findings assert that thoughtful, continuous involvement from users for control is critical to the success of both digital home technology and interventions that promote sustainable choices. We also argue for the importance of research into making systems intelligible [5], so that people can better adapt their communication with the system to achieve the desired effects, as well as recover from errors.

In our future work, we plan to conduct more diary studies. While overall experiences and general issues were reported from the interview study, we can learn more details about the situations, decision-making processes, changes in users' perception and understanding of the system over time from a more extensive diary study. We also plan to interview members of the household other than the one who purchased a Nest in order to learn the differences in adopting new technologies and their experience.

8. ACKNOWLEDGMENTS

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