Making Sustainability Sustainable: Challenges in the Design of Eco-Interaction Technologies

Rayoung Yang[1], Mark W. Newman[1], Jodi Forlizzi[2]

[1] School of Information
University of Michigan, Ann Arbor, MI, USA
{rayang, mwnewman}@umich.edu

[2] HCI Institute
Carnegie Mellon University, Pittsburgh, PA, USA
jforlizzi@cs.cmu.edu

ABSTRACT
The smart home is here. One area where smart home devices promise to deliver great benefits is in the control of home heating, ventilation, and cooling (HVAC) systems. In this paper, we seek to inform the design of future heating and cooling systems by investigating users' experiences with the Nest Learning Thermostat, a commercially available smart home device. We conducted a qualitative study where we compared people's interactions with conventional thermostats with interactions with the Nest. A key finding was that the Nest impacted users' pattern of HVAC control, but only for a while, and caused new problems in unrealized energy savings. In leveraging these findings, we create a set of design implications for Eco-Interaction, the design of features and human-system interactions with the goal of saving energy.

Author Keywords
Sustainability; Thermostat; Eco-interaction; Smart Home

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

INTRODUCTION
The smart home is here. Long envisioned by HCI and Ubicomp researchers, the promise of a home that can learn its occupants' needs, desires, and behaviors — and adapt itself appropriately — is being realized. Networked digital devices and services are being manufactured and marketed in ever-increasing numbers, performing a variety of different roles in the home including entertainment, health, security, and home automation. These new capabilities bring great potential, but also great concern — are "smart" devices going to make our lives easier, more productive, or more enjoyable? Or are they going to bring a new set of frustrations, expectations, and responsibilities that will outweigh their possible benefits?

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An area where smart home devices promise to deliver great benefits is in the control of home heating, ventilation, and cooling (HVAC) systems. HVAC control is an important domain from the perspective of environmental sustainability. In the United States, for example, residential HVAC systems account for roughly 50% of all household energy consumption, which equates to about 9% of the nation's total energy budget [19]. Moreover, residential HVAC systems are not operated efficiently by their users [17], leading to unnecessarily wasted energy. A number of researchers have investigated ways to improve the operation of HVAC systems. Research into eco-feedback (e.g., [5,18,21]) has focused on ways to provide information to people about their resource usage in order to motivate them to change their usage patterns. Another approach that has been investigated is predictive heating control (e.g., [6,12,20]), which uses sensing and machine learning to try to learn the occupancy patterns of a house's residents in order to automatically adjust the temperature.

Both eco-feedback and predictive control can be seen as approaches to a broader problem we call *eco-interaction,* by which we mean the study of interaction between humans and energy-consuming systems with an eye towards minimizing energy use while preserving an acceptable level of user-perceived benefits. Eco-interaction includes eco-feedback and predictive control, but also includes the design of control interfaces, infrastructures, and basic functionality required to facilitate user interaction.

In this paper, we seek to inform the design of future eco-interaction systems by investigating users' experiences with the Nest Learning Thermostat (hereafter "The Nest"), a commercially available smart home device. The Nest combines elements of eco-feedback and predictive control with networked remote control to allow users to create a custom heating and cooling schedule that matches their preferences and helps them save energy [14].

The work in this paper builds on an earlier study [23] that looked at users' initial experiences with the Nest, including problems encountered with the Nest's learning and sensing capabilities, and users' strategies for dealing with the Nest's limitations. Here we look at a different aspect of users' experiences with the Nest, namely how the features of the Nest changed users' interactions with HVAC systems in the home over both the short and long term.

We do this by first examining how people interact with "conventional" thermostats — i.e., the ubiquitous manual and programmable thermostats that can be found in the vast majority of North American homes [17]. We then report users' initial experiences upon acquiring a Nest by re-analyzing the data originally collected for [23] from the perspective of the Product Ecology Framework [4]. The Product Ecology Framework allows us to more easily see changes in consumers' perception of and interaction with a novel product like the Nest, and to tease out different threads that impact the user experience. Finally, we report a new follow-up study that was conducted to learn about how their interaction with the Nest had changed after owning it for 12-21 months.

Our study found that the Nest impacted users' pattern of HVAC control, but only for a while. During the first few months after installing a Nest, many of the users we studied were more engaged, interacted with their thermostat more, and sought ways to save energy more actively than did users of conventional thermostats. After a period of time, however, the engagement with the Nest, along with the frequency of interaction, diminished and users' interactions settled into patterns that resulted in missed opportunities for energy savings. Based on these findings, we identify a set of implications for the design of eco-interaction systems.

BACKGROUND AND RELATED WORK

Our work builds upon and informs existing approaches to promoting energy savings, principally eco-feedback and predictive control. As our particular focus in this work is on the changes in use of eco-interaction systems over time, we also draw upon prior studies of long-term interaction.

Eco-Interaction

The goal of eco-feedback is to promote greater awareness of energy use, which could in turn, motivate people to save more energy (work in this area is extensive; [5] provides a survey). However, there has been little evidence that obtaining information reliably causes people to take action or change behaviors [21]. Rather, considerable motivation and engagement on the part of consumers is required for eco-feedback to lead to behavior changes. Moreover, even when people are aware and motivated, it can be difficult to effectively control their systems. Previous studies showed that poor usability was a significant barrier for the efficient use of programmable thermostats [17].

Given the challenges of persuading people to change their behavior, Pierce *et al.* [18] suggested designing interfaces to "nudge" people to save energy by default, thereby reducing the need for consumers to make conscious decisions or enact behavior changes. Hazas *et al.* [7] take this argument further, proposing that technology-centered approaches, rather than user-centered approaches, offer the greatest promise for saving energy. Following this thread, work in predictive control seeks to reduce or even eliminate the role of user choice in controlling HVAC systems by automating temperature adjustments based on occupancy predictions. By tracking occupancy patterns using GPS [6,12] or RFID and motion sensing [20], it is possible to build reasonably accurate models that can predict occupancy and make sure the house is heated or cooled to a desired temperature when people are home and a less energy-intensive level otherwise. Systems in this category have been built and tested in limited deployments. It remains to be seen what issues would arise in a more general deployment with people who vary more widely in terms of geographic mobility, schedule predictability, tolerance for error, and desire for control.

(a) (b) (c)

Figure 1. Users can control the Nest via the wall-mounted display (a), a mobile app (b), or a web app (c). © Nest Labs

The Nest Learning Thermostat[1] features an attractive wall-mounted device, as well as smart phone and web-based control capabilities (see Figure 1). In addition to providing access to a schedule and the ability to control the temperature in real time, the web and phone apps provide a detailed Energy History, an eco-feedback display showing when and how long the heating and cooling system ran and providing feedback about whether the day's performance was energy efficient. A green leaf icon appears when users set the Nest to a temperature that is considered energy efficient by the Nest's algorithms [15].

Additionally, the Nest includes Auto-Schedule and Auto-Away, intelligent features that utilize machine learning and motion sensing, respectively, to implement a form of predictive control. In contrast to the systems mentioned earlier that seek to predict occupancy, the Nest's Auto-Schedule feature generates a schedule based on temperature changes that were previously made. While the manufacturer of the Nest does not provide details of the algorithm, it claims the Nest generally takes about a week to compute an initial schedule and thereafter continually adapts the schedule based on users' temperature adjustments. Users can also use the web-based control interface to manually revise the schedule created by Auto-Schedule, and Auto-Schedule can also be turned off. The Nest has a motion sensor embedded in the wall-mounted unit that detects the movement of occupants within a certain range. If the Nest does not sense movement for some time, it goes into Auto-Away mode, which automatically adjusts the temperature to a user-defined setback level to avoid excessively heating or cooling an empty home.

[1] The description of the Nest presented here is based on the version of the Nest our users had at the time of the study, as described at http://www.nest.com (Accessed: 2012-09-24.).

As a precursor to the work presented in this paper, Yang and Newman [23] studied households that had installed a Nest, focusing on users' initial impressions of the Nest and their experiences with the Nest's "smart" features, namely Auto-Schedule and Auto-Away. Whereas [23] drew on early-stage usage experiences to inform the design of usable intelligent systems for the home, our goal here is to identify challenges and opportunities in the design of eco-interaction systems for long-term use.

Understanding Product Use and Long-Term Interaction

Numerous approaches exist for understanding how and why technological products are acquired, adopted, and used. Models such as the Technology Acceptance Model [22] and Orlikowski's duality of technology [16] help explain how particular features of a product or system, along with contextual factors such as user expectations, social dynamics, and temporal trajectories impact how the product is integrated into the life of an individual or collectivity.

In this work, we draw on the Product Ecology framework to look specifically at how the Nest changed users' relationship to their HVAC system over both the short and long term. The Product Ecology is a theoretical framework that describes social product use [4]. It is informed by social ecology theory, which is broadly concerned with the dynamic relationship between an individual and the physical and social environment. From the Product Ecology viewpoint, the product is the central unit of analysis. The functional, aesthetic, symbolic, emotional and social dimensions of a product, combined with other units of analysis, or *factors* in the ecology help to describe how people make functional, social, and symbolic relationships with products. These include the product; the surrounding products and other systems of products; the people who use it, and their attitudes, disposition, roles, and relationships; the physical structure, norms and routines of the place the product is used; and the social and cultural contexts of the people who use the product [4]. The Product Ecology has been used in the long-term study of adoption of semi-autonomous products in the home to understand how they change interactions in the household (e.g., [3]).

Other work has looked at long-term interaction with interactive products. Several papers, for example, have looked at the change in user satisfaction and perception over time (e.g., [10,13]), but these did not focus on how users' interaction patterns changed or what impact those changes had on outcomes enabled by the product, such as comfort or energy savings. Our work contributes to both the literature on Product Ecology and long-term interaction by investigating the changes in users' relationship to and usage of a novel device over both the short and long term.

METHODS

We conducted two qualitative studies, one with manual and programmable thermostat users and another with the Nest thermostat users. Both studies consisted of a diary study augmented by semi-structured interviews.

Study 1: Conventional thermostat study

We conducted a three-week diary study with 16 participants between September and December 2011 in order to understand how people use their thermostat to manage their thermal comfort in their homes. We recruited participants using personal networks, mailing lists, and the snowball sampling method. Eight participants had manual thermostats, and the other eight had programmable thermostats. Our participants lived in six different states in United States. Participants made daily diary entries for three weeks and participated in two interviews. We employed a diary study to capture participants' day-to-day heating and cooling control and to avoid limitations of interview data such as participants' inaccurate memory of their actual behaviors and perceived comfort for each day. Each participant reported the arrivals, departures, and sleep times of their household members, how they felt about their comfort, and what changes they made to their thermostat and why. The initial interview focused on participants' household routines, general thermostat control practices, and thermal comfort preferences. The exit interviews elicited additional details related to diary entries.

Study 2: The Nest thermostat study

To understand users' experiences with the Nest, we drew from a re-analysis of data collected for a previous study [23] and a new set of 15 follow-up interviews conducted with members of the households that participated in the original study. For the initial study reported in [23], 23 participants from 19 households who had purchased a Nest were interviewed between February and September 2012. Ten of these also participated in a three-week diary study and two additional interviews, which took place during and after the diary entry period. Diary entries described participants' comings and goings, changes made to the thermostat, and reactions to the Nest that they had, positive or negative. Participants also submitted periodic screenshots of the Nest's Energy History and schedule.

Follow-up interviews were conducted between August and September, 2013. Fifteen participants from nine of the original households agreed to participate for the follow-up (two household members participated in the follow-up who did not participate in the initial phase). Participants sent us updated screenshots of their Nest schedule and the Energy History prior to the interview and we asked them about their long-term experience and use of the Nest.

Data collection and analysis

In total, we conducted 90 interviews and collected a total of 508 diary entries. All interviews were audio-recorded and transcribed. The conventional thermostat study data was coded and analyzed using an iterative process of generating, refining, and probing the themes that emerged. The data from the initial-phase and follow-up Nest usage studies were analyzed using the Product Ecology Framework [4]. We chose to employ the Product Ecology Framework in order to investigate how dimensions of the product influenced thermostat control activities that took place around the use of thermostat. Our interest in this study was two-fold: first, to better understand how product features influence users' interaction with a thermostat and second, how users' interaction with a semi-autonomous thermostat changes over time within the home. We were also interested in aspects of behavior that supported energy savings.

In the following sections, we draw on the conventional thermostat study data to describe people's current practices with regard to thermostat control as well as existing problems. Then, we discuss how the Nest changed the practices, interactions, and relationships associated with the thermostat, how it addressed existing problems, and what new issues it presented. Finally, we present the breakdowns that occurred with the Nest over time. In the Discussion, we reflect on these findings to extract a set of implications for the design of future eco-interaction systems. In the findings below, we refer to participants by thermostat type and subject number, for example, PT1 is the first participant interviewed who had a programmable thermostat. MT is used for a manual thermostat. For the Nest study, we use same participant codes, P1-P23, that were used in [23], adding P24-P25 for additional follow-up study participants. We indicate whether source was an interview (I) or diary entry (D), and note the number of months the participant had been using the Nest at the time.

COMMOM PROBLEMS WITH THERMOSTAT CONTROL

In our study of conventional thermostat usage, we observed common problems in participants' thermostat control patterns that echoed those described in previous work [17]. With manual thermostats, people often forget or find it inconvenient to manually adjust temperatures to increase energy savings. While programmable thermostats ought to make it easy to reduce energy consumption, people find it difficult to program their thermostats due to usability flaws [17]. Here, we look beyond the well-documented usability problems with existing thermostats to shed light on more fundamental reasons that efficient management of thermostats is challenging. Specifically, we show how practices surrounding thermostat control are tightly related to people's comfort and convenience as well as frequent changes in routines and schedules in daily life.

People do not use a setback temperature.

Making effective use of a setback temperature—i.e., an energy-efficient temperature setting to be used when the house is unoccupied — is one of the most important steps people can make to reduce the energy used for heating or cooling their homes [17]. Many of our participants did not consistently use a setback temperature, and cited various reasons. Many participants wanted to avoid the long wait time until the house heated or cooled upon returning home, while others simply forgot or were unaware of the potential energy savings.

People do not use schedules.

Interestingly, some participants did not even try to figure out how to program their devices. PT1 did not use a schedule even though it meant he had to frequently wait up to two hours for the house to cool down to his desired temperature. He said, *"There's a button called PRG, which I figure is probably for Program,… I was too lazy. I never really bothered to figure out how to use it."* Rigid scheduling options were another reason that participants avoided scheduling. Many programmable thermostats offer limited options for scheduling, allowing only a "weekday" and a "weekend" schedule, each with limited preset times when temperature changes can occur (e.g. morning, day, evening, and sleep time). This rigidity made it difficult to effectively set a schedule for more complex and nuanced daily routines. More importantly, inflexible scheduling options combined with a difficult scheduling process hinders participants from accommodating frequently changing schedules and temperature preferences.

People fail to reassess existing control patterns.

Some participants kept non-optimal temperatures that were "more comfortable" than they actually needed. Several participants programmed their thermostats for the season and stayed with the schedule throughout the season. PT2 referred to a programmable thermostat as "*a little more maintenance-free"* than a manual thermostat, as she only needed to adjust the schedule twice a year: "*I kind of do an assessment, if you will, before winter starts and before summer starts to make sure my temperatures are kind of where I want them to be."* However, we believe that this "set-and-forget" approach will not be optimal for energy saving because both weather and people's schedules change frequently during the season.

In addition to failing to reassess their schedules, participants used temperature settings that were not optimal for *either* saving energy *or* achieving thermal comfort. This was revealed accidentally, for example, when MT1 at one point forgot to change the temperature back to 70°F from 64°F as she usually did upon arriving home during the winter. She only realized her oversight when, two days in a row, her husband came home and said; *"It's kind of cold in here isn't it?"* She wrote in her diary: "*I guess that people do adapt to the temperature and can tolerate a wide range (more than we initially recognize)."*

In the next section, we describe how our participants with the Nest used and interacted with it differently from those participants with manual or programmable thermostats.

PRODUCT ECOLOGY ANALYSIS

As described earlier, we used the Product Ecology framework to analyze how the Nest impacted people's interactions with their heating and cooling systems as mediated by their thermostats and whether and how this, in turn, affected behavior, roles and relationships in the household. We coded for three factors in the product ecology of the thermostat, *people, activities,* and *products,* with special attention to the dimensions of the Nest as a product (*functionality, aesthetics, symbolism, emotion,* and *social attribution*).

As a *product*, the Nest was well-received by most users, especially in terms of its *symbolic, aesthetic,* and *functional* aspects. Symbolically, the Nest was seen as a "cool," "stylish" gadget that reflected its owners' good taste and technical savvy. Most participants thought that the Nest was designed for anyone because it was easy to use. However, a few mentioned that it was designed for young, technically-savvy users because they felt they were not taking full advantage of all of the Nest's features. It also held the promise of saving energy, which was a significant factor in many participants' decision to purchase the Nest in the first place, and it reinforced self-images of the purchaser as an energy-conscious consumer.

All participants mentioned energy savings as one of their motivations for getting a Nest, but ultimately, they were most motivated by the perception of Nest being a cool, beautifully-designed product. *Aesthetically*, the Nest was seen as a huge improvement over the dull plastic thermostat it most frequently replaced, and it was praised for its appealing appearance. P9(I-1.5m) expressed that *"just having something on the wall that's not an ugly piece of plastic from [brand name] is also totally worth it."* The smart phone and Web interfaces were similarly seen as elegant and attractive, leading to an overall positive *emotional* experience for most of our participants. While some participants used anthropomorphic language when discussing the Nest (e.g., talking about what the Nest "knows" or "thinks"), *social attribution* did not seem to be a dominant dimension in users' experience.

The Nest's novel *functionality* was, however, very prominent in participants' minds. The Nest's functional aspects, along with a heightened sense of engagement due in large part to the positive emotional response and changes in the relationships of household members vis-à-vis thermostat control, impacted the *activities* that users performed with and around the Nest.

INITIAL EXPERIENCES WITH THE NEST

Through our analysis, we noted several ecological changes that occurred among adopters of the Nest as compared to those using a traditional thermostat. Here we focus on two. We first provide insight into how key dimensions of the Nest (particularly *functionality, aesthetics, and symbolism*) led to greater engagement, which, in turn, led to increased awareness and interaction with the system. Second, we provide details about how changed interactions with the Nest impacted activities related to thermostat control and energy savings.

Increased engagement and awareness

Conventional manual or programmable thermostats were not seen as exciting to use. Conversely, several dimensions of the Nest combined to promote greater engagement, and more importantly, stimulated our participants' interest in thermostat control and energy savings. The Nest's novel features (*functionality*) such as the Energy History and its interactivity led participants to be more aware of their heating and cooling system. P15(I-8m)'s interaction with a thermostat control changed in the following way after getting a Nest:

I'm much more in tune with what my heating and cooling systems are doing. I'm much more aware of their presence and their function. I know it sounds kind of silly because it's a heating and cooling system. But, before I just avoided. … I only dealt with it when I had to, but now I just like to see what it's doing when I walk by.

The Energy History feature and appealing graphical interface motivated and facilitated to assess and improve their settings. P6(I-1.7m) had previously bought a programmable thermostat for about US$20 and never programmed it during the four years he had it. He stated that he *"didn't want to bother with it"* because it was *"old technology."* With the Nest, though, he explored the Nest's different functions and was motivated to optimize its schedule:

I was sort of messing around with [the schedule] and then got excited about it. Then, suddenly I was adjusting all the temperature… It's really fun… It's almost a game like, 'OK, let me see if I can make it a little bit warmer on this day and try to save a little energy there.'

Here, we find that the Nest's *symbolic*, *social*, and *functional* aspects successfully engaged participants in performing tasks that were problematic for conventional thermostat users, namely using schedules and reassessing them for energy savings.

Changing practices and interaction with the Nest

Along with increased engagement and awareness, the Nest's functional aspects also impacted thermostat control activities in key ways, as we now describe.

Scheduling becomes an interactive and iterative task.

The Nest participants' scheduling activities became more ***interactive and iterative***, as compared to the tedium of conventional thermostats. Once the Nest generated a schedule based on its learning of a participant's input, many participants reviewed and revised their schedules, often repeatedly. Thus scheduling was not a one-time task but instead was ongoing, as the Nest automatically kept updating the participant's schedule over time and the participants kept reviewing the changes. P18(I-9m) described how he interacted with the Nest's schedule and why the scheduling could not be solely left up to the Nest:

Reading [the schedule] now, it says, 'On Wednesday 4:30, sent from my Nest thermostat' is when I put it at 75°F, but then it shows that Monday, Tuesday, Thursday, and Friday were set to 75°F because of the learning feature… I look at it occasionally to see why it's set like that… If it has added something in there that I didn't think… was something good, then I would change it back to something else.

For other participants as well, keeping an eye on the schedule became necessary once they realized that the Nest remembered temporary changes and added them to the schedule. During the diary study, P2(D-2m) "*noticed a few aberrations in the schedule.*" Once he found that the Nest quickly responded to temporary adjustments and made them part of a regular schedule, he monitored how the Nest was changing his schedule. P8(I-1m) said, *"I look at it [the schedule] every now and then to see if it has added something crazy in there."*

Temperature control becomes more fluid and adaptive.
While participants found that conventional programmable thermostats offered limited options for scheduling, and thus, it was hard to accommodate temporary changes, many participants appreciated the fact that the Nest was ***flexible and adaptive***. The Nest's functional aspects, such as Auto-Away, remote control, and flexible options for scheduling enabled participants to accommodate frequently occurring changes in their schedules. P5(I-1.5m) felt that he gained more control with the Nest and pointed out that the Nest's flexibility and adaptivity in scheduling actually allowed him to save more energy.

The previous one wasn't very flexible so you were kind of at its mercy. You didn't have a lot of control over your energy usage ... [N]ow, I can a lot more proactively manage [my energy usage]… [The Nest] is very flexible ... [T]he best thing so far is being able to set the temperature from when out of the house, being able to set it Away. I like the Auto-Away and just the ability to manage it on a day-to-day hour-to-hour basis is helpful.

Establishing a setback temperature becomes easier.
P5(D-1.5m) further described in his diary that having remote access led him to employ a setback temperature. He wrote, "*Really what changes our behavior is setting it to Away or turning it off while we're gone.*" The Nest's ability to adjust the temperature based on occupancy and to control the temperature remotely enabled the participants to employ more flexible, temporary, and immediate temperature setback strategies. With Auto-Away and remote control, it was okay to forget to change the temperature before leaving. P13(I-9m) described having the remote control as freedom and empowerment: *"The freedom that the Nest gives you from having to… remember to turn it down. You're empowered wherever you are to make those changes."* Adjusting the temperature was no longer on her husband's vacation to-do-list. In addition, they did not need to worry about wasting energy because they forgot to turn down the temperature. The couple P15(I-8m) and P23(I-8m) did not need to call their housekeeper to check whether she had adjusted the temperature after cleaning. Instead, they could check remotely and avoid wasting energy.

Monitoring the Nest emerges as a new task.
Supervising and monitoring the Nest emerged as a new task, as participants were intrigued by how it learned from their temperature adjustments and operated autonomously.

In addition to monitoring changes to the schedule as described above, many participants monitored their energy histories to see how the Nest was performing. While traditional thermostats do not provide means for users to see how their heating and cooling systems have been working, the Nest's Energy History allows users to track how the Nest has been operating on a daily or weekly basis. A few participants drew on the Energy History to reassess whether their behaviors and existing schedules were aligned with their comfort and energy-saving goals. For example, P12(I-2.5m) noticed that the A/C was running ten or more hours a day, based on the Nest's Energy History. After he raised the temperature setting by just one degree, he found that the A/C ran only six hours or seven hours a day. By monitoring the Energy History, he found ways to save and experienced the impact of making minor changes to his schedule.

SETTLING INTO A ROUTINE

The changes in engagement and awareness described in the previous section did not, however, persist over the long term. Our follow-up study identified major changes in the use of the Nest that were apparent after a year. First, far less interaction with the product was cited. Over time, the device became mundane, and people rarely interacted with features like the Energy History and the schedule. Second, a decreased effort to improve energy performance was noted. While participants were initially interested in monitoring their energy use, they came to rely on the Nest's automatic functions more over time. In essence, participants' thermostat control practice changes — such as monitoring the Energy History and fine-tuning the schedule for energy efficiency — did not last over time. The effort and engagement required to maintain such behaviors was not sustainable.

Less interaction with the Nest over time

Our follow-up interviews revealed that by 12–21 months after installing the Nest, many participants did not remember when they last checked their schedules or energy histories. Many had stopped reviewing their energy histories, checking or adjusting their Nest schedules over six months or more prior. Only two participants explicitly said they kept paying attention to the Nest in order to save energy. Most participants in the follow-up study interacted with their Nest thermostats only to directly adjust the temperature. P1(I-13m) said, *"We don't interact with the Nest, really. ... We just use it as a regular thermostat."*

Over time, the Nest schedule became static, and the system made few adjustments. Accordingly, some participants became less concerned about what the Nest was doing. P4(I, 13m) said, *"The Nest takes care of all the changes in temperature… It doesn't require me to babysit it."* P6(I-15m) did not check the schedule or the green leaf anymore to see if the temperature settings were energy efficient:

I haven't checked the schedule or the green leaf because mainly, I think, the Nest has learned pretty well what we

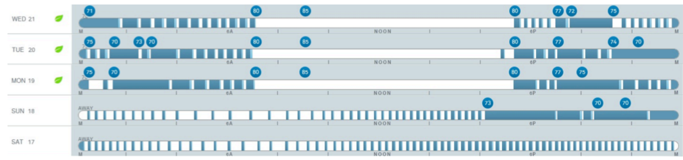

Figure 2. P4's Energy History shows the A/C was running during the weekend while he was not at home (bottom two rows). When he left home, he set the Nest to 'Away' mode, which was set to 80°F, a temperature lower than his normal daytime setback of 85°F (shown in the upper three rows). P4 was surprised to discover that his system was wasting energy while he was away.

like so I don't really think about the thermostat too much anymore. Maybe, it's almost working too well because I don't think about looking for the green leaf. On the occasion that I do go up and adjust the thermostat, like let's say it just gets too hot or too cold, then I do look for the green leaf on those occasions. But in general, I don't interact with the thermostat that much. I don't even think about checking it anymore. It kind of faded into the background for me.

As long as the Nest did not set the temperature abnormally, it did not call for our participants' attention, and he or she did not need to actively get involved in controlling or interacting with it.

Reduced effort in improving energy performance

During the follow-up interview, participants were asked to take a look at their current schedules and energy histories. To five participants' surprise, the Nest thermostats were not working as they had expected. For example, P4(I-13m) failed to reassess his default settings, resulting in wasted energy. He was away during the weekend, however, the Away temperature setting was set to 80°F, and the Nest was cooling the house during the weekend, as shown in Figure 2. When asked why he set the Away temperature to 80°F while he had an 85°F setback temperature, he answered, *"Oh, I have no idea. I think [the] Away [temperature] was already set at 80°F [about a year ago when he installed the Nest]. I just didn't change the setting. I just turned on the 'Away.'"* He continued, *"I guess left to my own devices, it would have stayed at 80°F. It makes sense to turn it to 85°F. I really didn't even pay attention to what it was at."*

Reduced engagement with monitoring and over-reliance on the Nest functions caused surprises regarding its automation routines. P14(I-18m) trusted the Nest and rarely looked at his schedule or Energy History. He believed that the Nest was saving money due to its functions, such as Auto-Schedule and Auto-Away. However, during the follow-up interview, he found that the Nest was actually running during the weekend while he and his wife were away. He had checked the Nest on his phone and had seen that the Nest was in Away mode after leaving home on Friday. He thought the Nest would maintain the Away mode the entire weekend. To his surprise, the Nest somehow turned on and cooled the house, as shown in Figure 3.

One couple, P15 and P23(I-20m), thought the Nest was adjusting the temperature autonomously as it understood their needs. P23(I-20m) said, *"It senses when we're home and it knows what temperature we'd like it to be at various times of the day and so it adjusts it on its own."* However, her husband P15(I-20m) found that one of their two Nests did not have a schedule even when its learning function was active. He was *"actually surprised"* since *"[he and his wife had not] noticed that it didn't have a schedule."*

Participants also felt that their schedules could be improved but usually lacked the motivation to do so. P24(I-14m) explained he could make two adjustments to save energy. First, he would create an additional setback temperature of 81°F at 1 p.m., which was earlier than the 81°F setting he already had at 3 p.m. *"because I know it gets above the temperature in the day before then so there's no reason to keep it at 81°F until that late in the afternoon."* He would also raise the 81°F setting at 3 p.m. to 83°F to save more.

Note that in all of these examples, had we not conducted follow-up interviews, participants would not have seen problems with the Nest. They all believed that their Nest thermostats were working as they had expected. These anecdotes call into question the desirability of having the Nest fade into the background even though this might be desirable from a customer satisfaction standpoint. The perceived promises of the Nest's energy-saving features might have led participants to rely on the Nest and allowed them to be less active in controlling their heating and cooling systems.

Changes in behavior were not sustained

A number of factors could explain why people's interest in interacting with the Nest faded over time and why changes in energy-saving behavior were not sustained. The first was simply that the novelty effect wore off, a phenomenon commonly seen with technology products [8]. For example, P6(I-1.7m) was explicitly motivated to save energy, but it took less than two months for his excitement to wane: *"When we first got it, it was really exciting. A new gadget, we're trying to figure out what it can do. Now we're sort of used to it … [T]he novelty … has kind of worn off."*

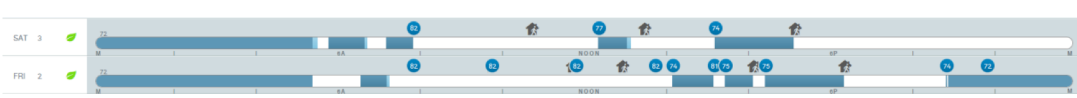

Figure 3. P14's Energy History is showing that the cooling was on during the weekend when nobody was at home.

Second, many participants began to rely on the Nest. As it turns out, they might have over-estimated the Nest's capabilities. P1(I-13m) and P25(I-13m) had not checked the schedule and the Energy History for about a year. Nevertheless, P1(I-13m) explained why he believed the Nest was doing its job: *"I just have faith in it. I assume that it's doing its job, but I don't really know. I haven't checked up on it."* When we asked what caused him to have such faith in it, he answered: *"Well, because it's a computerized thing, and it's fancy and it lights up when you put your hand near it."* The Nest's features, such as recognizing them when they passed by, might have played a role in the trust that the participants felt with the system.

Third, participants often became forgetful in their interactions with the Nest. As long as the Nest did not drastically change a participant's schedule and maintained the user-guided/revised schedule, most would not bother to reassess it in order to make it more efficient. This may have led to wasted energy and missed opportunities to save energy and money. For example, both P14(I-18m) and P24(I-14m), who mentioned finding ways to improve their schedules, forgot about the idea because they were doing something else at that time. P24(I-14m) gave more fundamental reasons, *"I have to do so little adjusting to the Nest that I did not remember to doing with it ... We have not had unusual activity on other fronts, so I was not motivated to check on it and make the necessarily change."*

Finally, the motivation to save energy might not be strong enough to overcome the inertia of existing behavior. After learning that the Nest was working while she was not home, P22(I-18m) mentioned that she might start *"taking a more active role, at least checking [the Nest] before [she] leave[s] for the day,"* and she even expressed a desire to learn how to check the Nest schedule and use other Nest features. However, she quickly admitted that she would not actually do this.

DISCUSSION

In our study of Nest usage, we observed that participants' thermostat control practices changed immediately after the installation of a Nest. Many of our participants actively tried to save more energy when they first got the product. However, after time passed, their engagement with saving energy decreased. In many cases, participants showed a tendency to trust the Nest and neglect active monitoring or decision-making for energy savings as long as they did not notice any problematic issues.

In our follow-up interviews, several participants (four out of nine households) were surprised that the Nest was not operating as they had originally believed. It is possible that participants might never have discovered incidents of energy loss and stayed with the current schedule when the ability to set a more optimal one existed. This highlights a central tension with the Nest—its success from a user experience standpoint (it performed well enough that people felt they did not need to pay it much attention) impeded its success from a sustainability standpoint (users' trust and resulting inattention led to missed opportunities for energy savings).

Designing eco-interactions

As we saw in our findings, some degree of active involvement by participants happened early on but needed to happen iteratively over time to sustain or increase energy savings. A challenge for designers, then, is to preserve the benefits of system autonomy and automation while facilitating interaction to promote and sustain users' engagement for achieving desirable energy efficiency over time. In the remainder of this section, we reflect on the tensions elucidated by our study and propose a set of design implications for eco-interaction systems, emphasizing the design of mixed-initiative systems that invite participation and reflection with the goal of saving energy at home.

Use mixed initiative to balance competing concerns.

In discussing the potential energy savings that can be obtained using the Nest, Nest Labs notes that the Nest's goal is not "solely energy savings," and that the Nest "places a high priority on the user's comfort" [15]. This prioritization of user comfort and control is reflected in the fact that Auto-Schedule attempts to learn the pattern of users' manual temperature changes rather than occupancy or some other implicit signal indicating intent behind users' inputs. As noted, in Yang and Newman's initial study of Nest usage [23], participants were not always sure that learning from their temperature adjustments would result in an optimal schedule for energy savings as, oftentimes, temperature adjustments were made to improve comfort. Even though many of our participants had a high-level goal of saving energy, the more immediate goal of achieving comfort would often win out. It follows that a "learning" thermostat that receives all of its initiative from users could end up optimizing for comfort rather than savings, resulting in undesirable outcomes over the long run.

An alternative design might be to create a mixed-initiative system [9] wherein the system primarily pursues the goal of energy savings and the user is free to pursue their goal of immediate comfort within certain system-defined bounds. The general notion of a mixed-initiative thermostat was proposed in [11,12], and here we extend this notion to articulate a clear goal for the system: to maximize energy savings while respecting users' expressed comfort preferences and desire for control. To balance these needs, it will be necessary for the system to *push* information, requests, and suggestions to the user rather than allow the user to initiate all interactions. As we saw, users' initial engagement with the system, which included active monitoring of system performance and fine-tuning the Nest schedule, waned after a few months. Thus, over the long term, a thermostat with an agenda may need to be assertive in getting the user's attention. The question remains: how can a smart device assert and pursue its goals without annoying or alienating the user?

We propose that designing spontaneous, enjoyable interactions to prompt users to engage with the system sporadically over time might be a valuable direction to explore. Here we emphasize that sustaining user engagement while not requiring constant attention is an important goal. As an example of a possible opportunity, our participants enjoyed seeing the Nest light up as they passed by, briefly attracting their attention. Perhaps such moments could be leveraged to alert users to situations that require attention, or to remind them to re-engage and reassess existing settings. However, merely alerting users to problems or reminding them to reassess may not be enough, as the challenge of converting information into action remains. We address this challenge next.

Bridge the gap between awareness and control

Horvitz suggested that mixed initiative systems should ultimately leave the user in control [9]. In particular, *allowing direct invocation and termination* of system services and *employing socially appropriate behaviors* (e.g., informing users of actions that will affect them), systems can maintain users' trust while providing significant value. In the case of the Nest, we saw situations where users recognized an opportunity for savings but were unable to follow through and take the required action.

Designers should consider ways to generate concrete plans for increasing energy savings that leave users in control but are easy for users to implement. As an example, consider a recommendation for an improvement to the user's schedule that appeared on the home screen of a thermostat control app or in an email. This recommendation could include an option that allows the user to implement the recommended change instantly. To help users decide whether such recommendations ought to be followed, systems could further provide *eco-feedforward* messages or visualizations to convey the projected impacts of the recommended changes. Providing actionable recommendations along with information about the projected benefits of those recommendations would enable systems to suggest courses of action that align with system goals while allowing users to stay in control. As a system does more prompting to assist with goal setting, it may also prompt a person's curiosity and motivation. Designers should thus provide opportunities for deeper interaction and reflection alongside the simple courses of action presented for easy invocation.

Reframe interactions around reflection and reassessment

In addition to drawing users' attention to potential energy saving opportunities, it would also be valuable to maintain lightweight engagement between users and the system on an ongoing basis. Smart devices like the Nest are not as 'smart' as users might expect. Limitations of current intelligent systems require users to monitor and remain involved in order to maintain and improve performance [23]. When the Nest was actively creating a schedule early in the study, participants were more curious and engaged with the Nest. Participants willingly paid attention and felt their interaction with the Nest was necessary. It seems likely that by the end of the first few of months of interaction, participants had taught the Nest a reasonable set of temperature changes that reflected their household routines and preferences, yet saved energy where possible by using a scheduled setback temperature or Auto-Away.

The normal ebb and flow of the household, however, combined with changes in people's needs, caused changes in ideal heating and cooling schedules. Our Nest participants often failed to negotiate making these changes, leaving the thermostat schedule as it was and reducing the potential to save energy. To overcome this, eco-interaction systems need to *stimulate reflection and reassessment*. Doing so requires rethinking the interaction design to emphasize reflection and reassessment rather than control and convenience. As an example, designers might consider designing ways to periodically perturb the user's routine interactions with the system. Mechanisms could be designed for the system to periodically initiate the evaluation and reassessment of the schedule, perhaps by expiring schedules after a period of time or asking users to choose between an existing schedule and a more efficient one proposed by the system.

People thought the Nest, with its clean aesthetic appearance and friendly UI, worked well enough. However, this was problematic because the Nest did not necessarily seek out optimal control patterns or adjust its control patterns to changing circumstances in the home. The resulting control patterns were often not as efficient as those that could be achieved by human intervention, yet users did not know when and how to enact changes to improve performance.

For the successful adoption of eco-interaction systems like the Nest, and to achieve the goals of energy savings for early adopters and the general population, we need to design more cooperative, collaborative and coordinated interactions between semi-autonomous systems like the Nest and their users, and figure out how to sustain those interactions over time. We suggest that tighter feedback loops between eco-interaction systems and their users can help them to develop and maintain more sustainable practices while users achieve their desired benefits such as comfort and energy efficiency. Employing mixed-initiative designs, providing actionable recommendations, and stimulating reassessment may be starting points for designing more effective eco-interactions in the future.

Caveats and Limitations

It is worth noting that, in this paper, we are not challenging the notion that people have relatively stable expectations for thermal comfort and that they expect indoor temperatures to be mechanically maintained at a level concordant with those expectations. More specifically, we are not engaging critiques of the cultural construction of thermal comfort (e.g., [1]) or models of adaptive thermal comfort (e.g., [2]) that suggest that people can or should attain comfort through other means than mechanical heating and cooling.

While we find such alternative views compelling and highly deserving of consideration, we are focused here on investigating the bounds of energy efficiency that can be obtained within the commonly understood constraints of thermostat-controlled temperature regulation for obtaining personal comfort. From this perspective, we believe that finding a balance between automation and user engagement will be key to optimizing energy efficiency in the face of consumer expectations of comfort. We also believe that finding such a balance is a challenge that the field of HCI is particularly well suited to address.

Even within the frame of improving thermostat control to achieve better energy efficiency in the face of a presumably stable comfort requirement, our study has limitations. Our study was restricted to the continental United States, and looked at a restricted set of people over a constrained period of time. The Nest users we studied were relatively affluent and technologically savvy compared to a more general population. Our conventional thermostat study participants were a bit more varied in these regards, but still not representative of the vast diversity of living situations, housing types, and individual differences found in US residences—to say nothing of differences across the globe. Understanding the issues with improving user control of HVAC systems more broadly remains a significant challenge, and we look forward to further studies that will deepen and fill out the findings of the present work.

CONCLUSION

The availability of smart home devices offers great promise in multiple arenas, most significantly in reducing consumers' energy usage through more efficient HVAC control. To inform the design of eco-interaction technologies—i.e., technologies that help people save energy while meeting comfort goals—we investigated how the Nest Learning Thermostat situates in the home and affects human behavior. We conclude that such systems can be better designed to better project their benefits, and to help users realize their goals in saving energy. We hope our research on eco-interaction will inspire the community to understand and improve upon products that work on behalf of people in everyday life.

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