Home Automation in the Wild: Challenges and Opportunities

A.J. Bernheim Brush, Bongshin Lee, Ratul Mahajan, Sharad Agarwal, Stefan Saroiu, Colin Dixon*
Microsoft Research, *University of Washington
{ajbrush, bongshin, ratul, sagarwal, ssaroiu}@microsoft.com, ckd@cs.washington.edu

ABSTRACT
Visions of smart homes have long caught the attention of researchers and considerable effort has been put toward enabling home automation. However, these technologies have not been widely adopted despite being available for over three decades. To gain insight into this state of affairs, we conducted semi-structured home visits to 14 households with home automation. The long term experience, both positive and negative, of the households we interviewed illustrates four barriers that need to be addressed before home automation becomes amenable to broader adoption. These barriers are high cost of ownership, inflexibility, poor manageability, and difficulty achieving security. Our findings also provide several directions for further research, which include eliminating the need for structural changes for installing home automation, providing users with simple security primitives that they can confidently configure, and enabling composition of home devices.

Author Keywords
Home automation, smart home, domestic technology.

ACM Classification Keywords
H.5.2 User Interfaces, H.1.2 User/Machine systems.

General Terms
Human Factors.

INTRODUCTION
Smart homes with sensing, actuation, and networked devices have been anticipated for a long time. Research and commercial versions have been built, including Mozer's adaptive house [23], Georgia Tech Aware Home [18], Orange [15], eHome [20], and MIT's House_n [17]. Although the term "smart home," with the implication that a home adapts to inhabitants [e.g., 15, 23], has caught the attention of the media and researchers, the term "home automation," defined as the capability to automate and control multiple disparate systems [21], more closely describes currently available technology. Automated homes can be seen as the stepping stones to smart homes.

CHI 2011, May 7–12, 2011, Vancouver, BC, Canada.

However, home automation itself has not been widely adopted. This adoption failure is particularly surprising because many of the devices needed to enable home automation, such as motion sensors, programmable lighting, and video cameras, have been available to consumers since the 1970s. While some automation technologies are gaining acceptance in commercial settings (e.g., motion sensitive lights), broader adoption is severely lacking with the exception of security systems installed and monitored by a service company (e.g., ADT [16]). ABI Research estimates that only 204,000 home automation systems were shipped globally in 2009 [21].

To better understand the current state of home automation and learn about barriers to broader adoption from people's long term experience of living with home automation, we conducted 14 semi-structured interviews and household tours. Our interview explored why the household had installed home automation, their experience of living with it, and how they handled guests and security considerations. We also asked participants about their interest in a set of possible home automation applications to elicit information about configuration and access control considerations.

We classified the people who have already adopted home automation in two groups: 1) Do-it-yourselfers (DIY) who have installed automation themselves and 2) Outsourced households who have outsourced the installation and management to professionals. These groups offer a rare opportunity to study the use of automation in people's own homes, in contrast to studies conducted in home laboratories [e.g., 18, 20, 26] or focused on homes that adopted automation for religious purposes [33]. To compare and contrast these two groups, we recruited both DIY and Outsourced households.

While the majority of households were quite positive about their experience with home automation, our participants' experiences also highlight four significant challenges. These are high cost of ownership, inflexibility, poor manageability, and difficulty achieving security. While the general appeal of home automation and smart homes is an open question, these challenges represent barriers that would need to be overcome before the general population could consider using home automation, a building block in many smart home visions.

We believe that some of the problems we observed will be alleviated through market competition and developing

standards, but our findings also highlight problems that require further research. These include eliminating the need for structural changes for a good home automation experience, providing end-users with simple, confidence-building home security, and enabling composition of home devices. More broadly, we hope that research to overcome these barriers will enable a home technology ecosystem that allows people to easily adopt the subset of home automation technology that appeals to their household.

RELATED WORK

Visions of smart homes have long caught the attention of researchers, not to mention the popular press. Considerable effort has been put toward enabling the technology necessary for home automation. One example is the work to improve device interoperability (e.g., DLNA [9], SpeakEasy [11]).

Research related to smart homes has suggested principles of smart home control [7], outlined challenges [10, 31], and recommended approaches to controlling devices [14]. A common theme in this research has been the importance of placing people in control, thus avoiding the paradox observed by Randall [26] where control systems were so complex that people experienced a lack of control. Both [15] and [2] provide excellent overviews of smart home research over the years. Chapters in [15] explore people's conception of the home, designing for the home, and the home of the future. Bell and Kaye [2] draw from media portrayals of futuristic kitchens and smart home installations to argue that experiences and desires should be valued over efficiency.

Unfortunately, due to the relative rarity of people living with home automation, most studies have been conducted with people who have consented to reside in smart home laboratories for some period of time (e.g., Orange [26], Aware Home [18], House_n [17], Tampere [20]). Two notable exceptions are Mozer's experience living in his Adaptive House [23] which attempted to adapt to his routines using machine learning techniques, and Woodruff *et al.*'s study of 20 American Orthodox Jewish families' use of home automation for specific religious purposes [33]. Most of these households used the X10 technology and expressed that automation would not be worth having if not for Sabbath observance. In contrast, the households in our study had a range of non-religious reasons for adoption and used a diverse set of systems. Thus, our work offers an opportunity to learn from people's long-term and general use of home automation.

While not focused on home automation, a related set of research has studied home networks [e.g., 5, 12, 13, 25, 29, 30], exploring how households configure, manage, live with their home networks and manage access control for sharing data and devices [e.g., 19, 22]. Shehan and Edwards [29] described different models for addressing home networking challenges and advocated for research on exploring ways to make network management easier for people. This area of research highlights the effort necessary to manage home networks [13], the diversity across households both in terms of their technical setups and their household routines [12], the importance of planning for change, and role of the technology guru in the home [25, 28]. While we observed these behaviors in our study, we focus on use of home automation which introduces additional sensing and control into households. Grinter *et al.*'s [12] suggestion that future research should study financial considerations inspired us to explore issues of costs with our households.

STUDY METHOD AND PARTICIPANTS

Our study took place in the summer of 2010 when we conducted semi-structured visits to 14 households with home automation. We recruited households that had at least one of the following home automation systems: remote lighting control, multi-room audio/video systems, security cameras (not counting standalone professionally monitored security systems such as ADT [16]), or motion detectors. We spoke with households with a range of brands including X10, Control4, Elk M1, HAI, Creston, Lagotek, and Leviton. It was not uncommon for households to have several brands installed. Nine of our households were DIY households, while five had Outsourced their installations (see Table 1). We considered Household O1 Outsourced, because the DIY father had died recently and the rest of the family members were only consumers of the technology.

We spoke with 31 people across the 14 households: the technology *guru* of every home and typically one to two other technology *consumers*. We initially wanted households with more than one resident and achieved this for 12 of 14 households. However, recruiting households with home automation was challenging and so two households (D3, O5) with only one primary inhabitant were included, although D3's girlfriend often stayed with him. In Household D5 only the guru agreed to speak with us.

We found our households through mailing lists at Microsoft for home automation enthusiasts (8 households) and a recruiting service that found 6 households external to our organization. Households with a member that worked at Microsoft were compensated with a $50 gift card while households with external participants received a software gratuity for each participant up to four per household (max value $600 each). The majority of the households were located in the northwest United States. We also conducted four interviews using video conferencing software allowing us to interview households in North Carolina, Minnesota, and North Dakota in the USA and near Reading in the UK.

Our household visits had four main parts. First, a short technology inventory modeled on the one used by [5] to help us understand the technology installed in the household. Next, we interviewed families about their experience with home automation technology including what led them to install it, favorite and least favorite aspects of each member of the household, use by guests, how often they modify the system, and whether remote access was

	ID	Time (years)	Brands	~ Cost (USD)
DIY	D1	4	Elk M1	$5,000
	D2	2	Elk M1, Charmed Quark	$10,000
	D3	1.5	mControl, Leviton	$5,000
	D4	1	X10	$200
	D5	2	Lorax, BayWeb	$14,500
	D6	2	Control4	$50,000
	D7	5	X10 Active Home	$300
	D8	2	Lagotek	< $5,000
	D9	10	ISY-99i, Insteon, X10	$3,000
Outsourced	O1	3	HAI	Unknown
	O2	6	Creston	$60,000
	O3	2.5	Control4	$120,000
	O4	10	EIB Instabus, KNX	$13,500
	O5	2	Lagotek, AudioQuest,	$20,000

Table 1. Household Information. Number of years household has lived with automation, brands installed, and estimated cost.

enabled. While we had some specific questions, this section was semi-structured and each interview included additional discussion as we followed up on topics of interest that arose as we discussed use in each household, which varied greatly depending on the systems installed, composition of household (e.g., kids), and type of installation.

We then asked the participants to imagine a "Home Application Store" from which they could purchase applications and enabling hardware. We gave each participant a list of 17 applications, shown in Table 2, that were inspired by industry websites [e.g., 6, 9]. To understand if households had any concerns or constraints related to installing applications in their home, for each application we asked each household member if they already had the functionality, or would or would not be interested in purchasing it.

Finally, household members gave us a home tour (either in person or via web camera if remote) to show us their home automation devices in situ (e.g., motion sensors, wiring closets). We photographed the devices and asked additional questions about their installations as needed to better understand their experience. All interviews took roughly two hours and were audio recorded. Interviews were transcribed and then analyzed using the affinity diagramming technique [3].

LIVING WITH AUTOMATION

All of our participants had lived with home automation for more than a year (see Table 1), and 2 households had 10 years of experience. In this section, we describe the diversity in automation functionality across households, their use of it to augment their houses, and participants' favorite aspects: convenience, peace of mind, and control.

Diversity in Installations and Desires

One might expect the self-selected group of people interested in home automation to have installed similar

	Application	Have	Buy	Not
Con.	Ability to set 'Scenes'	24	5	0
	Centralized control of automation systems	24	4	1
Media	View computer content on TV	19	5	5
	Watch recorded TV on any TV in house	16	11	2
	View computer content on mobile phone	4	20	5
	Show mobile phone content on TV	3	13	13
	Transfer video calls between devices	0	13	15
Security/ Monitoring	Remote Access to home cameras	16	10	3
	Automatic Alerts (e.g. Stove left on)	9	18	2
	Remotely open front door	4	18	7
	Log people's use of devices	3	9	17
	Time limits across multiple devices	1	15	12
	Watch child pc use on TV	0	17	12
Environment	Thermostat that learns routines	16	10	3
	House Energy Monitor	3	23	3
	Turn devices on/off based on presence	3	20	6
	Adjust windows and shades automatically to keep house comfortable	1	24	4

Table 2. Participants' responses to a set of applications about whether they have the functionality, would be interested in buying it, or would not (N=29, two children did not answer).

functionality; however the households we interviewed had diverse installations and desires, consistent with differences previously observed in home network installations and household routines [12]. Households ranged from using X10 to control a few lights (D4) to systems with wall panels to access functionality that includes viewing cameras (O5). Example automation devices are shown in Figure 1.

Installed functionality generally fell into one of four categories: Lighting, Security, Media, or Environment. Automated lighting with programmed lighting scenes (e.g., "All Off") was the most common type of automation and was present in all but 3 households. Households with automation for security have motion sensors and/or cameras. Five households (4DIY, 1O) managed the security aspects themselves, while five households (3DIY, 2O) had professionally managed security systems in addition to their other automation systems. In fact, two DIY homes with professional security systems have additional separate motion sensors or cameras they manage themselves. Eleven households (6DIY, 5O) had media related functionality including multi-room audio (8) and/or video systems (3) and home theater systems (4). Ten households (6DIY, 4O) had environment related automation including automation to control the heating system (8) or window blinds (2).

At a high level, similar to the diversity in what functionality they had already installed in their homes, participants' interest varied across the set of applications we asked about (see Table 2). For example, not surprisingly, monitoring applications were more popular among some families with children, and universally uninteresting to the six households without. Indicating people's diverse interests, when we asked to participants to rank their top 5 favorite applications

Figure 1: Home Automation User Interfaces: remote control for lighting scenes (left), augmented light switches (center), wall panel with remote camera view (right).

from the ones they would buy, no application was ranked first by more than six people. We did find that energy conservation applications were most appealing among the applications that most participants did not already have.

Comparing Outsourced and DIY households at a high level, we generally saw that Outsourced installations were static and unchanging, while DIY households had more functionality and iteration.

Augmented Homes, Not Smart Homes

Our participants primarily used *augmentation* to add automation, closer to the vision of unremarkable computing advocated by [32] than the typical smart home vision [23]. Households left a traditional interface (e.g., light switch) available, but augmented it with additional functionality and typically the ability to be controlled remotely (see Figure 1). D9_G[1] said "the wall switches are still there and they can still be used manually. That's generally how people use them, especially [if] they come over here."

Across our households we observed two levels of automation in use, *user controlled* and *rule-based*. In user controlled automation the household member explicitly takes a single action which causes several things to happen. For example, an "All Off" lighting scene button (physical or virtual) turns off all lights in the house. In Household O4 manually arming the alarm system affected heating settings as well as lights. Triggering Household O3's theater scene included lowering automatic blinds and the projector screen, and dimming the lights.

In rule-based automation, rules trigger automation based on events or at certain times. These rules are configured by the guru or professional installer. Not all of the households we visited used rules as they definitely represented an additional level of automation complexity. Event-based rules were typically motion sensor based. For example, turning the lights on when someone walks into the bathroom. Rules triggered by timing included actions taken at sundown (e.g., turn on outside lights), at sunrise, or related to wake-up or evening routines. As we will discuss in future sections, introducing rules often introduced problems as well.

Convenience, Peace of Mind, and Control

Several household members, particularly spouses of DIYers (e.g., D2_C, D6_C, D8_C), described being initially skeptical of home automation. However, after living with it the majority of household members, with the exception of those in Household O3 and D7, seemed quite satisfied with their experience. For example, D8_C said, "At first when Bob introduced it to me, I kind of thought it was silly, but just the convenience of it, just pressing one button, I mean, it's just amazing how – just to see the whole lights on the first floor come on instantaneously." Three common themes *convenience, peace of mind,* and *centralized control* emerged for people's favorite aspects of home automation.

Thirteen participants, across both DIY and Outsourced households mentioned convenience as one of their favorite aspects, sometimes with a bit of embarrassment about laziness. D6_C said "It allows me to be lazy, honestly, because every day [before automation] I would go double check the locks, make sure all the lights are off on all the floors and make sure that everything's closed."

D6_C also felt automation gave her "peace of mind. I can track things when I'm not there and know that on your way to work that it's sort of secure and set the way you want it to be." Eleven household members similarly emphasized security as one of their favorite aspects. Household D4's primary motivation for installing automation (a set of X10 based sensors primarily on doors and windows) was for security. In Household O1, external security cameras viewable on a TV channel were the favorite of two household members.

Finally, nine participants mentioned control as a positive aspect. Five participants in Outsourced households emphasized the value of having centralized control of various devices. For example, media control that allowed displaying the same DVD in multiple rooms (O2_C) or controlling a variety of devices from an iPod (O4_C). DIYers tended to emphasize control over what automation they installed, what functionality they enabled, and

[1] Participant Ids denote household (see Table 1) and technology guru (G) or a consumer(s) (e.g., C, C1). Names have been anonymized.

knowledge about what is happening at their house. D6_G said "I like just being in control, like during the day, I get an email every time somebody comes to the door."

Not Ready For Broad Adoption

Our participants have extensive personal experience living with home automation, so we felt they were well informed to comment on the potential value of home automation for others. Given the frequent mention of eldercare as one application for smart homes, we asked participants their opinion about home automation's value to their parents or older friends. Almost universally, participants thought this was a bad idea. D8_G felt "it's just too expensive; there's no payback for the benefit you receive," while D2_G felt there was potential benefit but "[home automation] is not robust enough, I think, to be stable for the average person."

Participants' comments in response to this question, along with their responses throughout the interview illustrated four barriers to broader adoption: *high cost of ownership*, *inflexibility*, *poor manageability*, and *difficulty achieving security*. In describing these, drawing on our participants' experiences, we want to be explicit about two points. First, many of these issues we describe were not barriers to use for the households we spoke with because they were uniquely qualified (DIYers) or spent money to overcome them. Second, we explicitly do not address the question of whether home automation functionality appeals to a broader audience. The barriers we have identified would need to be overcome before the general population could even consider using it.

BARRIER 1: HIGH COST OF OWNERSHIP

The first barrier to wider adoption is the high cost of ownership of home automation, either money or time and sometimes both. We describe our participants' experience, and how little most were willing to spend on additional functionality.

Expensive in Money or Time (or Both)

As Table 1 shows, money spent by the households on home automation varied widely from about $200 to $120,000. Monetary cost was one of the most frequently mentioned consideration determining both the brand and amount of functionality to install. Household O2 said they had looked at higher end systems which had more capabilities, but the prices were much higher. Not surprisingly, DIY households typically spent less ($200 to $50,000, median $5,000) than Outsourced households ($13,500 to $120,000, median $40,000), reflecting that the DIY households paid for hardware, but not for installation or support.

However, even the hardware alone can be quite expensive. For example, individual panels to replace standard light switches might cost around $100. DIY household D6, who spent around $50,000, had augmented light switches and panels that could display pictures in almost every room and automated door locks. At the other extreme, Households D4 ($200) and D7 ($300) used very inexpensive X10 motion sensors and wall-socket plug-in controllers that are much cheaper but have more limited functionality.

Five participants mentioned cost as one of their least favorite aspects of home automation. For example, D2_G said "Costly, that's the only disadvantage." O3_C expressed "it's been expensive, heart-wrenching." Household O3, as we described later, struggled with the reliability and usability of their system and seemed particularly dissatisfied, not surprising given the amount they had spent on their system ($120,000).

Outsourced households require an outside consultant to come when their system needs adjustment or repair. To our initial surprise, the cost of these consultant visits did not seem to concern the households as much as we expected. We then learned the visits were relatively infrequent and had a low cost relative to the initial installation cost. After initial setup, consultants were primarily called only when problems occurred. Household O4 had a consultant visit only three times over the 10 years for about $200 each time. Household O2 had not needed a consultant in so long that they could not remember the hourly cost (either $45 or $65 per hour). O5_C frequently had his installer back to deal with problems but did not pay because the installer was a friend of the family who had sold him the system.

In addition to monetary cost, for DIY households the time cost currently required to install and manage home automation should not be underestimated. Frequently the guru who drove the installation had a long standing interest in automation and carefully researched which brands they installed. D8_G said "I've been following this space probably for about five years, and just waiting for something that didn't require me to be a developer [of code]." For several DIY gurus (e.g., D2, D7, D9), automation was their hobby and they described happily spending hours tweaking their systems.

Low Perceived Value of Additional Applications

For applications participants were interested in (see Table 2) we asked them about how much they would be willing to pay for them. We started asking this question after the first three interviews to learn more about how valuable the participants perceived the applications to be. While their responses are speculative, the relative value participants assigned to different applications helped us understand how desirable they were.

In general, participants did not seem to put a high value on the home automation functionality we presented, which surprised us given the amount of money and/or time they had already invested. Of the 143 times participants reported the price they would be willing to pay, 61% of the values were $20 or less. Comments included O2_C: "Anything over $20 it's got to be something very important to want." and D5_G: "Not more than two or three dollars, I think." In ten cases, participants were interested in the functionality only if it was free.

BARRIER 2: INFLEXIBILITY

We now describe how current installations are inflexible, often requiring a choice between a single integrated system or flexibility, as well as the need for structural changes in many installations, which limits when automation can be installed and raises concerns about moving.

Choice between Integration Ease and Flexibility

Several participants, especially DIYers did not want to be locked in one specific vendor, and expressed resistance to brands more typical in Outsourced houses (e.g., Creston, Control4, etc.) because of a perceived lack of personal control. D9_G said "But the problem with those systems is that you can't really do anything yourself." While D2_G commented "It's like the Control4 [a home automation system] stuff is, you know, integrated but [then] you're locked in to their stuff." O4_G, who Outsourced, chose to use an open standard (EIB) specifically because it meant he could buy from many vendors.

However, choosing to use multiple brands meant dealing with the challenge of integrating separate systems. D2_G commented "it's kind of a task to keep it all integrated and working." Integration difficulties caused some of the devices with network capabilities to be not connected. Eight households had some devices not get connected to their home automation system. For example, D8_G had not integrated his alarm system with his Lagotek automation system because of the cost and work involved. In his case, integrating the devices and pieces was complicated enough that it was easier to keep them separate systems.

Structural Changes Common

Perhaps one of the biggest challenges to broad adoption is the structural changes needed to install home automation. The most common trigger for installing among our participants was building or remodeling a house. Of our 14 households, nine put automation in place either during a remodel or new construction. This was seen as the ideal time to have appropriate wiring installed either by themselves or by the contractor. These changes at the structural level [27] were often complicated as builders, contractors, and even permitting agencies got involved. D6_G told us that "all the local wiring for the home automation was one of the things keeping us from getting our occupancy permit, the inspector didn't know the code very well when it came to the low voltage stuff." Frequently, the DIY gurus put in their own devices after the wiring was complete or immediately replaced standard devices installed by contractors.

In an approach more suited to broad adoption, five households (3DIY, 2O) did retrofit installations leveraging wireless to avoid wiring. D8_M described choosing his brand, "it's Lagotek, a wireless system. So it's really strong in the retrofit model and that's why we went ahead and did it." Although D8, in fact made some structural changes as well, installing Cat 5 cables for audio streaming. The other four retrofit installs had more limited functionality (e.g., the X10 installation in D7 involved only X10 wall-plugs to turn on and off devices). One participant, O5_C felt that using wireless for audio streaming was the reason it frequently stopped working. He was happy the new home he was moving into was already wired.

Given the structural changes households made, the challenge of moving was a concern. Several participants felt adding home automation would make their houses more difficult to sell. Household O4 had done the most extensive planning ahead. The guru opted to outsource even though he had the technical expertise to manage the automation. He hired a consultant to have a person available to support any new owners. O5_C described to us the challenging process of moving and reinstalling his $20,000 worth of audio equipment and other hardware to his new home.

BARRIER 3: POOR MANAGEABILITY

Living with a home automation system requires managing it. We should stress that most of the households we spoke with were well-equipped to managing their installations. However, their experience suggests challenges that would need to be addressed before broader adoption of home automation including support for the iteration necessary to customize, issues with reliability and complex user interfaces, and concerns raised by reliance on consultants.

Iteration Required

We asked households how often their home automation set-up changed. As Chetty *et al.* [5] observed for home networking there was a set of DIYers who were constantly changing their home automation set-up (D2, D3, D7, D8, D9). However, most households, even those with unchanging set-ups, described an initial period of iteration right after they installed as they customized their set-ups to their homes and household needs.

We found it particularly interesting that a few households described scaling back their initially installed functionality as they became aware of a difference between what they thought they wanted before installing automation and what functionality they actually wanted. For example, D8_G described his changing desires:

"I thought when I went into this, I'd want my alarm system integrated and I'd want these automatic features firing off in the background like, you know, I'd wake up and music is playing in my bathroom and the lights come up, you know all these Jetson type things. And the challenge with that, while they're all great, I don't live that structured of a life, not waking up into [it] every day, and I'm not going in the shower every day at the same time. And you know, I don't want to hear music all the time. So I don't think the routineness of automation is what I was really wanting."

In addition to changing desires, the challenge of creating rules that worked reliably caused iteration and scaling back. D1_G said "I came to discover that you can't really create hard rules to describe every single situation that you might want to automate." DI_G's experience is an excellent

example of Edwards and Grinter's challenge of inference in the presence of ambiguity [10].

Household changes could also cause iteration. D3_G told us that he expected to change all his rules when his girlfriend moved in because they had different preferences around whether the lights should be on or off when watching TV. After the birth of their second child, Household O4 had a consultant come back to set-up a switch for turning off lights in the child's room from their bedside.

Unreliable Behavior is Frustrating

Fourteen participants explicitly mentioned problems with their current system's reliability, which typically resulted in unpredictable behavior. Four households' problems were related to rule-based automation. For example, consumers in O4 and D7 both reported the lights sometimes went off unpredictably in their homes (e.g., D7_C: "I'm sewing and the light goes out."). Participants felt rules in general were hard to debug when they did not work and so participants lived with problems or turned off the rules.

Lack of responsiveness was a related frustration. Four households described waiting several minutes for a system's response. Similarly, Household O3's central control device was extremely unreliable and finicky. O3_C commented "you have to be really, really careful …, you have to talk to it first and do what it wants to do."

Even households not struggling with reliability emphasized its importance. D9_G said "it [home automation controller] pretty much never fails, and that was important, because otherwise it was not really helpful." He switched from using his PC as his central controller to an ISY-99i unit, with the loss of some functionality and additional expense, because his previous setup was unreliable.

Complex User Interfaces Limit Use

The augmentation strategy many households adopted, particularly for lighting scenes, aimed for a simple interface that could be used by anyone including guests. While some households were more successful than others at achieving simplicity, problems with complex user interfaces faced by participants, particularly the technology consumers, and guests illustrate that user interface challenges exist.

Eight participants mentioned complex user interfaces (e.g. Fig. 1) as one of the things they most dislike about home automation. D3_G commented he disliked "Teaching other people how to use it, the girlfriend acceptance factor is not that high." The other seven participants (3DIY, 4O) had trouble learning the user interfaces. For example, the younger brother in the household O3 mentioned that "He [his brother] spent hours trying to show me how to use it, and I still don't know how to use it."

Complex user interfaces including some augmented light switches could be confusing or even frightening to guests. Six households told us that they do not tell guests about the home automation system. Others explained problems guests experienced. O4_C1 noted people's fear: "I started explaining the panel (how to call fire department) to them and they looked in dread. People just don't want to touch it. And my own mother sat in our house in the dark, because she was scared to touch any of the controls."

Consultants (Internal or Hired) Required

To handle manageability problems, the DIY guru served as the on-site consultant, while Outsourced households relied primarily on professional consultants. In contrast to the Outsourced homes that Woodruff *et al.* [33] studied who seemed to find value in ceding control to the consultant, households we visited described downsides to being reliant on a consultant including inability to fix their own system, inability to customize, and password management.

O2_C expressed discomfort with her inability to fix their system saying: "I don't like that we can't fix it ourselves." Household O1, with the death of their guru, had a particularly challenging situation. They used the system daily, but were unsure what they would do if anything broke. O5_C also expressed his difficulty learning to troubleshoot issues.

Reliance on consultants, whom they typically only contacted for problems, also restricted households' ability to customize. O5_C also told us he would have liked to try out different scenes if he knew how to experiment with the system. While O2_C knew the brand they installed (Creston) did not restrict people from learning how to program it, she thought it was very complicated to learn how. Lastly, Outsourced households must also decide how to deal with passwords. Household O2 had explicitly decided not to share the password to their system with the consultant, while O3_C did not know the password for changing rules and assumed the consultant had it.

BARRIER 4: DIFFICULTY ACHIEVING SECURITY

During the interviews we asked participants how they managed access to their current automation functionality and what, if any, usage restrictions they would want to place on future applications they desired (see Table 2).

Presence Based Access Mostly Sufficient

Most automation functionality, (e.g., lighting, media) participants had enabled could be used by anyone physically present in the house. Because households had augmented the physical controls, when inside a house you could access the functionality using wall switches or a remote control device. The main exceptions were home security systems which always required passwords, and interfaces for writing rules, which often did. Households were also particularly concerned about remote access which we describe next.

Handle Remote Access with Care

Remote access was a double-edged sword for people. The functionality was appealing, but participants worried about introducing a security risk. Eight households currently have remote access enabled, all but one with password protection.

Households used remote access for a variety of tasks including remotely controlling lights to make a house appear occupied when no one was home, turning on heating before they arrived home, checking the state of the house using cameras, or verifying the doors had been locked.

In general, participants perceived remote access to be valuable. When asked the importance of remote access to them, participants' median response was "Important" on a 5-point Likert scale (Very Important to Very Unimportant). Remote access appealed particularly for vacation scenarios; five participants commented that it is or would be useful when they are away from home for a long time.

However, seven participants mentioned that remote access makes them concerned about security. D9_G told us that "There is a way to have the system respond to text messages… But, for security reasons, I decided not do that because anybody could send text message. So, I actually don't want to have that hooked up." O4_C who had not hooked up remote access said "I don't want software controlling my front door. I don't want it opening at random whilst I am on holiday… Once something is software controlled, it can be hacked in some way."

Even very technically savvy participants expressed concerns that enabling remote access would make their house vulnerable. D2_G had chosen not to make his automated door locks available remotely because even though it was password protected he was not 100% sure of the security. Similarly, D8_G expressed that security concerns about his wireless automation system, which was remotely accessible, were "part of the hesitancy of hooking up the alarm system" to his automation system.

Finally, the level of concern of some participants was directly related to what technology was in the house. D4_G commented "if it had cameras I would be concerned about it. But for what I have, I'm not that concerned." Similarly, D3_G, the only participant with remote access that was not password protected, was unconcerned about people accessing his system: "If you knew my port number and my IP address you could log in and turn the lights on and off."

High-Concern Devices: Door Locks and Cameras

Two devices we discussed with participants, door locks and cameras, raised the most security concerns and illustrate the tension participants felt between convenience and security. For example, two DIY households already had automated door locks. D6_G enthusiastically described remotely unlocking his front door while away on vacation (he also has a camera at his front door) to let the house cleaners in because he had forgotten to give them a new key. On the other hand, as previously mentioned D2_G had not made his automated door locks available remotely due to security concerns. He also keeps a separate password for his alarm system so that if someone steals the door access card they could not disarm the alarm system.

Cameras also raised additional security concerns for participants. Five participants described increased security restrictions being necessary for the "remote access to home cameras" application. For example, D7_G said before installing that functionality he would want "A drop dead firewall to prevent outsiders from logging in and wandering around your house visually." D9_G wanted increased security for access inside the house as he would prefer guests could not view a camera setup in his child's room.

Temporary Access Important

Participants raised the importance of being able to give temporary access to automation functionality to guests. Specific examples they shared with us included the need for babysitters to have control over media applications or grandparents staying with kids, temporarily having the same access as the parents. D8_G said "We've got my wife's parents quite often come and watch the kids. So you'd want to have the ability to delegate that." Similarly, two of the participants interested in buying the "Automatic Alerting" application wanted the ability to send the alerts to someone else temporarily while on vacation. Cisco's Valet router does provide guest access to the Internet. While a step in the right direction, the router allows Internet access only, with no access to home resources or automation.

Simple User Groups for Future Needs

For applications participants were interested in buying (see Table 2) we asked them what restrictions, if any, they would want to place on who could use the applications. Typical responses included "anyone in the house," "parents only," and "no guests." For example, not surprisingly, participants interested in logging-related applications typically felt access should be restricted to parents. For a few applications, they were very specific about wanting to limit guest access. For example, limiting guests from access to home cameras (D7), preventing guests from seeing people's use of devices in the home (D4, O2), or seeing data about the house energy monitor (O2). Occasionally, a guru also told us they would like to restrict the ability to configure an application to themselves (e.g., for automatic alerts, scenes, and setting up centralized control). Given the complex needs found for home file access control [22], we were pleasantly surprised that for times when physical presence in the home did not suffice as access control, all the restrictions our participants expressed could be handled by a small set of user groups: adult household member, child household member, guest, and technology guru.

We also asked participants if they had any concerns about the devices an application might want to access. A few participants wanted to limit the set of devices an application could access. Participants' comments suggest that having applications ask for permission, similar to methods suggested for user permissions [e.g., 1, 22], to use devices during configuration would address concerns.

IMPLICATIONS FOR HOME TECHNOLOGY RESEARCH

Our study illustrated four barriers faced by households that adopt home automation: high cost of ownership, inflexibility, poor manageability, and difficulty achieving security. The barriers existed for both types of households, DIY and Outsourced, that we interviewed, although they impact each group differently and each group has made different trade-offs to overcome them. For instance, while the Outsourced households suffer from cost of ownership primarily in terms of money, the DIYers trade-off lower monetary cost for increased time commitment. Similarly, DIYers address inflexibility with expertise, while Outsourced household tend to choose one brand.

While we believe that some of the problems we observed (e.g., reliability of individual devices, basic interoperability) will be addressed through market competition and developing standards, our findings also highlight harder problems that merit the attention of the research community. We discuss three such problems below.

Bandwidth Needs vs. Structural Changes

Requiring households to make structural changes to their homes for the best experience dramatically raises the installation cost and reduces the appeal of home automation. The primary driver for structural changes is the need for wires, either special electrical wires to power devices or network wires for reliable, high-bandwidth connections. While wireless networks have taken a huge step in the right direction; our participants' experiences with audio streaming make clear the trade-off they face between reliable bandwidth and structural changes. Continued research on reliable high-bandwidth home networks that require no additional wiring (e.g., wireless or power-line) remains critical. Emerging technologies such as 60 GHz, IEEE 802.11af and Femtocells are promising and their utility in the home environment needs investigation.

Standalone Devices vs. Home Integration

Aristotle claimed "The whole is greater than the sum of its parts," but unfortunately due to challenges with integration and manageability, several households we interviewed were forced to keep pieces of their home technology separate. This separation creates three problems: 1) each sub-system (e.g., media) must be independently managed, which can become a management nightmare; 2) it becomes difficult to add cross-device functionality such as tying changes in the home alarm state to thermostat control; and 3) careful attention needs to be paid to which devices are compatible with various sub-systems, which makes it much harder to incrementally grow the network and forces users to buy all devices in the sub-system together to ensure compatibility.

Given the diversity we saw in homes and the iteration our participants engaged in to customize their automation, ideally users would be able to organically acquire devices from a range of manufacturers, conduct lightweight experiments to understand if the functionality fits their needs (as also argued for in [24]), and reap greater benefits as they add more devices. Unfortunately existing smart home technologies do not consider this incremental growth or composability aspect [e.g., 4]. At the other extreme, device inter-operability standards allow users to buy devices from different vendors but they are insufficient alone because they provide no basis for coordinating across devices [24]. We thus see need for a more composable architecture for organizing technology in the home that includes both a basis for device coordination and incremental, vendor-independent extension of functionality.

Simple Confidence-building Security vs. Desired Functionality

Our study showed that the security and access control needs of both DIY and Outsourced households are unmet. We thus believe that research is needed to develop simple security primitives that are custom-designed for the home environment. Our work suggests that the security needs of homes, while superficially numerous, can be met with a few simple, well designed primitives that take advantage of the unique nature of the domain. For instance, proximity implies a level of trust, also noted by [19, 22], and our participants tend to think of access control in terms of a few simple groups (e.g., "parents," "kids"). We believe these provisions along with streamlined temporary access for guests would go a long way in meeting householders' needs. It would be interesting to explore whether the simplicity of using groups outweighs possible exceptions.

Our participants' choices and concerns about remote access also highlighted that households are making trade-offs between security and desired functionality. Not only must home security primitives be simple to configure, users need to be able to fully understand the implications of their security settings, so they can build confidence in them. Without this, users are likely to give up some of the convenience (e.g., remote access) for peace of mind, as we observed, or inadvertently live in insecure environments.

CONCLUDING REMARKS

Our study of long-term use of home automation illustrates why participants use automation, the diversity of use across households, and how both Outsourced and DIY households struggled, albeit in different ways. It also uncovered four barriers that need to be addressed before home automation becomes amenable for broader adoption. These are high cost of ownership, inflexibility, poor manageability, and difficulty achieving security. Most participants were positive about their experience with home automation, having addressed these barriers using a combination of expertise, effort, and money. Our findings suggest three future research problems: eliminating the need for structural change to install home automation, providing households with simple, confidence-building security mechanisms, and the ability to compose household devices. We are beginning to address these problems [8].

ACKNOWLEDGMENTS

We thank our participants for opening their homes to us.

REFERENCES

1. Bauer, L., Cranor, L., Reeder, R.W., Reiter, M.K., Vaniea, K. A user study of policy creation in a flexible access-control system. *Proc. CHI 2008*, 543-552.
2. Bell, G., Kaye, J.J. Designing Technology for Domestic Spaces: A Kitchen Manifesto. *Gastronomica 2*, 2(2002), 42-62.
3. Beyer, H., Holtzblatt, K. Contextual Design: Defining Customer-Centered Systems. Morgan Kaufmann, 1998.
4. Brumitt, B., Meyers, B., Krumm, J., Kern, A., Shafer, S.A. EasyLiving: Technologies for intelligent environments. *Proc. HUC 2000*, *LNCS 1927*, 97-119.
5. Chetty, M., Sung, J-Y., Grinter, R. How Smart Homes Learn: The Evolution of the Networked Home and Household. *Proc. UbiComp 2007*, 127-144.
6. Control4 home automation and control. http://www.control4.com.
7. Davidoff, S., Lee, M., Yiu, C., Zimmerman, J., Dey, A. Principles of Smart Home Control. *Proc. UbiComp 2006*, 19-34.
8. Dixon, C., Mahajan, R., Agarwal, S., Brush, A., Lee, B., Saroui, S., Bahl, V. The Home Needs an Operating System (and an App Store). *Proc. HotNets IX.*
9. DLNA. http://www.dlna.org/home.
10. Edwards, W.K., Grinter, R.E. At Home with Ubiquitous Computing: Seven Challenges. *Proc. UbiComp 2001*, 256-272.
11. Edwards, W, Newman, M., Sedivy, J., Smith, T., Balfanz, D., Smetters, D., Wong, H., Izadi, S. Using SpeakEasy for ad hoc peer-to-peer collaboration. *Proc. CSCW 2002*, 256-265.
12. Grinter, R., Edwards, W., Chetty, M., Poole, E.S., Sung, J.-Y., Yang, J., Crabtree, A., Tolmie, P., Rodden, T., Greenhalgh,C., Benford, S. The ins and outs of home networking: The case for useful and usable domestic networking. *ACM ToCHI 16*, 2(2009), 8:1-8:28.
13. Grinter, R., Edwards, W., Newman, M., Ducheneaut, N. The Work to Make a Home Network Work. *Proc. ECSCW 2005*, 469-488.
14. Hamill, L. Controlling Smart Devices in the Home. *The Information Society 22*, 4 (2006), 241-249.
15. Harper, R. (ed.) Inside the Smart Home. Springer, London, 2003.
16. Home security systems, home security products, home alarm systems - ADT. http://www.adt.com.
17. Intille, S. Designing a home of the future. *IEEE Pervasive Computing 1*, 2(2002), 80-86.
18. Kietz, J., Patel, S., Jones, B., Price, E., Mynatt, E., Abowd, A. The Georgia Tech Aware Home. *Ext. Abstracts CHI 2008*, 3675-3680.
19. Kim, T., Bauer, L., Newsome, J., Perrig, A., Walker, J. Challenges in Access Right Assignment for Secure Home Networks. *Proc. HotSec 2010*.
20. Koskela, T., Väänänen-Vaninio-Mattila, K. Evolution towards smart home environments: empirical evaluation of three user interfaces. *PUC 8*, 3-4(2004), 234-240.
21. Lucero, S., Burden, K. Home Automation and Control, ABI Research 2010.
22. Mazurek, M., Arsenault, J., Breese, J., Gupta, N., Ion, I., Johns, C., Lee, D., Liang, Y., Olsen, J., Salmon, B., Shay, R., Vaniea, K., Bauer L., Cranor, L., Ganger, G., Reiter, M. Access control for home data sharing: Attitudes, needs and practices. *Proc. CHI 2010*, 645-654.
23. Mozer, M.C. Lessons from an Adaptive House. In D. Cook and R. Das (eds.) Smart Environments: Technologies, Protocols, and Applications (pp. 273-294). J. Wiley & Sons, Hoboken, NJ, 2005.
24. Newman, M., Elliot A., Smith T. Providing an Integrated User Experience of Networked Media, Devices and Services Through End-User Composition. *Proc. Pervasive 2008*, 213-227.
25. Poole, E., Chetty, M., Grinter, R., Edwards, W.K. More than Meets the Eye: Transforming the User Experience of Home Network Management. *Proc. DIS 2008*. 455-464.
26. Randall, D. Living Inside a Smart Home: A Case Study. In: Harper, R. (ed.) Inside the Smart Home, 227-246. Springer, Heidelberg (2003)
27. Rodden, T., Benford, S. The evolution of buildings and implications for the design of ubiquitous domestic environments. *Proc. CHI 2003*, 9-16.
28. Rode, J., Toye, E., Blackwell, A. The Domestic Economy: a Broader Unit of Analysis for End User Programming. *Proc. CHI 2005*, 1757-1760.
29. Shehan, E., Edwards. W.K. Home Networking and HCI: What Hath God Wrought? *Proc. CHI 2007*, 547-556.
30. Tolmie, P., Crabtree, A., Rodden, T., Greenhalgh, C., Benford, S. Making the Home Network at Home: Digital Housekeeping. *Proc. ECSCW 2007*, 331-350.
31. Tolmie, P., Crabtree, A., Egglestone, S., Humble, J., Greenhalgh, C., Rodden, T. Digital plumbing: the mundane work of deploying UbiComp in the home. *PUC 14*, 3 (2010), 181-196.
32. Tolmie, P., Pycock, P., Diggins, T., MacLean, A., Karsenty, A. Unremarkable computing, *Proc. CHI 2002*, 399-406.
33. Woodruff, A., Augustin, S., Foucalt, B. Sabbath Day Home Automation: "It's Like Mixing Technology and Religion" *Proc. CHI 2007*, 527-536.