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Domestic Robot Ecology

An Initial Framework to Unpack Long-Term Acceptance of Robots at Home

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Abstract It has been recognized that long-term effects exist in the interaction with robotic technologies. Despite this recognition, we still know little about how the temporal effects are associated with domestic robots. To bridge this gap, we undertook a long-term field study. We distributed Roomba vacuuming robots to 30 households, and observed the use over six months. During this study, which spans over 149 home visits, we identified how householders accepted robots as a part of the households via four temporal stages of pre-adoption, adoption, adaptation, and use/retention. With these findings, we took the first step toward establishing a framework, Domestic Robot Ecology (DRE). It shows a holistic view on the relationships that robots shape in the home. Further, it articulates how those relationships change over time. We suggest that DRE can become a useful tool to help design toward long-term acceptance of robotic technologies in the home.

Keywords Domestic robots · Long-term interaction

1 Introduction

It has long been recognized that long-term effects exist in the use of technology [15, 17], and people exhibit different interaction patterns over time [16, 23, 31]. Despite the recognition, we still know little about the long-term effects associated with domestic robots. Studying interactions over a long-term is crucial because it deepens our insights about what truly occurs when a robot becomes a part of people's everyday lives, and inform how to make products remain useful beyond initial adoption [8]. However, few have explored how to promote long-term interactions between human and robots in domestic spaces. As more robots enter home as pets, caretakers, and more, we contend that it is a timely subject to investigate in depth.

To address this agenda, we undertook a longitudinal field study with 30 households who had never owned any kind of robotic appliances. We gave our participants Roomba vacuuming robots and then visited each household repeatedly over a six months period to better understand their evolving usage patterns. In total, the entire study spanned more than a year, and involved 149 household visits. Through the study, we aim 1) to identify how householders accepted robots as a part of the households, and then 2) to establish a theoretical framework (referred to as Domestic Robot Ecology) that systematically articulates long-term acceptance in order to help guide interaction design of domestic robots.

We begin this article by reviewing related work and describing our study procedure. Next, we present an overview of Domestic Robot Ecology, and introduce how it frames the long-term experience with robots. Following, we describe empirical data to support how we derived the framework, and then discuss how it can help designers to create long-term interaction experiences with domestic robots. Finally, we conclude by reporting the current limitations of DRE and the future plans to enhance it.

2 Related Work

In this section, we address related work in two folds. First, we review the studies that have explored long-term robot

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adoption in social settings. Then, we discuss how the studies on domestic robots have probed this agenda, and highlight how our study can contribute further to this body of research.

2.1 Studies of Long-Term Human-Robot Interaction

The long-term Human-Robot Interaction has been actively studied in the areas of non-domestic spaces, such as such as offices [12, 19], schools [13, 26], and hospitals [17, 18]. They demonstrate that people exhibit different usage patterns as they pass the novelty excitement. For example, Kanda et al. deployed a robot for nine weeks in a classroom and observed elementary school children's engagement [13]. Robovie engaged in personally customized conversations with children. At first, children were excited and wanted to play with Robovie, but over time the frequency of playful interactions decreased. Nevertheless, Robovie's continuous interaction made children see the robot as a part of the classroom, not a temporal toy. At eighth week of interaction, researchers found that the children decided to share their knowledge on Robovie by collaboratively making an information board about it so that they could better understand its characteristics. The studies with PARO (the baby seal robot) also showed long-term effects. Marti identified that the use of PARO over three months brought changes in social behaviors (i.e., touching other people and expressing emotion) among children with mental disabilities [17]. Also, children showed the manifestations of emotional bond, such as writing a letter to PARO's parents to have them stay with the robot for longer period of time. However, the long-term interaction with robots does not always appear in positive directions. Other studies have documented the decline in people's interest with robots over time. In their three month study, Tanaka et al. tried robot (Qrio) dancing as a way to stimulate longer sustained interaction between children and the robot, but they saw the children's interest decrease over time [26]. Also, people began to ignore a large robotic guide in a hallway after just days of interaction [19], and even forgot about the robot on a mission in a three-month-long field trial [12].

These researchers not only offered empirical evidences of how long-term interactions occur between human and robots, but also provided design implications to make such relationship possible. Kanda et al. state that "long term interaction capability is a composition of various factors such as vision processing, speech recognition, number of capable physical tasks and plays, memory and so forth" [13]. Marti provides different perspectives that the long-term interaction can occur successfully when people view robots as social agents with affection instead of a mere objects [17]. Goakley et al. note that environmental factors may also influence the long-term interactions, such as the number of people (group vs. individual) and the time of the day [9]. While these studies provide insights about what may contribute to successful long-term interaction, few have explored this agenda in domestic spaces.

2.2 Studies of Domestic Robots

Recently, a growing body of research (e.g., [6, 8, 15, 16]) has shed lights on understanding how to design user interactions for domestic robots. Forlizzi and DiSalvo's seminal field evaluation of Roomba usage uncovered that this cleaning robot has influenced the housekeeping practices by increasing both opportunistic and planned cleaning. Also, they noted that physical environment played an important role in the use and assistance of the robot (i.e., removing obstacles). Further, they reported cognitive and emotional responses among householders triggered by the novelty of the robot, such as finding a lost earring by using Roomba [8]. Forlizzi describes how such bonds can create social dynamics among family members in her later work comparing Roomba with Hoover, a lightweight upright vacuum cleaner [6]. According to her, the use of robot has made cleaning as a concern for all householders as opposed to a single person. More importantly, she argues that it can be the basis for a long-term commitment by describing how Roomba was still used a year later, whereas the Hoover had been replaced by another vacuum cleaner. Kim et al. undertook a similar study, deploying five different vacuuming robots to homes in Korea in order to identify user trends that persisted across the robots [15]. From this empirical work, they identified that cleaning occurred in smaller units than an entire house, such as specific spots in the room from which they derived a design guideline for pathfinding. Despite these rich accounts of how people interacted with robots at home, we still know little about these interactions over a long period of time. In the remaining paper, we explore this agenda through our longitudinal field study.

3 Study Design

3.1 Methods

We distributed 30 Roombas to 30 households in Metro-Atlanta area in U.S. To learn long term effects, we studied them over six months. We chose to study Roombas because they were the first robots distributed in the mass market, and hence became most familiar with people and made it easier to recruit. We visited each household five times to follow up on their experience. We had one household dropped out after fourth interview. In total, we conducted 149 home visits. We compensated our participants by allowing them to keep the robot after study completion. During the five home visits, we used a variety of techniques to uncover the long-term experience. In between home visits, we encouraged our participants to report on their experiences, such as via email. We separately published the study procedure with detail in [24]. Here, we briefly outline the methods we employed as follows.

We visited homes for the first time without Roomba. We wanted to document the overall domestic space including home layout and social dynamics among householders. To learn these points, we did semi-structured interviews with the head of the households (e.g., parents). In addition to interviewing, we asked them to take us on a home tour, during which we focused on learning their cleaning routines including when, how often, and with what they cleaned. We used it as a baseline to compare the robot use against. We completed the first interview by asking them to draw a blueprint of their homes, and highlight the areas they expect to run the robot. We brought this blueprint in the recurring visits to compare with the actual use.

Approximately a week later, we visited for the second time. On this visit, we brought Roomba and observed the household's initial reactions to it. During this time, we asked all the householders including children to be present because a previous study noted that the initial participation might influence the later use [8]. We observed how they unpacked and operated Roomba for the first time. Then, we conducted a debrief session during which, participants rated their first impression on a seven point Likert scale. They rated five categories of user experiences including, 'ease of use', 'usefulness', 'emotional attachment', 'entertainment value', and 'degree of impact on the household'. We collected this experience rating from each head members of the household individually because previous studies have shown that householders could form different perceptions (e.g., Dad likes the robot whereas Mom decides not to use it [25]). We repeated this experience rating on the recurring visits.

We returned two weeks later to find out what had changed since the arrival of Roomba. We conducted semi-structured interviews about their "Roomba routine" such as how often it was used, who used it, and how, when and where they cleaned. Additionally, we asked if they used the robots in non-cleaning activities, such as showing it to other people, and giving names and personalities. Then, we asked our participants to do three activities to better assess their experience. First, we asked them to re-highlight the blueprint of their homes to show precisely where they had run and kept the robot. Second, we re-collected the experience rating. Third and finally, we asked participants to check off the activities that they had done with Roomba from a pre-generated list, such as hacking, naming, and demonstrating to others that we pulled from the previous Roomba studies [6, 7, 24, 25]. Because these studies note that Roomba activities often occur collaboratively among multiple householders, we asked them to check together. Yet, we followed up individually to understand the detail, such as who led the activity and who participated. We repeated this activity checklist in the remaining interviews, and it became a good indicator whether or not Roomba usage changed over time.

We revisited the house two months later to learn if anything had changed since our last visit. We kept the general interview format similar to compare how experience had changed over time. We conducted a semi-structured interviews about Roomba routines, during which we focused on how they used and maintained the robot because participants began to express difficulties about managing technical problems. Then, we asked our participants to complete three activities: blueprint, experience rating, and activity list.

The final visit occurred approximately six months after the arrival of Roomba. We completed the interview by asking participants to reflect on the overall experience and potential improvements.

3.2 Participants

We used a snowball sampling method to recruit people for our study, asking our participants for referrals to others who might show interest. We limited the participating households to have at least one adult (18-year-old and above), and not to have plans to move in the six months since prior research shows that home layouts impact interaction patterns [7]. In total, we had 48 participants (22 men and 26 women) from the 30 households. Below we summarize demographic information.

Household composition: We tried to balance the household composition because who they live with or not impacts the experience [23]. We had 17 dual-head and 13 single-head households. In total, we had 48 adults across these households who became the main respondent of our study (e.g., drew the house blueprint, and filled out rating forms). Their age ranged from 18 to 67 years (mean = 42 years old). Most of the dual head households ($N = 13$), and two single-head households had children. These 15 households had 22 children who lived in the house, ranging from one child to three children per family. The mean age for children was nine years, ranging from one month to 18 years. Given a focus on vacuuming, we also recruited families with pets ($n = 16$), of which 13 owned dogs and three owned cats.

Education and technical expertise: We gathered information on education and technical expertise of our main (adult) participants who joined all five home visits. Most of them had received college or higher education. We had 24 people with graduate degrees, 20 people with college degrees, and two with high school degrees. More than half of the participants ($N = 19$) self-reported as technical, meaning that they had an academic education, professional training, or hobbies in technology related fields. Despite high rates of technical knowledge (one person worked at a robotics company), just two households had a robotic toy: AIBO and a Robot Dinosaur. None had robotic appliances (i.e., Scooba) as it was one of our screening conditions. Our participants had a large array of occupations. Examples include an aviation safety auditor, a software engineer, a physician, a lawyer, a head hunter, a landscape designer, a chef, and more.

Household income: Perhaps due to the level of education and technical knowledge, about half of the households ($N = 14$) made an annual income more than 100,000 USD. Except for two participants, these households had dual incomes. According to the census data, Georgian household that had dual incomes made around 75,000 USD per year (www.census.gov). Based on this data, we contend that the seemingly high income does not deviate much from the average households in Atlanta area. Also, this data indicates that many of our participants could afford to buy the robot. Indeed, three participants bought additional Roomba to give as a gift to their families during the study. Further, seven of these 14 households had a regular maid service, allowing us to compare robot use with outsourced cleaning. We also included households with less income as we felt that their finances might shape their domestic lives, and we sought a diversity of experiences with robotics. In the study, we had eight households with an annual income of less than 50,000 USD.

Home layout: House layout varied among our participants. Most common were multi-story houses ($N = 17$), followed by single story ($N = 9$), lofts ($N = 2$) and apartments ($N = 2$). House size ranged from 550 square feet (studio apartment) to 3,900 square feet (four bedroom, four bathroom house). Houses also varied in floors including hardwood, linoleum, tile, and carpet (and stained concrete in lofts). Shared spaces such as living rooms and dining areas tended to have non-carpeted floors, while bedrooms and stairs tended to have carpet. Two houses had no carpeting due to severe allergies that family members had.

3.3 Analysis: Identifying Long-Term Interaction

During the data analysis, we transcribed all interviews, and scanned and entered data from the user-generated materials, such as ratings, activity checklists, and blueprints. The analysis primarily focused on identifying how robots became adopted and accepted as a part of the household over time. Because we had a large volume of data (e.g., over a thousand pages of interview transcripts), we decided to turn to the existing literature related to technology adoption (e.g., [1, 3, 20, 21, 27, 29]), and used the findings as guidelines to code temporal experiences. Collectively, we identified four temporal steps that householders experienced while accepting a robot in their house. The steps include:

1. *Pre-adoption*: During this process, people learn about the product and determine the value. Also, they form expectations and attitudes toward objects [3], which largely impacts the later user satisfaction [8].
2. *Adoption*: It refers to the first impression gained at the moment of purchase, or during the initial interaction [20].
3. *Adaptation*: During this period, people try to learn more about the artifacts by experimenting complexity in use and compatibility in the current environment, and make necessary changes to better incorporate [20]. Through this stage, people determine reaffirmation or rejection of further use [20].
4. *Use and retention*: It indicates the period when people begin to show a routine with a technology. Also, people show tendency to retain the use beyond the life cycle of the current product by upgrading it or changing to the next generation model [11].

We re-organized the interview transcripts based on these four steps, and then used Grounded Theory, an emergent qualitative analytical method [22] to identify interaction patterns that appeared for each temporal stage. We tried to keep the coding labels consistent in all four stages in order to compare and contrast the interaction patterns more easily. For example, we labeled the types of roles that robots played in the interaction as one of these three forms: a tool to complete tasks, a mediator to incur changes in the environments, and an actor to elicit social responses (inspired by [7]). As the result of the Grounded Theory, we produced an initial framework that hypothetically explained how robots shaped relationships with the domestic environment over a long-term period, which we refer to as Domestic Robot Ecology. In the next section, we describe the underlying concepts of this framework.

4 Domestic Robot Ecology (DRE): Framing Long-Term Interaction

DRE is an initial framework that articulates the dynamic relationships that robotic products elicit with their surrounding environment (visually depicted in Fig. 1). We particularly chose the term,'ecology' inspired by [7] to emphasize that our framework shows a holistic view on the interaction experiences that robots create across all four temporal stages.

Overall, this framework shows three key attributes that largely influenced the interaction experiences across all temporal stages. They include physical and social space, social actors, and intended tasks. We explain each factor with detail.

A.1 *Physical and social space* provides a platform for interactions to occur. Venkatesh et al. describe that today's home comprises physical, social and technical space [30]. Physical space refers to the indoor environments, such as floors, rooms, and furniture within. Social space refers to family lifestyle and activities that constitute an important part of the domestic living. Our previous study shows that robots do affect

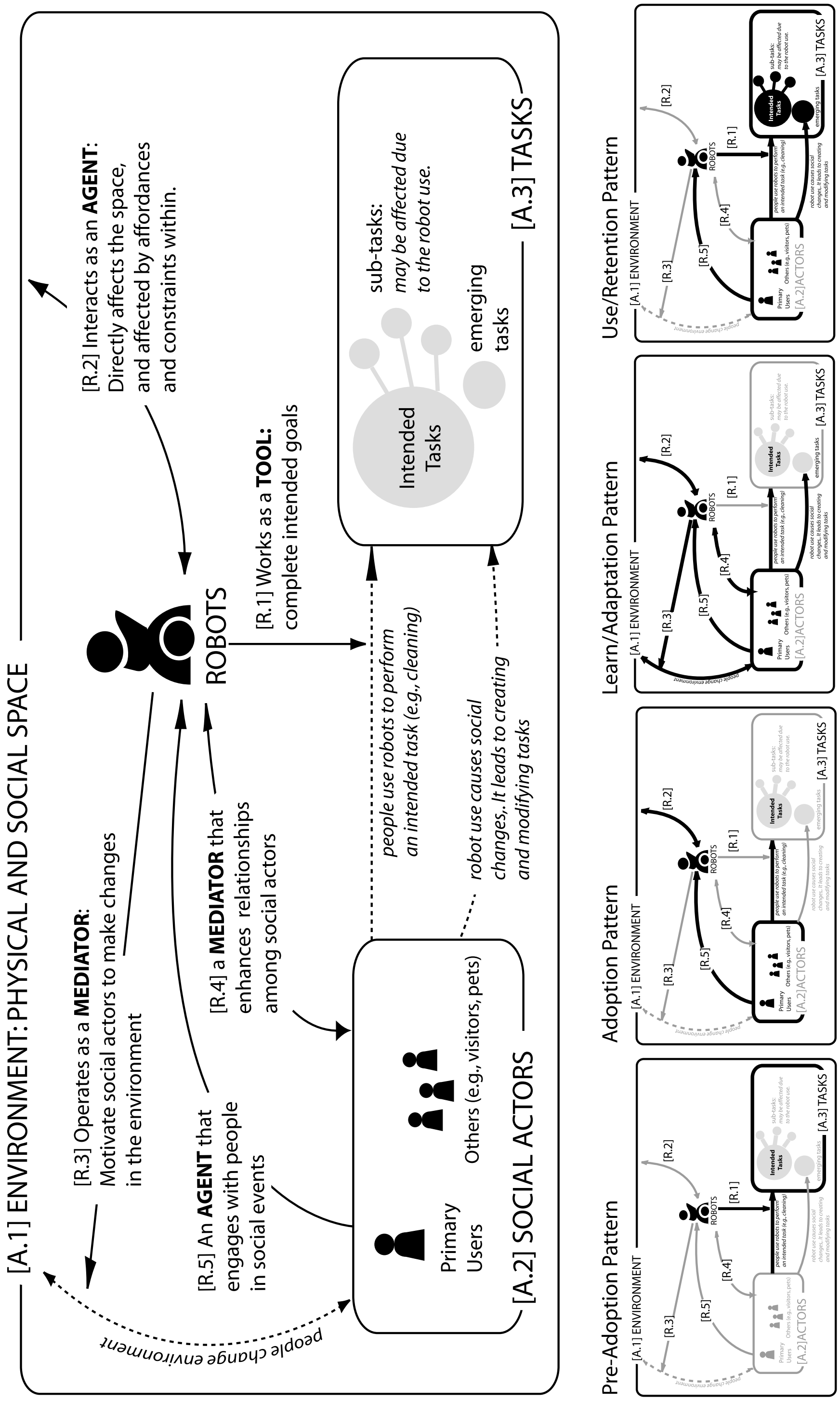

Fig. 1 *Above*: Domestic Robot Ecology (DRE), the holistic view on the long-term interaction with robots. *Below*: DRE displays the interaction pattern changes over a prolonged period of time (pre-adoption, adoption, learn/adaptation, and use/retention)

this social space as people share stories, photos, and videos of their robot experiences [25]. Technological space indicates the total configuration and organization of technologies in the home, such as the location of their placement. We contend that the technological space for robots virtually overlaps with the entire physical and social space. Unlike screen-based computing technologies, robots have ubiquitous spatial presence because they move autonomously in various parts of the house [16, 31]. That said, robots elicit impacts in broader physical space. Also, robots can intelligently respond to people, and establish connections on their own, which can consequently increase the opportunity to get involved with social activities [14]. Therefore, we suggest that the technological space of domestic robots should be understood with physical and social spaces altogether.

A.2 *Social actors* are the living members in the home, such as householders, guests, and pets. Existing studies classify home technology users into two groups: internal members (e.g., family) and external members (e.g., visitors and friends) [10, 30]. However, studies have shown that household technologies, particularly appliances are not used equally among internal members (most notably examined in [2]). It led us to reflect on social actors not by who live in and out of the house, but who actively use and did not use the target technology. That said, we divided social actors into two groups: 'users' who interact with robots on a regular basis to complete a task, and 'non-users' who do not regularly use but engage in social activities with this technology. We note the inclusion of pets as a part of social actors. Similar to how children's involvement increased the adoption of digital technologies [28], pets' lively responses and active interactions with robots play an important role for householders to accept them. Previous Roomba studies show that pets followed around the moving robots, and even learned to get a ride on them, which increased people's positive responses [23, 25].

A.3 *Tasks* refer to the activity that the robot is designed to serve. Domestic tasks are closely inter-related and have unclear boundaries from each other [5], and therefore automating one task by using a robot may bring substantial changes to the connected tasks. In addition, the use of robotic products may emerge new types of domestic tasks that did not exist before prior to the robot adoption. Taking Roomba use as an example, householders created leisure activities such as creating a race track to compete with neighbor's Roomba [23].

As robots interacted with these attributes, five types of relationships occurred during the long-term acceptance. Robots form a relationship as:

R.1 *A tool* to perform tasks: robots served as a utilitarian tool to replace the manual labor, and to improve the quality of life.

R.2 *An agent* that directly impacts the surrounding environment: robots induced physical impacts, such as removing pet hair on the floor, and moving smaller objects during the navigation.

R.3 *A mediating factor* that motivates people to make changes in the environment: robots sometimes elicit negative impacts, such as breaking a mirror and dragging wires. The limited compatibility with the existing environment mediates people to make necessary changes to incorporate robots better.

R.4 *A mediator* that enhances social relationships among household members: in our study, we found that children and men took more responsibility in cleaning after robot adoption. Further, robots often became a new means for social activities. For instance, people demonstrated robots to the visitors, and even took them on their vacation to show around.

R.5 *An agent* that engages with people in social events: people ascribe lifelike qualities to a robot, and directly engage in social activities, such as giving names, genders, and personalities.

Overall, DRE in Fig. 1 (above) articulates the holistic interactions patterns that may occur during the long-term interaction with robots. We created this holistic view to establish a common ground to compare and contrast the interaction patterns developed in the four temporal stages of pre-adoption, adoption, adaptation, and use/retention. We visually depict the most prominent interaction patterns per each stage in Fig. 1 (below), which we highlighted in bold lines.

The visual depiction of the interaction patterns in each temporal stage show a clear contrast in the types of user experience people engage with robots over time. Briefly explaining (see next section for more detail), people envisioned the robot experience to center around task performance prior to the adoption. The simple expectation toward a robot as a utilitarian tool largely shifted when people first interacted with it in their homes. Robots drew strong social responses, and made immediate changes in household dynamics, such as attracting children to participate in cleaning activities. After the initial adoption, people continue to spend time and effort to learn about the robot, and made necessary adjustments. Venkatesh referred to this stage as a co-evolving process, an important part to make the home receptive to new technologies [28]. During this period, we saw most active and dynamic changes in physical environments and social relationships. At the same time, people assessed Roomba's role as a useful cleaning tool, which largely influenced them to determine whether to continue adapting, or discontinue the effort and reject further use. Through this period, householders found the robot routine that fitted into their domestic lives, and consequently reduced the efforts to make changes in physical and social space. Instead, they began to see the robot as a specialized tool to manage cleaning tasks that had become increasingly strategic and complex.

Thus, we introduced Domestic Robot Ecology, a framework to articulate long-term interactions shaped by robots at home. More specifically, we presented two types of views within this framework. First, we showed a holistic view (Fig. 1: above) to capture the overall interaction experiences that robots create across all temporal stages. Second, we showed the temporal view (Fig. 1: below) that highlighted the key interaction patterns that respectively emerged over time. In the following section, we discuss these four temporal views with empirical examples from our long-term field study.

5 Unpacking Long-Term Acceptance

The six-month-observation uncovers that long-term patterns exist in the use of domestic robots. In the households where Roomba was persistently and actively accepted, the long-term effects showed visibly through the status of cleanliness as in Fig. 2. Here, we explain with empirical examples how such long-term patterns exist through four temporal stages of: pre-adoption, adoption, adaptation, and use/retention.

5.1 Pre-adoption: Forming Expectation

Perhaps due to the little experience with robots, our participants envisioned a rather simple relationship. People mostly described robots as a *tool* to improve the cleanliness of the home, and ultimately their current life style. They expected minimal human intervention in cleaning, and planned on increasing the vacuuming frequency from once a week (on average) to everyday. Moreover, they expected the robot to manage floor cleaning in the entire indoor areas. When we asked our participants to draw the blueprint of their homes, and to highlight the areas they would run Roomba, all of them marked the entire indoor areas. For example, P25 in Fig. 3 (above) highlighted all three floors to run Roomba except for the garage that they did not consider as a part of the indoor area.

While people expected the robot to bring visible impact in the cleanliness of the home, we learned that the user profiles, such as technical expertise and the need for cleaning assistance led them to anticipate different levels of impact by using a robot. The participants with high level technical knowledge, including one person who owned a robotics company knew the limitations of the current robotic products, and did not expect the cleaning quality to surpass manual vacuums. Six participants who were technically naive and had not known the existence of vacuuming robots prior to seeing the study recruitment relied much on the movies and fictions, and hence expected advanced services, such as being able to detect dirt from a distance. Also, the household composition affected the expectation of Roomba as a practical tool. For example, people who owned pets wanted

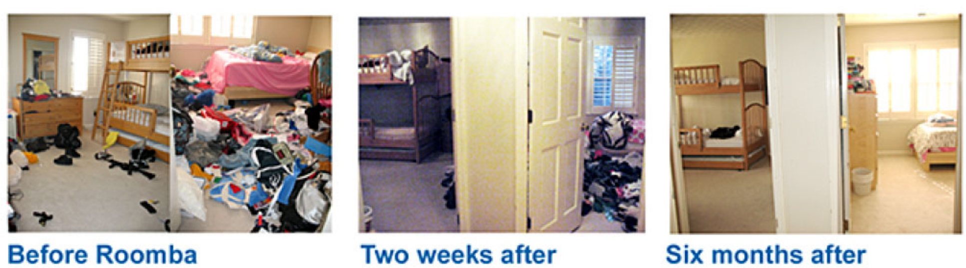

Fig. 2 Long-term effect of robot usage in P15: the mother described that the robot use motivated her to undertake major cleaning throughout the house. Robots kept the floor clean and clutter-free, and she wanted to keep the rest of the house up to the same standard

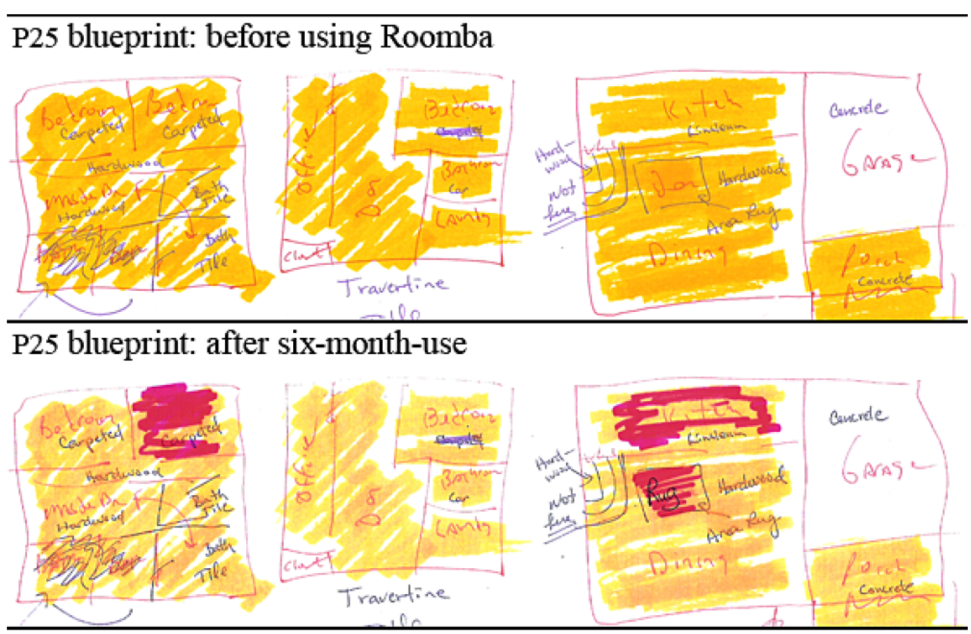

Fig. 3 *Above*: P25 highlighted entire home as expected areas for Roomba use. *Below*: P25 localized cleaning areas as highlighted in red after six months

the robot to decrease the amount of pet hair present in the house, and those who had physical disabilities expected a more independent way of living as they would not have to rely on others for floor cleaning.

Thus, people expected the robot to become a primary and an independent tool to manage the intended domestic task. And it led people to address two particular concerns, which we identified to impact the satisfaction during the actual use. First, participants discussed how the robots would interact compatibly with the current environments, such as navigating in different floor types (e.g., tiles in the bathroom and unpolished wooden floors in the den), and operating through small objects (e.g., children's toys). People expected robots to come prepared to handle these challenges. One male participant (P22) noted that he would rather not use a robot if he would have to put manual effort to help it navigate in the house, such as clearing up the wires off the floor. Indeed, during the actual use, he stopped running Roomba after a few trials because he had to pick up clutters before each operation. Second, and finally, our householders emphasized durable and reliable robot performance, particularly because Roomba entered the domestic space to replace an existing cleaning tool that normally lasted for years. In fact, some of our participants kept their floor vacuums over ten years. They added that the potential high-cost of robotic products made them to expect the reliable performance even more. In fact, one household (P9) gave up using it after five months due to the frequent technical failures despite reporting satisfaction in the cleaning quality that Roomba delivered.

5.2 Adoption: Getting the First Impression

Participants responded more positively toward the robot experience after having used it for the first time. Participants showed higher satisfaction in all categories of user experiences that we asked them to rate after the initial experience (Table 1).

During the initial operation, participants tried to assess the expectations and concerns they had prior to the adoption. For example, all households ran the robot for about 15 minutes, and confirmed the utility of Roomba as a cleaning tool by checking how much dirt and pet hair it picked up in the dust bin. In most of the households, Roomba showed a better cleaning quality than expected, and hence received higher rating in 'usefulness for cleaning' category after adoption (Table 1). Also, householders used the initial operation to assess robots' compatibility with the environment. They followed the robot around the house, and began to make changes where necessary, such as by picking up the wires, and removing the area rugs. Further, they experimented the robots in the places they thought it would have difficulties with, such as near the staircase, and the door thresholds. Furthermore, they conducted experiments

Table 1 Comparing differences in the user ratings (1 = least positive, 7 = most positive) before and after the initial use of Roomba

	Before adoption (mean score)	After adoption (mean score)	Differences (T-test)
Intelligent operation	3.6/7	4.04/7	$t\ (47) = 3.07$, $p < 0.005$
Useful in cleaning	4.93/7	5.19/7	$t\ (47) = 1.60$, $p > 0.1$
Ease of use	5.13/7	5.35/7	$t\ (47) = 1.24$, $p > 0.1$
Entertainment value	4.27/7	4.75/7	$t\ (47) = 2.34$, $p < 0.05$
Emotional attachment	3.92/7	4.42/7	$t\ (47) = 2.97$, $p < 0.005$
Overall Impression	4.58/7	5/7	$t\ (47) = 2.11$, $p < 0.05$

to protect their homes from potential Roomba hazards, particularly if they had pets and children. Parents put their feet under Roomba to see if it is accident proof. Also, all 16 households with pets made the robot run in the presence of their pets, and watched the reaction. In one household with chemically treated concrete floors, the participant carefully observed if the Roomba brush made any scratches on the surface.

In addition to confirming Roomba as a useful tool, we saw a new type of relationship formed between householders and robots. Our study revealed that householders began to view robots as *social agents* after the initial interaction. The data in Table 1 support this finding. Participants rated non-cleaning related user experiences, such as intelligence, and emotional attachment significantly higher after the actual use. Our empirical observations report similarly. During the initial interaction, people immediately ascribe lifelike qualities, such as Roomba's intention to go to a certain place. Our participants noted that they felt Roomba's movements led them to perceive lifelike qualities even though it did not resemble any living objects. They added that robots' performance beyond their expectation, such as going under the couch, and returning to the charging base by itself increased the level of perceived intelligence because it did more than automating and replacing manual labor.

Perhaps owning to the richer social interactions, people felt the robot experience more entertaining. Boys in P20 (3-year-old and 6-year-old) chased the robot while yelling "It's alive!", and tried to jump over it. One teenage boy (P15, 13-year-old) recorded a video of Roomba operation on his cell phone to show to his friends at school. Children began to ask their parents if they could run it in their rooms. In both P25 and P29, we saw how parents instantly used Roomba operation as a reward for completing the homework. Such excitement from children increased the positive experience to the parents. One mother in particular told us that she wanted Roomba to become an inspiration for the girls to clean up more often and put the clutters off the floor.

5.3 Learn and Adaptation: Learning Affordances and Limitations

After the initial adoption, people continued to explore the robot to learn the technical limitations and affordances better, which we refer to as a stage of 'Adaptation'. For example, our participants made exploratory operations, such as running in the porch and inside a van that had crumbs on the floor. As a result of their active exploration, they reported to run robots more frequently than what they needed to keep the house clean. Our participants noted that this period normally lasted about a month since the adoption.

Robots constantly triggered changes in the physical environment as an active *agent*. They autonomously maneuvered around the home, and cleaned in the process. After a few weeks of usage, people noticed visual differences, such as seeing cleaner carpets and less pet hair, and feeling fewer crumbs while walking with bare feet. These changes in the environment assured the robot's value as a useful tool, and motivated the continued use. However, as robots ran in the environment that had not yet been modified to accommodate them, they encountered several accidents, such as breaking a full-sized mirror, eating toys, and damaging furniture. Householders appeared more forgiving to the accidents during this period as they perceived it as a part of robots' learning of the environment rather than as a result of their limited intelligence. Still, they did not want these accidents to occur again, and took actions to prevent them (Fig. 4). Some of the actions included causal and temporary changes that they needed to repeat in each operation, such as folding area rugs, blocking Roomba navigation with everyday objects (e.g. toy cars), and picking up clutters. Other changes were more permanent; people placed a book under a lamp so that Roomba would not get stuck while trying to climb on it, and even cut off the rug tassel to prevent it from getting stuck on the fringe. Indeed, these accidents led robots to become a *mediating factor* for householders to make changes in their homes.

In addition to the changes in the physical environments, robots elicited dynamic social interactions with householders, pets, and visitors. First, our participants continued to perceive the robot as a *social agent*, and began to apply social rules to it. Most notably, 13 households gave names to Roomba within the first two weeks of usage; 19 households engaged in conversations with it, and referred to it in a gendered way using both male and female terms; and finally 3 households purchased costumes. Although these activities occurred throughout six months, we saw them most actively during the adaptation period. For example, we only saw six new names for Roomba after the first two weeks, and saw a decreased number of households ($N = 12$) that reported to engage in conversations with the robot at sixth month.

Further, Roomba played as a *mediator* to influence social interactions among householders. People used it as a conversation topic and a source for family entertainment. For example, P2 told that they intentionally initiated the self-docking sequence in their presence because it was fun to watch. In their words,

> *"it will normally find its base (after completing the cleaning sequence). But I still bring it out here in the kitchen (where the charging stations was placed) and push the button to make it go back because it is fun to watch. It goes back and corrects itself and goes back and corrects itself again it's little bit incremental. That's our conversation piece. It's my favorite part."*

More notable social changes occurred in the households with teenage children who became primarily responsible for cleaning. Roomba attracted more householders to collaborate in the cleaning activities (as also observed in [7]). In some households, children took over the vacuuming responsibility. Children in P11 (boy, 11-year-old), P25 (boy, 10-year-old) and P29 (girls, 9-year-old and 12-year-old) became the primary Roomba users. They not only ran the robot to clean, but also maintained it, such as emptying the bin and changing the filters. They self-taught this rather complex maintenance process by reading the manual, and in fact they knew the procedure better than their parents.

Additionally, Roomba *mediated social interactions* with people outside the households (friends and neighbors). For the first two weeks, the majority of our participants have talked about it others ($N = 23$ households), and demonstrated it to the household visitors and relatives ($N = 18$ households). One household (P13) showed it to his friends in Guatemala via a Webcam. Two households (P8, P25) even brought the robot on their vacation, and ran it in the

Fig. 4 How people modified homes to incorporate robots

Fig. 5 Strategies for storing robots: subtly hidden to appear less obtrusive in the eye, but remained in a visible and highly trafficked area to get easily reminded of the use

house they stayed to demonstrate the performance. In particular, P25 and the visiting families used Roomba as a source of entertainment, such as running it on the pool table, and watched it hit the ball for fun. Thus, the novelty factor brought by the robot stimulated people to learn and adapt the technology better into home. Consequently, it caused much change in the environments, dynamics among social members, and the relationship with the robot.

5.4 Use and Retention: Routine Practice and Maintenance

After adaptation, people found a routine for robot usage in their homes. It made people view the robot as a *tool* to perform intended tasks as they did so prior to adoption. However, the cleaning activity was no longer simple and repetitive as before. As an effort to adapt the robot due to the technical limitations (e.g., unable to map the house), householders carefully created strategies to use. One notable strategy was to localize the areas to run Roomba (i.e., running it in one room per operation), and to rotate the cleaning areas each time. That is, participants ran the robot more as a spot cleaning tool. For example, P25 ran Roomba only in the highly trafficked areas, such as the living room and the kitchen (highlighted in red in Fig. 3: below), showing a contrast from how they expected to run it in the entire house prior to adoption (Fig. 3: above).

The strategic use of Roomba included getting prepared for the robot to run, maintaining it, and storing while not used. By sixth month, householders got into the habit of getting the house prepared for the robot to run; they quickly folded area rugs, and put away wires. Also, participants created their own ways to maintain the robot, and incorporated it as a new domestic routine. The maintenance task had become an important part of the robot experience over time because it encountered several technical problems, such as failing to operate and dock. Because these errors often resulted from poor maintenance quality, householders intentionally placed a Roomba's cleaning tool (a plastic brush) next to their home keys, computing equipments, and kitchen appliances. This way, they would get easily reminded to take care of the robot. In the study, we saw that if householders still perceived the robot as social agents and responded emotionally toward it, they were likely to place more effort in the maintenance process (also reported in [25]). Finally, householders developed strategies for storing Roomba. Functionally, the home base needed to sit near an electric outlet for charging. Yet, people felt negative to the idea of having a vacuum cleaner placed in an open space, and not in the closet. It led some of the participants to place Roomba in a less visible spot, such as behind a couch, and in an unused room. Then, another problem occurred; the robot became forgotten as it was out of sight. Ultimately, our participants sought places that were not obtrusive in the eye, but visible enough to get reminded (Fig. 5). For example, P25 put Roomba under the table right next to the main entrance, and described it as a perfect storage location. In their words:

> *"That place is perfect because it's not so obvious to the eyes but you can easily see it on the way out and get reminded to turn it on. And when you come back, the house is clean."*

To summarize, our empirical data show that robots interact differently with the surrounding space, people, and tasks over time. It stresses the importance of reflecting the long-term effects in the interaction design process, which we discuss in the next section.

6 Implications for Long-Term Interaction Design

As a way to reflect long-term effects in the interaction design, we first created a structured framework, referred to as Domestic Robot Ecology (DRE). Researchers state that the use of the framework-based design can bring benefits with three respects. First, it helps articulate the complex nature of real-world interactions, and hence facilitates better collaboration among designers from multiple disciplines by sharing a common ground of context [10]. Second, the framework can help the design less driven by designers' intuitive and prescribed notion of how things should be, and make it more grounded on the research-based user data [10, 12]. Third and finally, a framework can provide a solid ground to solicit ideas and concepts for the developers who are new to the design problem [10]. Considering the short history of the commercial application of domestic robots, many designers will feel the design challenge relatively new.

The DRE reflects the long-term interaction in two perspectives. First, this framework depicts the holistic and relational view of the robot interactions across all temporal stages (Fig. 1: above). It allows designers to easily project how their design choices would influence the overall user experience. Second, it breaks down the holistic experience according to the four temporal stages, and presents how the interaction patterns developed over time (Fig. 1: below). In this section, we create initial implications to help guide designers how to apply these long-term perspectives into an actual interaction design.

DRE "Holistic" View: The study findings show that robots elicit dynamic interactions with physical space, household members, and intended tasks. These relationships are inter-connected and relational to each other. In design, it means that designers should begin by articulating three interaction attributes: environmental context, user profiles, and tasks characteristics. Designers can also utilize the holistic vision of DRE by mapping their interaction ideas onto this framework, and easily create interaction scenarios with the five relationships we described (R.1-R.5 in Sect. 4). The interaction scenarios will help reveal strengths and weaknesses of the proposed design in an overall user experience.

DRE "Pre-adoption" View: Prior to adoption, people considered the robot as a utilitarian tool. They envisioned the robot experience to center around task performance (e.g., floor cleaning), such as how well it would work compatibly and durably with various types of physical spaces (e.g., floor types). And when these high expectations for compatibility and durability fall short, people lose their interest in further adopting robotic appliances. For design, it implicates the importance of envisioning and articulating a detailed list of obstacles that would limit the robotic appliances to operate autonomously and independently. Taking Roomba as an example, designers can suggest a large wheel as a potential requirement to prevent a robot from getting stuck in wires and clutters.

DRE "Adoption" View: When householders ran the robot for the first time, they exhibited strong social responses toward the robot, and engaged in exploratory activities, such as running it outdoor and on a pool table. They began to perceive it more than a tool and something closer to a lifelike agent. The elicitation of social relationship between human and robots contributed to increasing emotional and entertainment value in the experience. It leaves several implications to interaction design. First, designers may implement expressive motions at the beginning to increase emotional and entertainment value. Second, designers can consider making robots to exhibit and comprehend social actions, such as being able to greet and wave. Third and finally, designers can enhance a safety system that can protect the robot from people's random experiments, such as running it on a place with height. At the same time, robots should be able to inform participants through clear error feedbacks when people's experiments caused technical problems.

DRE "Learn/Adaptation" View: After the initial adoption, people continued to spend time and effort to make necessary adaptations, such as changing furniture layout. Also, householders engaged with robots in various social activities, and began to ascribe a unique identity (e.g., names, gender, and personality). Further, robots chanced social roles in the house. They induced collaborations among more householders to complete a manual task that used to belong to one person prior to robot use (e.g., Mom for cleaning). This finding suggests that even for a simple utilitarian robots, the ability to act according to social rules can become critical for long-term acceptance. To increase its agency and the unique characteristics, robots should be able to recognize their given characteristics. Further robots need to identify household members and respond differently to offer personalized interactions, such as triggering companion-like relationships with children. The key design factor for a robot is to be able to learn and evolve according to the social needs in the household.

DRE: "Use/Retention" View: Over an extended period of time, Roomba had become a tool specialized in keeping the house clean. However, in order to accommodate error-free autonomous operation, householders implemented several strategies, such as localizing and rotating the cleaning area. By default, robots should be able to map the entire house as localized cleaning routines could impose cognitive burden on users, particularly those that are young or technically naive. Further, they should allow users to select whether to run it in the entire house or a specific area of the home. In addition to operation strategies, participants put a particular emphasis on the maintenance by incorporating a whole new task in their domestic routines so that they could retain the use reliably. However, some participants easily forgot the time to clean the machine, which led to performance failure. To sustain a good quality performance, robots should be able to activate self-initiated notifications to users for timely operation and maintenance. Finally, our participants tried to strategize other related tasks, such as carefully selecting the place to store home base. Our participants sought a place that was less obtrusive in the eye but visible enough to get reminded of its presence and to continue the use. It indicates that robot exterior design should also be carefully crafted, and allow users to customize robots' look and feel to blend in or stand out in their domestic spaces.

7 Conclusions

In this article, we sought to understand long-term experiences with domestic robots. To learn the temporal effect in the interaction, we undertook a long-term field study in which we distributed 30 robots to 30 households, and observed their adoption and use over six months. The results we obtained in this study added value to understanding how people accepted robots as a part of the households. Based on the results, we took the first step toward establishing a framework, Domestic Robot Ecology (DRE) that articulates the holistic and temporal relationships that robots create with surrounding home environment. We contend that such articulation can help designers to approach the complex nature of long-term interaction with robots more easily.

Considering that Roomba is a fairly basic robot that only performs vacuuming, we acknowledge the limitations in our framework. We project that the interaction patterns would become more dynamic with advanced domestic robots, at least in three ways. First, we suggest a sixth relationship in DRE: an *agent* that interacts with other intelligent appliances at home. This particular relationship did not appear in the Roomba study because this robot does not have networking capability to communicate with other robots. However in the upcoming future, we can easily envision a security robot communicating with wireless cameras and other robots in the home (as depicted in [4]). Second, robots would act more as a *social actor* than as a *tool*. Current service robots primarily act as a tool to perform a task based on user needs. For example, people run Roomba when they want to clean. In the future, robots will be expected to handle complex tasks that other smart technologies manage, such as remembering and notifying schedulers, and offering personalized service based on user behaviors and user profiles (illustrated with detail in [10]). It means that future robots may act as social actors that determine and perform the tasks in need autonomously without user input. Third and finally, we envision that robots would act less as a mediator that leads people to modify the existing environment. With increasing capability to map the house and to track the navigation paths, future domestic robots will smartly sense and avoid obstacles. They may even pull the mechanical arms and adjust the environment themselves as needed. More case studies with other consumer robots would help verify these projected addition to the current DRE. Nonetheless, we hope that our initial attempt to create DRE would elicit scholarly interest among other researchers about how to incorporate long-term interaction into the design of everyday robots.

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