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Mennicken, Sarah ; Vermeulen, Jo ; Huang, Elaine May

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# From Today's Augmented Houses to Tomorrow's Smart Homes: New Directions for Home Automation Research

**Sarah Mennicken**
University of Zurich
Zurich, Switzerland
mennicken@ifi.uzh.ch

**Jo Vermeulen**
Hasselt University – tUL – iMinds
Diepenbeek, Belgium
jo.vermeulen@uhasselt.be

**Elaine M. Huang**
University of Zurich
Zurich, Switzerland
huang@ifi.uzh.ch

**ABSTRACT**
A considerable amount of research has been carried out towards making long-standing smart home visions technically feasible. The technologically augmented homes made possible by this work are starting to become reality, but thus far living in and interacting with such homes has introduced significant complexity while offering limited benefit. As these technologies are increasingly adopted, the knowledge we gain from their use suggests a need to revisit the opportunities and challenges they pose. Synthesizing a broad body of research on smart homes with observations of industry and experiences from our own empirical work, we provide a discussion of ongoing and emerging challenges, namely challenges for meaningful technologies, complex domestic spaces, and human-home collaboration. Within each of these three challenges we discuss our visions for future smart homes and identify promising directions for the field.

**Author Keywords**
Home automation; smart homes; domestic technologies.

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

**INTRODUCTION**
The vision of smart homes, homes that cleverly support their inhabitants through technology, has been around for several decades [2]. Previous work has discussed whether or how visions of Ubiquitous Computing – technologies seamlessly interwoven in daily life – have become a reality [1, 42]. It has also been argued that smart homes, as an important area of focus of this vision [27, 19], have gone from being a vision to a reality [58]. Several previously defined challenges, such as providing means to connect different devices, have already been addressed to some extent or could feasibly be addressed from a technical point of view. But new technologies have also introduced new challenges. For example, there is the increasing difficulty of maintaining and securing home networks due to the invisibility of connections introduced by wireless networks, and an increasing complexity of installations due to a larger quantity of devices.

Smart homes were an underexplored field of research a decade ago, but as smart and technology-augmented homes are now emerging "in the wild", there is a new body of knowledge from which we can draw insights and upon which to build. There are varied efforts to gain understanding, ranging from scientific approaches in academia to research and development in industry. An excellent synthesis of challenges for smart home research was presented thirteen years ago by Edwards and Grinter [19]. While these challenges are still relevant for the field, in many cases they have evolved in terms of technical feasibility and people's expectations as a result of the adoption of new technologies.

As people's expectations of what technology can do for them are changing, the vision of what a smart home entails is continuously evolving as well. Nowadays, many people call a home that can be remotely accessed to turn devices on and off "smart", even though there is in fact no actual automation involved. Researchers in this field might only call homes smart when they are responsive to their inhabitants and adapt autonomously in sophisticated ways, e.g., using intelligent machine learning algorithms to predict user occupancy and control the heating system. In industry, "smart" is often used simply as a marketing term to describe programmable technologies in general or devices that can perform some sort of action automatically. In this work, we define a "smart home" as a home that either increases the comfort of their inhabitants in things they already do or enables functionalities that were not possible before through the use of computing technologies.

In this paper, we provide a synthesis of current challenges and promising directions for smart home research based on an extensive literature review, an analysis of current smart home solutions, and our own field studies of deployed smart home technologies. First, we describe how we surveyed existing research emphasizing effects on inhabitants' user experience. Then we describe and discuss the challenges as well as our visions for three high-level themes we identified for smart home research, namely for creating meaningful technologies, addressing the complexity of domestic spaces, and fostering human-home collaboration. For each of these themes, we discuss the aspects that make them challenging, describe our vision of how future smart homes should address them and map out a set of research directions to guide the design of future smart home user experiences and technologies for the domestic context.

## BACKGROUND

The majority of research in the early years of ubiquitous computing in general – and smart homes in particular – was focused on addressing technical challenges in order to realize the Ubiquitous Computing vision. Several of those fundamental challenges have been addressed in the area of smart home research, for example, providing basic sensing infrastructure or means to actuate home appliances. Many other challenges regarding underlying technologies have been identified and described. One key example that provided an overview of these challenges is the seminal work by Edwards and Grinter [19] in which they offer detailed insights on technical challenges, such as allowing for the incremental addition of technologies, issues of interoperability, reliability of domestic technologies, and ambiguity in sensing. In addition, they also discuss socio-technical repercussions of these challenges, such as low adoption of such technologies due to inhabitants' lack of technical knowledge or the difficulty of predicting social implications. Other work [20] has focused more strongly on the sociological perspective of smart homes to identify challenges of general computing technologies in the home from inhabitants' perspectives.

Living lab initiatives such as the Aware Home [27] or MIT's house_n [25] facilitated the study of smart home technologies in more depth and in contexts that closely resemble real world domestic spaces. Mozer's approach of installing various sensing and actuating technologies in his own home to build Adaptive House [37] was another way of attempting to study actual user experiences of living with automation technologies. All these efforts focused further on people's direct interaction with the technologies and allowed for the exploration of numerous prototypes for novel ideas in the context of technologies in domestic spaces.

Much work has looked more specifically into assisted living as an area of application for smart home technologies. While several of the challenges identified in the specific context of this field, such as legal issues or ethical issues [12], might not be as urgent for smart homes as for a more general population, other challenges, such as reliability of sensing systems or cost effectiveness [12] remain just as important. Due to the breadth of this research, researchers were able to draw a wide set of insights on how to approach the design of smart home technologies.

More recently, researchers have been studying deployed smart homes technologies in their actual context of use in family homes [8, 35]. Work that looks at early adopters of smart homes provides us with a better understanding of what challenges and barriers result from transferring research to practice. Our research aims to connect synthesized research insights with challenges identified "in the wild" to further facilitate the creation of useful solutions in the context of home automation.

In our work, we explore new and ongoing challenges for smart homes and home automation technologies with a specific focus on the user experience and its implications for technology, rather than the other way around. While we believe it is impossible to separate smart home technologies from the human experience of living with them, we emphasize that the approach we take in this work is to draw directions for the technology by starting from the inhabitant experience. In the remainder of this paper, we describe our approach and the resulting findings in detail.

## METHOD

The insights we draw in this work result from a synthesis of several research activities. We conducted a formal literature review specifically to identify user experience-centered challenges in the smart home research landscape. We also drew insights from our previous research activities investigating smart homes, including empirical field studies and interviews with smart home inhabitants, interviews with and observations of smart home industry professionals, and surveys of current commercial smart home products.

### Literature Review

To identify themes within related work we first assembled a list of work known to the researchers and added any of the 50 top search results on the ACM Digital Library for "home automation" and "smart home" not already included in the known body of work resulting in a list of 131 papers, posters, and reports. To address our intended focus on the user experience, we then systematically filtered the literature set to extract papers that explicitly address the user experience to some extent. To achieve this, we reviewed the abstracts of the work on that list and sorted them into different categories of relevance:

(1) Focus on automation or building technologies in **domestic spaces** including a discussion of **end user experiences** (35 results)
(2) Focus on automation or building technologies in **domestic spaces**, but no discussion of end user experiences (12 results)
(3) Related to automation technologies in buildings, but **no discussion of end user experiences or domestic spaces** (84 results).

While technical contributions in the area of smart homes have been crucial to the advances of this field, our focus was to identify novel insights specifically for the user experience in the smart home. In order to focus on the insights and explanations of the researchers whose work we reviewed rather than imposing on own, we excluded the third category. In many cases this was work that solely focuses on providing technical innovations, such as sensor hardware, middleware, communication protocols, or contributions to the field of electrical engineering. Therefore, we reviewed the resulting set of 47 papers, consisting of the first two categories, in greater depth. From these papers, we extracted the parts specifically relevant to user experience for further content analysis.

The relevant parts selected for further analysis focused mostly on (a) understanding and intelligibility of smart homes [6], (b) means for controlling smart home technologies, or (c) potential social effects on users. We also included sections that addressed other issues relevant to user experience that we felt were relevant for the analysis. Then we analyzed our data using the affinity diagramming method [7], deriving themes that emerged when iteratively clustering the excerpts. We started by analyzing how different work addressed aspects (a), (b), or (c). Then, to derive recurring themes or tensions to put them into the broader, overarching context of user experience in a smart home, we iterated our analysis of the insights across these aspects.

Subsequent to our formal analysis of selected literature, we were also made aware of additional relevant related work through informal discussion with other members of the research community. When applicable, we have synthesized insights from these additional works into the analysis we present in this paper.

### Empirical Work

The findings presented in this paper are further based on the authors' cumulative research activities in the realm of smart homes, including:

- A semi-structured interview study with 22 participants (10 inhabitants in 7 households living in smart homes, 5 people in 3 households who were in the process of planning or building a smart home, and 7 smart home solution providers from industry) as well as home tours to six of the smart home inhabitants' homes. The results of this work have been published in [35].
- A mixed-methods study with five people without technical backgrounds who live in smart homes. The focus was to understand everyday interactions, capturing positive and negative aspects of living with automation technologies. The methods used in this study have been published in [36].
- Observations of two smart home interest group meetings including presentations of new products. In the first meeting one of the authors presented and discussed research results from the previously mentioned studies with the smart home inhabitants who make up the interest group. In a second meeting the same author attended presentations of novel smart home products coming out of industry.
- Two visits to different smart home construction sites guided by a smart home provider. Data was collected using contextual inquiry and participatory observation methods in order to develop an understanding of practitioner's everyday problems and discuss the contrast to approaches in research.

By drawing the data from various sources in research, industry, and practice, we aim to provide a set of directions for moving smart home research forward by taking a comprehensive and multi-faceted perspective on the field.

## CURRENT CHALLENGES AND PROMISING DIRECTIONS

In the following section, we reflect on challenges presented in related work as well as new challenges and themes we have found through our own empirical work. To structure the insights and findings that emerged from our data, we discuss them along three high-level themes, namely Meaningful Technologies, Complex Domestic Spaces, and Human-Home Collaboration. While we discuss them individually, these themes are all highly interconnected. Within each of these themes we discuss the specific aspects that emerged as most critical in our analysis, why they pose challenges for research, our visions for smart homes that overcome these challenges to provide better inhabitant experiences, and actionable directions for research that we believe have promise towards fulfilling these visions.

### Meaningful Technologies

Technological innovation is often still driven by a strong interest in providing a novel contribution and making advances within a specific field of technical research. This kind of systems-oriented research is indispensible for advancing the field of smart homes as it allows researchers who focus on applications to have access to more tools to realize their concepts. However, systems or tools that have been developed with a focus on pushing the boundaries of certain technologies can also introduce the risk of shaping the visions for future applications in a limiting or restrictive way.

#### *Interest in Social Values and High-level Goals*

As argued by Taylor et al. [49], technology is less to be understood as something intelligent, but more of a resource for intelligence, in which intelligence emerges through our interactions with technology. Similarly, Rogers argues for more engaging technology that "enables people to do what they want, need or never even considered before by acting in and upon the environment." [42] We therefore argue that an important consideration for advancing smart homes lies in supporting the goals and values of inhabitants.

In the review of related research we found that people are strongly interested in their own activities and the effects of their behavior in the home [33], often in order to assess their efforts towards achieving a specific goal, e.g., reducing energy consumption [5] or "optimizing their own resource use" [18]. In other cases, they wanted to learn more about the home and the dynamics within it in order to reflect on the way they live. Related work has identified people's interest in "feeling like good parents" [29] and suggests that smart homes could "participate in the construction of family identity" [16]. Other work poses the question of "how technology physically embodied in the home might support lifestyles such as green living, slow

living, or spirituality […]" [56] indicating an existing lack of support for such values.

A major motivation for acquiring home automation is the interest in achieving peace of mind [8, 35] or an interest in feeling connected to one's home [48]. These motivations have resulted in security-oriented solutions for the home [18] and suggest technologies that are "readily introspectable" with regard to the user's skills [48]. This strong desire to achieve "peace of mind" in respect to one's home is not only evident in the fact that there was an early emphasis within industry on developing solutions for a building's security, but also by inhabitants' stated desire to know that the things one cares about in the home are safe. Recent industry efforts, such as *Mother* by *sen.se*[1], or *WallyHome*[2] – which allow people to use one or more sensors to monitor their home environments – are intended to address this desire and are indicative of the interest of the market.

### *The Catch of Technological Advances*

At the same time however, homes augmented with technologies intended to provide "peace of mind", for example through remote connection via smart phones and Internet-connected devices, can also introduce perceived and actual threats to privacy and security.

The increased connectedness of our homes [21] can raise questions about what data is being collected, whether it is transferred outside of the domestic environment, and how it is being accessed [51]. As reported by Chetty et al. [13], users were often not aware that their homes were accessible to others beyond their physical boundaries through wireless or remote access. Data leaks from sensed data in the home could potentially be very sensitive and might allow for serious abuse, e.g., household rhythms that expose appropriate times to rob a home [13] or means for access-control [51] which could be hacked by others to turn off the lights as a relatively harmless example[1] or potentially for purposes with more malicious intent and worse implications. These scenarios would actually lead to the opposite of the intended goal.

These types of negative effects on complex environments with multiple inhabitants are hard to predict, and research efforts often focus on specific topics, rather than considering the home environment as a whole. Such Smart home research typically focuses on specific areas of applications (such as cooking, or communication, support for the elderly or disabled) or specific underlying technologies such as occupancy sensing, activity recognition or location tracking. As a result of this deep but narrow focus, technologies are often studied in a rather isolated manner focusing on their impact on the immediate context of use. Even if they are deployed into actual households, effects on the larger context of the household and whether inhabitants' larger goals and values are supported have rarely been studied.

Our literature review also indicated that people often worry about more philosophical issues, such as whether smart homes might make them lazy [35]. Stringer et al. [46] suggest that we need to design "technology [that] should require human effort in ways that keep life as mentally and physically challenging as possible as people age." There is a very delicate balance between enabling goals such as "comfort" and "convenience" without crossing the boundary to making inhabitants feel "lazy". This balance is incredibly difficult to meet, especially given the fact that households are often inhabited by multiple people, each with different values, needs, and roles.

### *Smart Homes Will Support Lifestyle Choices*

We envision that an ideal smart home will support its inhabitants in living the lifestyles they choose while still being able to cope with "irrational" exceptions from them. Instead of "rationalizing" the life of inhabitants, smart homes should contribute to inhabitants' lives by adding meaning and supporting their unique values. Research on smart home technologies or automation technologies in the domestic context therefore needs to put a stronger focus on whether it is in line with the intended users' social values and high-level goals.

Many questions remain unanswered that need to be addressed in order for smart homes to support those lifestyle choices: What kind of high-level goals do people even have? How are these manifested in domestic spaces and how are current technologies involved already? Are there ways for researchers to learn how goals can be mapped onto available technologies in order to create solutions that address such a vision? If researchers are able to target their efforts to address high-level goals, will it be possible to know whether novel technologies to support these goals will be successful when deployed "in the wild"? Can we find ways to predict, model, and possibly even deter potential negative side effects on domestic life?

Not only do researchers have to find ways to predict technical conflicts resulting from different configurations of systems, we also need to find ways to predict social conflicts that may arise from attempting to support multiple high-level goals. Conflicting values within a household also need to be considered, for example if parents want to live in a more energy-conscious fashion while the kids simply want a maximum level of comfort. Although these types of conflicts already exist in conventional households, smart technology intended to support goals and values adds a new level of socio-technical complexity that needs to be addressed.

### *Learn In and From "The Wild"*

One key approach towards the vision of a smart home that can support inhabitants' high-level goals entails putting a

[1] https://sen.se/store/mother/
[2] https://www.wallyhome.com/

stronger emphasis on studying technology "in the wild," as well as taking advantage of knowledge that we can distill from observations of developments in industry.

Studying technology in a representative context of use will be crucial to assessing its suitability for everyday use and whether or not it addresses inhabitants' intended goals. By grounding designs in reality, researchers might be able to "at least predict the effects of [their] technologies" [19]. As smart home technologies have to deal with interference from other technologies and react to non-standard situations, it is difficult if not impossible to evaluate them through laboratory studies. However, lab studies so far have been the dominant method of assessing smart home technology [8, 35]. Recently, developments such as the Lab of Things[3] have helped make it feasible to conduct studies in the wild. Other initiatives by researchers, such as workshops on methods to study technologies in the home[4] indicate an emerging need for further methods to tackle this complex problem.

The consumer electronics market for automation technologies is expanding quickly (e.g., [45]) and offers us an opportunity to observe what types of products actually address people's real world needs. There is an increasing number of solutions developed by telecom providers[5], media companies[6], dedicated startups, as well as an emerging set of crowd-funded smart home projects[7]. They provide the opportunity to study differences between prototypes coming out of research and products that are backed by the support or votes of the intended target audience.

The aforementioned suggestions focus on the identification of high-level goals. However, research prototypes are often by nature exaggeratedly forward-looking, developed for futuristic scenarios rather than the current reality. Such technologies therefore cannot be studied in the wild, because "the wild" simply does not reflect those scenarios yet. To study an agent-based system, recent work by Costanza et al. [15] included the scenario of changing energy-prices in their deployment of their prototype to investigate socio-technical implications around such technologies. Work like this provides a good example for creative ways to test prototypes in a setting that approximates the prospective context of use as closely as possible.

### Complex Domestic Spaces

Many of the current approaches to sensing and automatic actuation could already work pretty well in single-person households; even more so if the individual user mostly follows consistent routines. One example of these approaches is the Adaptive House by Mozer [37]. Unfortunately for research and development of smart home solutions, such a constrained environment is rarely the case in the world of average consumers. While necessary when conducting targeted research, working with an oversimplification of the real world can even lead to research insights that do not apply in the actual context of use. Research focusing on autonomous adaptation to sensed data without further context might lead to flawed solutions when their insights are used to create multi-user applications.

When several people are living in the same home they can have opposing or inconsistent patterns in their behavior [59], or simply different user preferences that interfere with or contradict each other [18]. The sensed data would result in a "mixed message" to the home and likely lead to a home that is not in tune with *any* of the inhabitants. Instead of enabling smart behavior for one of the inhabitants, it becomes a source of frustration for all of them.

#### *Increasing Complexity and Quantity of Solutions*

Coping with the complexity of domestic spaces and the difficulty of predicting everyday life in an average household is one of the toughest ongoing challenges discussed in the literature [50]. One household is never identical to another: it might have a different composition of people, or the individual household members might have other needs. Even if we focus on one individual only, that person's needs and preferences change over time [24]. There is an ever-growing number of devices in the home and the set of those devices is different from one home to another [53]. All these factors make it impossible to create simple solutions for automation technologies that can enable "smart" behavior independently of the specific context of use. Thus, designers and researchers face the challenge of developing solutions that will suit and benefit such diverse households and be flexible enough to deal with constantly changing needs.

The larger quantity of devices that can be found in households also results in a larger variety of input modalities being available to a broader audience. Solutions like *Siri* on the iPhone are starting to make speech control more widespread; there are industry efforts to take advantage of such means of control for home automation purposes[8], and in interest group discussions we also observed the development of DIY solutions. Entertainment systems that can be found in homes, such as the *Kinect*, have introduced gesture control to end-consumers and inspired novel concepts for smart home interactions[9]. While the broader availability of alternative input modalities allows for novel types of user interfaces, it also introduces

[3] http://www.lab-of-things.com/
[4] http://studyingthehome.wp.horizon.ac.uk/
[5] http://www.quing.com
[6] http://www.comcast.com/home-security.html
[7] https://www.kickstarter.com/projects/smartthings/smartthings-make-your-world-smarter
[8] http://www.ispeech.org/
[9] http://www.frogdesign.com/work/frog-room-e.html

more complexity for design. Related research discussed what kind of device should be used [28] and what kinds of smart home interfaces are suitable for different tasks or user characteristics [60]. But obviously, the suitability of a specific medium or interface depends strongly on the specific application and on the characteristics of the context in which it would be used.

With an increasing number of alternatives for smart home solutions and a subsequent variety of standards and devices, there comes a need to allow for connections between them. One approach to that is the online service *IFTTT.com* that allows end-users to connect different services, such as weather forecasts, or social media applications, with devices like lights or power sockets. Such a solution facilitates direct interoperability, addressing a longstanding pragmatic challenge for smart homes [19]. However, such services are opening up a new challenge: users are faced with an overwhelming quantity of potential combinations of devices and services created by a growing user base.

In our interviews and through discussion in the interest group meetings, we found that many people were very curious to see how others use technologies in their homes. They were keen to learn what technology can do for people with similar interests or households that are similar to their own. This need has recently been addressed by Microsoft Research's *HomeOS* [18], which includes a store for smart home-related apps that users can contribute to. Similarly, *IFTTT.com* offers the ability to download "recipes" for automation, thus allowing people to have access to shared configurations for devices. A study by Ur et al. [51] analyzed smart home-related recipes and found that even people without programming experience were able to create such configurations easily.

#### *Iterative Integration of Automation Technologies*

Discovering applications that might be of use could motivate people to acquire and add to the technologies already installed. In our earlier empirical work [35], our participants expressed an interest in exploring further additions after experiencing the benefits of one feature and having developed some sense of trust. Without the means to test it in the inhabited context of use, it is difficult for users to understand tradeoffs involved with automation [35]. The monetary investment is one immediate tradeoff, but others could include, for example, lack of control in exceptional situations that the home cannot detect. The compensating benefits are often less clear: Even if people understand the general sense of a novel technology, they might not see how it could benefit them in their everyday lives [41].

The suggestion of putting effort into deploying and studying research prototypes in the wild will help researchers to identify potential shortcomings of proposed technologies and address them. But this will not allow prospective users of such technologies to understand well whether or not they will be of actual use to them, what unique implications they might have for their household, or give all household members the chance to develop a sense of trust.

#### *Smart Homes Will Help to Identify Opportunities for Automation*

When developing technologies for future smart homes, researchers will not only have to consider interoperability with other devices or services, but also how end-users can identify and configure meaningful connections between them. Future smart homes need to incorporate services to help their inhabitants to identify whether there exist solutions created by others that will suit them, their needs and their current situations.

People might have the necessary technologies that could support them in smart ways already at hand, but how do they discover and identify this potential for automation? How could a home know what kind of applications would fit to a household? In what ways would it need to know the people it is inhabited by or the dynamics between them in order to come up with recommendations? For people that already have smart home technologies installed in their home, future smart homes will have to help inhabitants identify further opportunities for meaningful additions and allow them to incrementally add to their installation.

To increase the interest and trust in automated functionalities, future smart homes should allow their inhabitants to incrementally develop trust in the installed functionalities and in how they work. Such a home should provide means to encourage all inhabitants to be involved in order to facilitate configurations that enable automated behavior that is smart for all of the people living in one household.

#### *Support Finding Fitting Solutions and Safe Testing of New Functionalities*

Services like *HomeOS* or *IFTTT.com* already allow users to browse the available applications in various ways, such as identifying what apps are available for the hardware already installed or browsing the most popular applications. Inspiration can be drawn from recommender systems of other services that provide recommendations based on collected data of earlier behavior and compared to similar behavior in other users, e.g., "people who installed X also installed Y". But researchers could support inhabitants of smart homes even further in navigating the quantity of available solutions, applications, or services, as well as identifying potentially needed hardware. For example, by automatically identifying specific characteristic of one's homes, or allowing the contributors to tag the applications that they share with the high-level goals that they aim to address.

The number of possible combinations of and interactions between devices is huge, and so adding a new sensor, device or robot to the home could have unforeseeable results. Therefore, we further argue that it should be possible for inhabitants to gracefully integrate a new device into the home, observing the device in a trusted

environment to learn how it works and whether it fits their needs. One approach to do this could be enabling a sort of "sandboxed" environment: the device would tell the user what it would have done, if it had worked autonomously. In this sandboxed environment, users should be able to gradually increase the level of autonomy that an appliance has, and make adjustments where necessary. This might provide means to overcome users' lack of interest in learning how a technology works [58], and shift towards what the implications of the technology would be, which users *are* interested in. This is somewhat similar to how parents watch over their children, intervening when they would do something wrong (e.g., turning on the oven), and gradually teaching them what is acceptable and what is not [44].

### Human-Home Collaboration

Autonomous technologies often leave users feeling out of control [4], especially when there is insufficient or inappropriate feedback [38]. Inappropriate means of interaction with automated functionalities can result in users imposing limitations on autonomous systems. For example, people would limit applications to certain devices [18], reduce the level of autonomy of the automation [3] or only allow a robot to use a small and predefined subset of items [40]. If users feel more comfortable when restricting technologies, it will never be possible to exploit the full potential of automation, and as a result, benefits of home automation will always be limited.

#### *User-Imposed Limitations of Automation*

An interest in going "analog" and escaping from "always on" technology was found to be an important user need [34]. In our own empirical work, we also often found that inhabitants of smart homes wanted the ability to turn off automation technologies in the home in order for the technology to be in line with their high-level goals, such as: getting a break from technologies and feeling disconnected, or being good parents and teaching their kids about responsibilities by turning off the automatic sprinkler system to have the kids perform this household chore. Another situation when users may turn off technology or decide not to use it is when they feel a lack of trust due to unexpected behavior or interruptions [11].

However, deactivated automation will not be able to support the inhabitants at all. A sensitive balance is needed to prevent this scenario, and while the user needs to feel in control, this should not require them to constantly monitor or be incessantly notified about details of the automated behavior when there is no urgent need for the user to be involved.

#### *Diverse Set of Strengths, Weaknesses, and Interests*

Besides sometimes being deliberately restricted by users, the potential benefits of automation are also limited by the human capability for information processing. A large variety and quantity of sensors in the home can create a huge amount of diverse information. Inhabitants could potentially benefit from this information, e.g., by reviewing the data to identify opportunities for automation, or simply gaining an awareness of what is happening in one's home. However, if such data is not reduced and visualized in a meaningful and reasonable way, it will overwhelm the user, perhaps to the point where she might decide to ignore available information altogether.

Similarly, users can easily be overwhelmed by technologies that try to provide "intelligibility": insight into the workings of complex context-aware systems (e.g., by automatically generated explanations [31, 54] or visualizations [26, 55]). Users with a non-technical background will have difficulties in understanding the rationale behind complex reasoning [32]. Furthermore, inhabitants of smart homes are not even necessarily interested or motivated to understand how the technology in their home works, and do not want to invest time in learning about it [10]. Their interest may rather be driven by their immediate needs, similar to the common attitude of not reading manuals for household appliances.

While computers can outperform humans in certain tasks in term of speed and data processing, and can even take over some tasks entirely, there are other tasks they cannot solve, although trivial for humans [43]. In our own studies we found that people did not consider their homes to be "smart" if they themselves are better or more efficient at carrying out the tasks the home is supposed to automate [35]. In combination with user-imposed limitations of technologies this might lead to the unfortunate situation in which the automation technologies cannot do what they are good at and the user will never consider them to be smart. What can designers of smart home technologies do in order to create user experiences and interfaces to prevent automation technologies to always be perceived as "dumb"?

Firstly, for both the smart home and its inhabitants, it will be important to understand the capabilities of what the other party can do [9] to create a system that meets inhabitants' expectations while inferring their intent if possible, and otherwise resort to users to help resolve ambiguities. Results of work we reviewed indicated that a focus on the mediation between the inhabitants' and technology's understanding of a home is important [10]. Instead of controlling and accessing individual devices and creating connections between them using the vocabulary and metaphors that were traditionally developed for people with a technical background, a more promising approach seems to be to "translate" and convey to the machine how inhabitants define their homes in their natural, less technical understanding.

Secondly, the fact that humans are better at certain tasks does not however imply that they are interested in doing so. Consequently, there is a particularly interesting opportunity for systems that mediate between human and computing capabilities [22]. As an example, while participants of

studies were able to offer precise descriptions of the relationships between the use of technologies and their routines [39], they felt that implementing those behaviors took too much effort [5], either because of a lack of options to "program their home" [23] or simply because "they did not want to spend time learning how to program the device" [14]. If these tasks can be facilitated or accelerated by taking advantage of computing, this could lead to a situation in which automation technologies would be perceived to be "smarter".

### *Smart Homes Will Collaborate with their Inhabitants Instead of only Being Controlled by them*

We believe that the research community needs to work towards a vision of true collaboration between human and home to address these challenges of automation. Considering a collaboration with the home instead of mere control or complete automation of the home might help to prevent the rationalization of domestic lives which was one of the fears of inhabitants living in smart homes. Such a mediation is especially important when conflicts of interest occur between what the users want to do and what the rational machine is programmed to do [6].

As can be seen in previous work, the existing paradigm regarding barriers to automation involves the human's responsibility for these decisions, and the technology's subsequent response. But what would it mean for a home to have the capability to provide suggestions or simulations regarding different configurations, thus taking a collaborative role in the decision making? The home, unlike the human, could conceivably have a comprehensive knowledge of its own technologies and associated challenges. The human, however, has an understanding of his or her needs and routines, as well as an intuition about the potential social consequences of technology failures.

### *Useful Intelligibility and Deviations from Routines*

As mentioned before, context-aware systems cannot always perfectly understand the situation due to certain aspects of context that cannot reliably be sensed or inferred [6, 19, 47]. This implies that they will have to rely on further explicit user input in case of ambiguities. Bellotti and Edwards propose that systems be made "intelligible" to help inhabitants build up a model of how their smart home works, including the possibilities it affords, how different technologies interact with each other, and when and why automatic actions are performed. However, there are two important problems that stand in the way of attaining intelligibility: (1) the difficulty of understanding the complex reasoning of sensing technologies by users without a technical background, and (2) users' lack of interest in and reluctance to invest time in learning how the underlying technology works [58]. Oftentimes, related work in this field provides detailed descriptions of these problems, but until now there has not been a lot of work that suggests specific or actionable solutions to address this tension in the context of home automation. Traditionally, smart home research has approached the topic of intelligibility by taking a rather technology-centric approach, i.e., "What is your technology doing and why?" We argue that a more promising way to achieve intelligibility is to take a more inhabitant-centered approach, i.e., "How are your tasks, activities, and well-being being affected by your technology and why?"

One example of this approach that we consider to be promising is providing intelligibility information that is specific to and embedded in the current task users are trying to accomplish. Yang & Newman call this *incidental intelligibility* [58], information that is tailored to helping users with the situation at hand. Moreover, instead of providing details about the inner workings of the system, we argue that intelligibility should be limited to the *high-level rationale* behind a certain automation action, with the potential to get more details if needed. This approach of in-situ, high-level intelligibility has already been applied successfully in recommender systems (e.g., Gmail's Priority Inbox that explains to users that a certain message has been marked as important because "of the words in the message").

Another promising approach to reduce the risk of overwhelming users with information relates to the importance of household routines in relation to technologies in domestic spaces [30]. Routines have been looked extensively looked at in this context, e.g. to identify further use cases for smart home technologies [31]. Digital technology will become part of even more aspects of everyday lives, and therefore cannot be separated from the domestic routines in which it is couched. Thus, it also cannot be looked at in isolation, as it becomes more interlinked and can create more side effects [57] that are difficult to predict by users.

Davidoff et al. [16], Yang & Newman [58] as well as our own studies [35] suggest that in order to reduce the informational complexity and meet the requirements of inhabitants, interfaces with automation technologies should rather focus on deviations from routines. Our studies confirmed this finding as our participants expressed that while their regular routines simply become an unnoticed part of their lives that they do not even need to be aware, they wished to have a better support in case of deviations from them. Previous work that provides design implications for how to deal with exceptions from rules raises the point that automation technologies should provide suggestions rather than full automation and provide "support for disambiguation" [17] depending on how much inference is needed [19]. People prefer to have options to choose from among automatically generated suggestions [56], and leaving inhabitants in control to some extent allows for a better understanding of details of the context, especially in the case of exceptions [25].

## CONCLUSION

In this work we provide arguments and a discussion for our vision of future smart homes. We envision such homes to

be context-aware domestic spaces that leverage automation to support inhabitants with the burdens of domestic routines, while at the same time keeping people from being disengaged and allowing them to maintain important values (e.g., have children contribute to household chores). These homes will be open to iterative and incremental integration of new technologies and appliances, allow every inhabitant to feel in control in a home that is a safe and predictable environment.

With this paper, we have provided a synthesis of current challenges and promising new directions for smart homes, focusing specifically on the user experience aspects of smart homes. Our synthesis is based on an extensive literature review, an analysis of solutions in currently deployed smart homes and on our own empirical work. We discussed the conflicting aspects and tensions that exist within each of the different highlighted themes and presented our visions of how future smart homes would look like. Those visions are intended to offer ways to rethink existing work in this field and to open up the discussion for changes of the original vision of ubiquitous technologies.

More specifically, we highlight that against visions of smart homes that would offer invisible and seamlessly integrated support for domestic life, living in and with an actual smart home today remains an imperfect experience. The challenges and approaches presented and discussed in this paper show that there are many more opportunities for further research. We identify promising directions and actionable ideas for researchers in this field that we consider to be promising approaches to address the described visions of future smart homes, and hope thereby to inspire work that will unlock the full potential of home automation.

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