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SURVEY

Social Robots for Long-Term Interaction: A Survey

Iolanda Leite · Carlos Martinho · Ana Paiva

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Abstract As the field of HRI evolves, it is important to understand how users interact with robots over long periods. This paper reviews the current research on long-term interaction between users and social robots. We describe the main features of these robots and highlight the main findings of the existing long-term studies. We also present a set of directions for future research and discuss some open issues that should be addressed in this field.

Keywords Human-robot interaction · Social robots · Long-term interaction · Longitudinal studies

1 Introduction

Human-Robot Interaction (HRI) is a multidisciplinary field concerned with the "analysis, design, modelling, implementation and evaluation of robots for human use" [18]. While a lot of work has been done in studying how users interact with robots within a single interaction, only in the last decade the first long-term studies, in which the same user (or group of users) interacts with a robot several times, have started to appear. There are several reasons for this. First, longitudinal studies are much more laborious and time-consuming than short-term studies [20], especially in naturalistic environments. Second, only recently technology has been robust enough to allow for some degree of autonomy when users interact with robots for extended periods of time. Finally, the appearance of the first commercial social robots (e.g., Pleo and Paro) and robots for domestic use such as iRobot's Roomba, together with demographic trends such as the ageing of the world population, are also fostering research in this area.

Longitudinal studies are extremely useful to investigate changes in user behaviour and experiences over time. Recently in Europe, several projects have received funding to explore the potential of long-term interactions with social robots and other agents (e.g., LIREC[1], Companions[2], SERA[3], CompanionAble[4] and ALIZ-E[5]). The main motivation behind these projects is that current robots and virtual agents lack social capabilities to engage users in the long-term. In fact, some of the early long-term studies show that the novelty effect quickly wears off and, after that, people lose interest and change their attitudes towards the robots [22, 34, 62].

In this paper, we present a survey on the existing long-term studies involving social robots. We limit the scope of this survey to robots designed to socially interact with people or to evoke social responses from them. As such, industrial robots, for example, are excluded from this survey. We present a structured overview with contributions from two different perspectives. First, we examine the main features that social robots should have to engage users for extended periods of time. By identifying such features, we aim to provide directions and guidelines for future research in this field. Second, the main findings obtained in the long-term interaction studies with these robots are presented, compared and discussed.

I. Leite (✉) · C. Martinho · A. Paiva
INESC-ID and IST, Technical University of Lisbon,
Av. Prof. Cavaco Silva, 2744-016, Porto Salvo, Portugal
e-mail: iolanda.leite@ist.utl.pt

[1] http://lirec.eu/
[2] http://www.companions-project.org/
[3] http://project-sera.eu/
[4] http://companionable.net/
[5] http://www.aliz-e.org/

The paper is organised as follows. We start by briefly describing the methodology used in this survey. Then, in Sect. 3, we present the state of the art on long-term interaction studies with social robots, organised by application domains. Section 4 contains some guidelines for future design based on the analysis of the presented state of the art and on theoretical research on human-social relationships. After that, in Sect. 5, we discuss some other open issues in this field.

2 Methodology

A comprehensive literature review was carried out with the goal of selecting the most relevant papers for this survey. First, we performed electronic searches using digital libraries such as Google Scholar, Microsoft Academic Search and CiteSeer. The keywords used in the search included "social robots", "long-term interaction" and "study". In a second phase, we manually searched the proceedings of the main HRI journals and conferences (e.g., HRI and RO-MAN). The search phase resulted in a collection of 45 research papers. From this sample, some papers were removed because they lacked detail, for example, on the robot's capabilities or crucial information regarding the study design (e.g., the number of interaction sessions). We also excluded studies that were not conducted in real-word environments such as offices, homes or schools, but rather in laboratory settings where users had to go to the lab to interact with the robot (e.g., [54]). After applying these criteria, a total of 24 papers were included in this survey.

We decided to organise the selected papers by their application domains because the robot's features and the study design (e.g., data collection methods) are more likely to be similar in the same domain, and therefore easier to compare. We identified four different application domains: Health Care and Therapy, Education, Work Environments and Public Spaces, and Home. With this division, there were some studies that could fit in two different application domains (e.g., Health Care and Home). In these cases, our criterion for assigning the studies to the application domains was the ultimate purpose of the robot present in the study. For example, Autom [39] is a robot specifically designed to monitor user's weight loss. Although the study was conducted at people's homes, the robot could be placed in a different setting (e.g., an office or a hospital) with the same purpose. On the other hand, the main goal of Nabaztag in Klamer et al.'s study[42] was to provide company to elderly people living alone. As such, the main goal of the robot was to be in people's homes, regardless of the fact that it tries to persuade users into having a healthier lifestyle.

For each application domain, we present the selected works by describing the main features of the robot (such as the type of embodiment, interactive capabilities, and so on) and the most relevant findings obtained during the long-term study. We conclude each section with a discussion of the main results of the studies in that application domain, highlighting emergent patterns and discussing inconsistent findings. For each application domain, a table summarising the robots' features and the experimental design of the studies (the number of different interaction sessions with the robot, the main results of the study, etc.) is also presented. In the number of interaction sessions, we considered only the sessions in which experimental data was analysed. For example, if a robot interacted with a group of users for 30 days, but the study reports only the results of the first 10 days, we consider the number of interaction sessions as 10 for analytic purposes. Finally, a more general analysis of the state of the art is presented through the discussion of some guidelines and open issues for future research in this field.

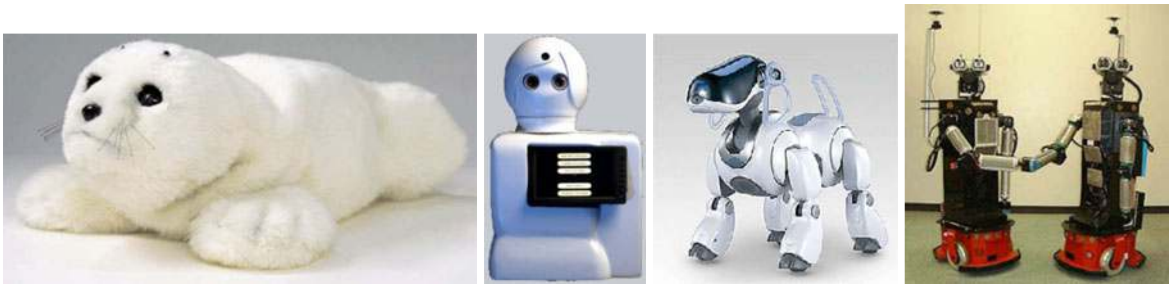
3 The State of the Art

Long-term interaction with social robots can be considered a sub-area of HRI that studies how the interactions patterns between users and social robots develop over time. As technology evolves, an increasing number of researchers have been focused on developing social robots that can engage and assist users for extended periods of time.

3.1 Health Care and Therapy

In the domains of health care and therapy, there is a great potential for social robots to assist users over extended periods of time. *Socially assistive robotics*, as defined by Matarić and colleagues [51], are expected to "augment human care and existing robot-assisted hands-on therapy towards both improving recovery and health outcomes and making the therapeutic process more enjoyable". It is argued that the physical embodiment of the robot, its personality and the ability to model some of the patient's motivational states, can have a positive impact in robots employed in this context. Additionally, the role (e.g., physical therapist, nurse's assistant, ...) and the task that the robot is meant to achieve must be clear to the user.

Of particular importance is the work by Wada and Shibata [74–76] with the robot Paro (Fig. 1(a)), which can be considered one of the landmarks in the field of long-term interaction. Paro is a seal shaped robot specifically designed for therapeutic purposes. The robot's behaviour contains a reactive layer for responding to certain stimuli (e.g., touch, sounds and light) and a proactive layer triggered by the robot's internal needs. Paro is also able to recognise certain keywords that users may use more frequently around it (for example, when they give the robot a new name), and gradually adapt its behaviour according to the stimuli of the user.



(a) Paro (AIST, Japan)[74, 75, 76] (b) Autom [39] (c) AIBO[19] ©Sony (d) Robovie [61, 35]

Fig. 1 Robots used in the health care and therapy related long-term studies (images used with permission of the authors)

Two Paro robots were placed in common living rooms of a care house where elderly residents could interact with the robot over 9 hours a day. The interactions of the residents with PARO were video-recorded during this period. After one month, the results of 12 subjects indicated that PARO strengthened the social ties among the residents of the care house and that most residents established moderate or strong ties with the robot (e.g., greeting Paro when they pass by). Also, urine tests showed that after introducing PARO, the stress levels of the residents decreased. The long-term effects of Paro in nursing home residents were also investigated by other researchers with similar results (see, for example, the studies by Turkle et al. [72] and Giusti and Marti [21]).

More recently, Sabelli et al. [61] reported an ethnographic study in which a humanoid social robot (Robovie, displayed in Fig. 1(d)) interacted with 55 residents of an elderly care centre for 3.5 months. The robot's behaviour was remotely operated to act as a conversational partner through basic dialogues that included greetings, questions about hobbies, travel experiences and other child-like questions such as "what is this?". The analysis to the interviews and direct observations of the interactions suggested that the robot was well accepted in the community. Behaviours such as greetings, calling participants by their names and the robot's role as a "child" were relevant for this result.

Social robots have also been employed successfully in autism related therapy [11, 52]. To investigate the impact of robotic companions in autistic children, François et al. [19] conducted a study in which six children played with an AIBO robot (Fig. 1(c)) for approximately 40 minutes once a week for a total of 10 sessions. AIBO was programmed to display several dog-like behaviours (e.g., wagging the tail, emitting "bark" sounds, or opening and closing the mouth) when users touched the robot's head, chin and back sensors. The experiment took place in a school setting and was inspired by non-directive play therapy, where the experimenter can participate in the trial but the child is the main leader in an unconstrained environment. The sessions were video-recorded and the behaviour of the children was later analysed according to three dimensions: play, reasoning and affect. Each child made progress in at least one of these three dimensions over the sessions. Children experienced progressively higher levels of play and developed more reasoning related to the robot (for example, by comparing AIBO to a real dog). Besides, they tended to express more interest towards the robot over the sessions, with occasional displays of affect.

In a different area, Kidd and Breazeal [39] studied the impact of social robots in terms of behaviour change while dieting. They developed a social robot, Autom (Fig. 1(b)), which is capable of establishing eye contact with the user and making small talk while helping individuals to keep track of their weight loss. The dialogue lines vary depending on the time of day, estimated state of the relationship with the user (initial, normal or repair), the time since the last interaction and the inputs of the user such as the number of calories. The study included 45 participants with ages between 17 and 72 years distributed through three different conditions: some participants interacted with the robot, others reported their weight loss in a computer and the third group used a traditional paper log. The main dependent variables were weight loss, usage of the system and the Working Alliance Inventory [27]. Although the weight loss results were not significantly different among the three groups, participants with the robot interacted significantly more days with the system (on average, 50.6 days against 36.2 and 26.6, respectively for participants who used the computer and participants using the log paper system) and expressed more willingness to maintain the interaction than participants in the two control conditions.

3.1.1 Discussion

All the presented studies (see Table 1 for a summary) found positive results regarding the long-term effects of social robots in therapeutic or health-related scenarios. However, the users who took part in these studies were very different (elderly, autistic children and adults), and thus further research is needed to consolidate these results. Moreover,

Table 1 Summary of the long-term studies in the health care and therapy domains

References	Agent/Robot	Capabilities	Exp. design	Nr. sessions	Main results
Wada & Shibata (2006, 2007)	Paro	Animal-like behaviour; responds to touch, sound and lights; limited-keyword recognition	Subjects: 12 Measures: degree of social interaction, stress levels Methods: video, interviews, urine tests	30 (9 hours a day)	Increased social interaction between participants, stress levels reduced
Kidd & Breazeal (2008)	Autom	Eye contact and small talk depending on time of day, state of the relationship with the user, etc.	Subjects: 45; 17–72 years old (3 conditions) Measures: weight loss, WAI, usage of the system Methods: questionnaire	50 (average)	Participants interacting with the robot reported their weight for more days and expressed more willing to continue interacting with the system
Francois et al. (2009)	AIBO	Dog-like behaviour (e.g., wag the tail); responds to touch	Subjects: 6 (autistic children) Measures: children's progress during interaction Methods: video observation	10 (40 minutes each)	Children tended to express more interest towards the robot over time, with occasional displays of affect
Sabelli et al. (2011)	Robovie	Remotely operated dialogues and child-like behaviours (e.g. "what is this?")	Subjects: 55 Measures: interaction patterns during interaction Methods: interviews, direct observations	15 to 35 (10 to 20 minutes each)	Robot was well accepted due to role as "child" and behaviours such as greetings and calling users by their names

in half of the studies the sample size was limited. Still, this area seems to benefit from the introduction of robots that can complement human activity and help users to achieve their goals, while receiving additional comfort or attention.

An important aspect in the studies presented here is that animal-inspired robots were used in two of them, namely in the work of Wada and Shibata [76] and François et al. [19]. In fact, recently some researchers have been trying to transfer the positive effects of Animal Assisted Therapy (e.g., reduced loneliness and the development of attachment bonds) into HRI, by comparing the effects of social robots with those of real animals [4]. If such results are verified, robots can substitute animals for example, in hospitals where for hygienic reasons animals are usually not allowed.

3.2 Education

Another popular area already with a significant amount of long-term studies using social robots is education. Virtual pedagogical agents have been used for many years in this context (for a comprehensive survey, please consult [45]), and it is expected that social robots might have the same beneficial effects on students, especially due to their physical presence. In this section, we included all the long-term studies performed with children in schools or other educational environments (e.g., chess clubs or day-care centres). Although, in some cases, there is no knowledge transfer, we consider that these studies have the ultimate goal of exploring the use of social robots in educational environments and, as such, they were grouped in the same category.

In 2004, Kanda et al. [34] performed a field trial evaluation for two weeks (9 school days) with elementary school Japanese students and two English-speaking interactive humanoid robots behaving as peer English tutors. The robots ("Robovie 1" and "Robovie 2") were capable of recognising children and calling them by their names using RFID tags, displaying several interactive behaviours such as greeting or hugging, as well as recognising 50 different English words and displaying some English utterances. The study revealed that the robots failed to keep most of the children interested after the first week, mainly because the first impact created unreasonably high expectations in the children. However, children who kept interacting with the robots after the first week improved their English Skills. They also found that, very often, children interacted with the robots together with their group of friends. These results motivated a subsequent study where Robovie's capabilities were extended to better support long-term interaction with children [35]. The new capabilities included a pseudo-development mechanism (the more a child interacts with the robot, the more different behaviours the robot displays to that child), and self-disclosure behaviours (e.g., the robot may reveal its favourite baseball player). The robot was also capable of estimating some of the friendship relations of children, by analysing the groups of children who interacted together with the robot. This newer version of Robovie interacted with children in Japanese in their classroom for 2 months (32 actual experimental days). In contrast to the results obtained in the previous experiment, Robovie was capable of engaging children after the second week (although with a slight

(a) QRIO[71] ©Sony (b) Keepon [44] (c) iCat[47] ©Philips Research (d) iRobiQ[30] ©iRobiQ Co.,Ltd.

Fig. 2 Some of the robots used in the long-term studies in the education domain (images used with permission of the authors)

decay), which the authors attribute to the new capabilities implemented in the robot. The children's motivations for interacting with the robot were also studied. Most children answered that their main motivation was to become "friends" with the robot.

Salter and colleagues [62] carried out a study to extract patterns of interaction between children and a commercial small robot equipped with infra-red sensors. Eight children with ages between 5 and 8 years old interacted with the robot five times each in individual sessions of approximately 5 minutes. In the first three sessions, most of the children seemed to enjoy playing with the robot while it was performing obstacle avoidance. However, as stated by the authors, "children become successfully bored of the robot over the first 2 sessions". For this reason, in the fourth session some plastic stickers simulating eyes were added to the front of the robot with the purpose of regaining children's interest, but this novelty factor quickly vanished. In the last session, the speed of the robot was increased, yet again, this did not seem to increase children's engagement. The technical limitations of the robot also affected negatively the interaction. For example, the robot getting "stuck" in the environment coincided with less activity from children. This study clearly demonstrates the importance of conducting long-term studies where children are exposed to robots over several interactions, since the interaction patterns and engagement towards the robot, as it happened in this study, is likely to change.

Using children from a different age group, Tanaka et al. [71] reported a longitudinal study where a QRIO robot (Fig. 2(a)) interacted with toddlers in a day care centre for 45 sessions of 45 to 60 minutes each. QRIO displayed several behaviours including choreographed dance sequences and mimicking some of the toddler's movements. The study was divided in three different phases, in which the robot's behaviour varied slightly. Five independent coders annotated the video recordings of 15 sessions in terms of quality of the interaction. The quality of interaction increased during phase I, then decreased sharply on phase II and on phase III returned to the levels observed in phase I. The same pattern was verified for the amount of times children touched the robot. Moreover, when introducing two inanimate toys in the environment (a teddy bear and a toy very similar to QRIO), QRIO was still the most hugged by the children followed by the toy that looked like the robot. The results of this study suggest that toddlers progressively started treating the robot as a peer rather than as a toy, as they exhibited an extensive number of care-taking behaviours towards the robot. These results are in line with the work by King and Ohya [40], who found that anthropomorphic embodied agents, especially the ones with subtle behavioural displays (such as eye blinking) were perceived as more intelligent and capable of higher agency than agents with non human-like appearance.

Kozima et al. undertook a similar study to investigate the interaction between toddlers and Keepon (Fig. 2(b)), a small robot designed to interact through non-verbal behaviours such as eye contact, joint attention and emotions [44]. A group of 27 children interacted with Keepon in their class during 90 minutes for 20 sessions. As observed in Kanda et al.'s studies, Keepon often played the role of social mediator between children, who exhibited a wide range of spontaneous actions towards the robot. Children maintained their interest over the sessions, which was not observable in previous studies using the same robot with older children. The authors report that children's understanding of the robot changed over time, from a mere "moving thing" to a "social agent". Keepon was also introduced in the play room of a day-care centre for children with developmental disorders for more than 3 years. The results of the first 15 sessions (spanning through five months, approximately one hour per session) indicate that, even though eye contact between children and Keepon gradually decreased, children were able to spontaneously approach the robot and establish physical and social contact. As they gradually learn the meaning of the robot's actions and responses, dyadic, triadic and empathetic interactions start emerging.

In our own previous work [47], we studied how the perception of social presence [46] towards a robotic chess companion changed over time. We conducted a study in a chess club where children played an entire chess match with an iCat robot (Fig. 2(c)) during five consecutive weeks (once per week). The robot's affective state was influenced by the state of the game, so that users can have feedback on their moves through the iCat's facial expressions and mood. The results suggested that the perception of social presence decreased from the first to the last interaction, especially in terms of attentional allocation, and perceived affective and behavioural interdependence. The last two dimensions are related to the extent to which users believe that their affective (and overall) behaviour affects and is affected by the robot's behaviour. We also observed that the amount of time children spent looking at the robot decreased over the sessions, especially between the second and third interactions.

Another research topic that has been receiving increasingly more attention is children's preconceptions and judgements of robots [5, 6]. With this goal, Hyun et al. [30] interviewed 111 children who interacted with an iRobiQ robot (Fig. 2(d)) for around one hour over a two-week period. The robot is capable of moving its head and arms and express emotions through lights. The interviews consisted of 50 items around three main themes: robot's comparison to other media, a perception survey and appearance of robots. The results indicate that robots are well accepted in educational settings, and that mechanisms that promote social and emotional interactions between robots and children contribute to a great extent in this acceptance.

3.2.1 Discussion

Table 2 summarises the studies within this domain. When conducting studies with children, additional efforts are needed to collect and analyse the data. For example, most of the existing validated questionnaires are tailored to adults and, when conducting interviews, children tend to answer what they think adults want to hear [23]. For this reason, most of the studies in this section were analysed using behavioural data (e.g., collected through video recordings of the interaction sessions).

As we can see from the "main results" column of Table 2, these studies show conflicting results that can be explained, at least partially, by the differences in the age groups of the subjects and by the variety in terms of complexity of behaviour of the robots employed in the experiments. Regarding age, younger children are more likely to engage with robots, possibly because they do not have any preconceptions of what a robot is supposed to behave, and they may see it simply as a very special/advanced kind of toy, as shown by the results of Tanaka et al. [71] and Kozima et al. [43]. In this latter work, the authors even state that another experiment with the same robot but with older subjects was not so successful.

An aspect that seems to play an important role in sustaining long-term engagement with children is the complexity of the robot's social behaviour, and the amount of diverse behaviours that the robot can display over the interaction. Salter et al. [62] found that a robot without any social capabilities was not capable of engaging autistic children after the third interaction. Similar results were found in [47], where after the second week children's eye contact with the robot decreased a lot, even though they kept performing the task with the robot. As studied by Kanda et al. [37], the incremental implementation of novel behaviours (e.g., self-disclosure) did play an important role for maintaining users engaged with Robovie. This can be explained by the habituation effect [28], a phenomenon characterised by children's tendency to, after a certain period of exposure, shift their preferences to novel (rather than familiar) stimulus.

In this domain, researchers also need to pay special attention when selecting the embodiment of the robot. The initial expectations that children create by looking at the robot might influence the whole course of the interaction. It is believed that very human-like embodiments create higher expectations. To avoid this, robots designed to interact with children usually have more caricatured embodiments, as we can see in Fig. 2. Another example that illustrates this comes from MIT's Personal Robots Group. They developed a robotic companion, the Huggable™, which has the form of a teddy bear because "the use of a fantasy animal alleviates the expectation of how the Huggable should behave" [66].

In sum, even though social robots are well accepted by children in educational environments, they should be able to simulate complex and diverse social behaviours in order to engage children in the long-term. Considering the findings presented above, it seems to be the case that the older the children, the more complex, diverse and dynamic should be the robot's behaviour.

3.3 Work Environments and Public Spaces

There are already some successful examples of commercial robots deployed in work environments and public spaces. Examples include Robotdalen's RobCab[6], a transportation robot for hospitals, the Siga Robots[7] developed by YDreams to guide and interact with guests visiting the headquarters of Santander bank, and the robotic characters developed by Walt Disney Imagineering for the Disney parks[8]. As we will see from the long-term studies presented in this section, social robots deployed in these environments should be able to adapt to different and unexpected situations, as well as to different types of users.

[6] http://www.robotdalen.se/en/Projects/RobCab—transportation-robot-for-hospitals/

[7] http://www.wired.co.uk/magazine/archive/2011/08/start/friendly-bank-bots

[8] http://disneyparks.disney.go.com/blog/tag/autonomatronics/

Table 2 Summary of the long-term studies in the domain of education

References	Robot	Capabilities	Exp. design	Nr. sessions	Main results
Kanda et al. (2004)	Robovie	Identify users, recognising and speaking English	Subjects: 228 Measures: length of interaction, English skills Methods: video observation, English tests	9 school days	Interaction after 1th week declined; improvement of English skills in children who kept interacting with the robot
Kanda et al. (2007)	Robovie	Identify users, pseudo-development mechanism, confiding personal information	Subjects: 37 (10–11 years) Measures: length of interaction Methods: questionnaire, video observation	32 school days	Children kept interacting with the robot after the 2nd week
Salter et al. (2004)	Wany	Obstacle avoidance, move in the environment	Subjects: 8 (5–8 years, male) Measures: activity around the robot Methods: video observation, analysis of interaction data	5	Children lost interest in the interaction from the third session
Tanaka et al. (2007)	QRIO	Choreographed dance sequences and mimicking children's movements	Subjects: 11 (10–24 months) Measures: quality of interaction, haptic behaviour towards the robot Methods: video observation	15 (45–50 min. each)	Toddlers progressively started treating QRIO as a peer and exhibited several care-taking behaviours towards the robot
Kozima et al. (2009) (study 1)	Keepon	Display non-verbal behaviours (gaze, emotions, ...)	Subjects: 27 (3–4 years) Measures: children's responses Methods: video observation	20 (90 minutes each)	Robot played the role of social mediator; children maintained interest over the sessions
Kozima et al. (2009) (study 2)	Keepon	Display non-verbal behaviours (gaze, emotions, ...)	Subjects: 30 (2–4 years, autistic) Measures: children's responses towards the robot Methods: video observation	15	Although eye contact decreased, children gradually approached the robot more and established physical contact
Leite et al. (2008)	iCat	Feedback on children's moves through facial expressions	Subjects: 5 (5–15 years) Measures: social presence, eye contact with the robot Methods: questionnaire, video observation	5 (aprox. 1 hour)	Some dimensions of social presence decreased; eye contact with the robot decreased after the 2nd week
Hyun et al. (2010)	iRobiQ	Move head and arms, navigate in the environment, express emotions	Subjects: 111 (5 years) Measures: children's perception of the robot Methods: interviews	10 (approx. 1 hour)	Robots are well accepted by children in educational settings

Severinson-Eklundh et al. [64] reported probably one of the first long-term studies in a real-world setting involving a social robot. The goal of the study was to investigate social aspects of the interaction with a fetch-and-carry robot for motion impaired users in an office environment. The robot, Cero (Fig. 3(a)), was evaluated during 3 months in the workplace of a target user, a female academic with a walking disability. From the analysis of the videos recorded during the trial, the internal logs of the system and a post interview with the target user, the authors extracted patterns of how people interact and relate with robots in work environments. One interesting finding was that very often other people than the target user (e.g., office workers, cleaning staff, etc.) wanted or needed to interact with the robot, but didn't know how to do it. Thus, it is important that social robots immersed in public spaces can provide clear instructions on how to be operated and be "easy to use" by people who are unfamiliar with the robot. They also raised some issues for future research in long-term interaction such as the personality of the robot, the dialogue between users and the robot, and the relevance of group collaboration.

In a different context, Stubbs et al. [67] examined how people's cognitive model of a robot changes over time. The target robot was PER (Fig. 3(c)), a robot designed to educate people about NASA's Mars exploration robot, and the selected subjects were museum employees who interacted

(a) Cero [64] (b) Valerie [22, 41] (c) PER [67]

Fig. 3 Robots used in the long-term studies in work environments and public spaces (images used with permission of the authors)

with PER on a daily basis. The study consisted on interviewing 11 museum employees at different stages of their relationship with the robot: the first interview was conducted before the PER exhibition was installed, followed by three other interviews, more precisely two weeks, one month and three and a half months after the installation. The results of the open-ended interviews indicate that regular interactions influence people's cognitive model of the robot. Over time, references to anthropomorphisation increased significantly, together with discussions about the robot's intelligence. Conversely, themes related to the technical capabilities of the robot became less frequent.

Gockley et al. [22] developed Valerie (Fig. 3(b)), a "roboceptionist" installed at the reception of one of the buildings at the CMU campus. The robot has a personality and a background story that is gradually disclosed to people through monologues. Students and university visitors interacted with the robot over a nine month period. The results indicated that while many users kept interacting daily with the robot, after a certain period only few of them interacted for more than 30 seconds. From the analysis of the interactions, the authors proposed some design recommendations so that Valerie (and possibly other robots) can be more engaging in the long term. Such recommendations include proper greeting and farewell behaviours, more interactive dialogue (rather than monologues, which did not attract visitors the way authors were expecting), a robust way of identifying repeated visitors and the ability to display emotions. This last design recommendation inspired another long-term study with the same robot [41] where Valerie also exhibited different moods (positive, negative or neutral) matching its life stories. The length and number of interactions were measured for a total of nine weeks, during which the robot operated eight hours per day, five days per week. Some users filled in a questionnaire that measured their subjective experience towards the robot. The analysis of the results was separated in two different groups, one for frequent users of the building (more familiarity with the robot) and another group for visitors (less familiarity). It was concluded that the robot's moods were easily recognised by all visitors, and that interactions were different depending on the level of familiarity: frequent users interacted more times when the robot was in a positive mood, but the amount of time they dedicated to the robot was higher when it was in the negative mood. The authors justify these results with the common ground theory (e.g., a smile can be understood as a positive signal that carries a certain amount of conversational content) and with the questionnaire answers, where participants found the positive mood robot less enigmatic. On the other hand, visitors spent less time interacting with the neutral mood robot, which may indicate that any form of affect display can be enough to sustain interactions. In short, the interaction patterns change according to the mood displayed by the robot, and how such patterns change depends on the person's level of familiarity with the robot. The authors use this argument to reinforce the idea that social robots need to properly identify users (to change their behaviour whether users are newcomers or repeated visitors), and that "a rich model of affect is necessary for forming long-term human-robot relationships".

More recently, Kanda and colleagues [36] also evaluated Robovie in a shopping mall. In this study, the robot was programmed with a different set of behaviours particularly relevant to a shopping mall environment: apart from building rapport with users by identifying them using RFID tags, employing self-disclosure mechanisms and adjusting the dialogues based on the previous dialogue history with each user, Robovie was also capable of offering directions and advertising specific shops and services of the mall. Although the long-term study considered 162 participants, 72 of them interacted with the robot no more than 2 times and only 23 participants interacted with the robot more than 5 times. The authors explain in the paper that this effect might have been caused by the continuous presence of many people (visitors of the shopping mall but not official participants of the study) around the robot. Due to the large cues, participants hesitated before deciding to interact with the robot. Questionnaires mailed to the study participants (even the ones who only interacted with the robot once) suggested that their perception of the interaction was positive, not only in terms of perceived familiarity, intelligence and interest towards the robot, but also regarding intention of use and adequacy of the route guidance behaviours. Moreover, repeated visitors provided significantly higher rankings in the questionnaire. In addition to these results, the study also concluded that people's shopping behaviour was influenced by the robot's suggestions.

3.3.1 Discussion

It is difficult to generalise and draw conclusions from the studies in this section because they were performed with very different robots, both in terms of embodiment and functionality (see Table 3 for an overview) and, apart from the studies with the Roboceptionist and Robovie, the sample size was small. Yet, these studies show that deploying social robots in public environments, where they can interact with almost every type of person, requires additional efforts in terms of usability and adaptation, so that they can better deal with the uncertainties of the environment. As the study by Severinson-Eklundh et al. [64] shows, people should easily learn how to interact with the robot and have access to its internal state, for example, to understand where the robot is going and eventually how it may be able to help. To address this issue, Rosenthal and colleagues [60] are developing a robot that can ask a human for help to overcome some of its limitations (e.g., when it needs to pass by a door that is closed). On the other hand, robots should be able to adapt their behaviour to different types of users (for example, distinguishing between new and repeated visitors, as suggested in the "roboceptionist" study) so that interactions become more natural and intuitive.

Overall, the robots in these studies lack perceptual capabilities that would enable richer social interactions with users. While in the first two studies this was clear to users due to the robot's embodiment being extremely functional (and as such did not seem to affect the interaction), in the

Table 3 Summary of the long-term studies in work environments and public spaces

References	Robot	Capabilities	Exp. design	Nr. sessions	Main results
Severinson-Eklundh et al. (2003)	Cero	Fetch-and-carry objects such as books or coffee cups	Subjects: 1 target user in a work group of 30 Measures: long-term effects of a service robot Methods: video and direct observation, system logs, pos-trial interviews	66	Social robots in public spaces should be able to interact with everyone, not just the main users
Stubbs et al. (2004)	PER	Simulated scientific testing	Subjects: 11 Measures: people's cognitive model of the robot Methods: interviews	3 months	Regular interactions influence people's cognitive model of the robot
Gockley et al. (2005)	Valerie	Reveal back-story, recognise people around the booth, limited natural language user interaction through text input	Subjects: 233 Measures: length of interactions Methods: analysis of interaction data	180	Many users kept interacting daily with the robot, but after a certain period only a few interacted for more than 30 seconds
Kirby et al. (2007)	Valerie	Additional mood displays while telling stories	Subjects: 62 Measures: length of interactions Methods: analysis of interaction data, questionnaire	45 (8 hours a day)	Interaction patterns change according to the robot's mood and level of familiarity with the robot
Kanda et al. (2010)	Robovie	Guiding, rapport building, identify repeated users, advertisement	Subjects: 162 Measures: intention of use, interest, perceived familiarity, intelligence and adequacy of route guidance Methods: questionnaire	2.1 (average); from 2 to 18 sessions	Perception of the robot was positive; shopping suggestions of the robot were accepted by visitors

(a) PeopleBot [43] (b) Roomba[68, 69] ©iRobot (c) Pleo [16] (d) Nabaztag [42]

Fig. 4 Robots used in the long-term studies in home environments (images used with permission of the authors)

study by Gockley et al. [22] users were more disappointed by Valerie's monologues, as they expected more from its human-like embodiment. These results highlight the relevance of interactive experiences, where the user plays an important role influencing the robot's behaviour rather than being a mere spectator. Note that there are examples of rich social interactions with limited communication modalities (as seen, for instance, in interactions with Paro robot). However, if the robot's appearance suggests the existence of more human-like social communication capabilities (such as the embodiment of the Roboceptionist), then it should be able to interact with users using those modalities.

Nevertheless, robots in public spaces such as offices or shopping malls appear to be well accepted by users, and thus further long-term studies should be conducted within these application domains. These results are in line with a study performed by Takayama et al. [70] about occupations for which people consider that robots are qualified and desired. The results indicate that people envision robots performing jobs that require memorisation, perceptual skills and service-orientation, in contrast with the notion that robots should only do dangerous, dirty or dull jobs.

3.4 At Home

Domestic environments are receiving increasingly more attention as an application for social robotics research. Even though robots at home were envisioned many years ago in science fiction, only recently technology has been robust enough to allow the execution of long-term evaluations in these settings. Long-term studies in this domain are even more challenging due to the privacy issues and consequent lack of control of users' activities.

In the work of Koay et al. [43], the habituation effects between users and a social robot were investigated during eight interaction sessions over a five week period. More precisely, their goal was to isolate certain aspects of participant's preferences that may be influenced by the habituation effect. The experiment was conducted at the Robot House, a naturalistic environment especially designed to study human-robot interactions outside the laboratory conditions. Participants expressed their preferences when a PeopleBot humanoid robot (Fig. 4(a)) approached them in several forms. The findings suggest that even though preferences did not change in the first two sessions, in the last sessions participants allowed the robot to come closer than in the previous interactions.

Most of the longitudinal studies in domestic settings employ commercial robots. For example, Sung et al. [68] empirically evaluated how people used and accepted Roomba vacuum cleaner robots (Fig. 4(b)) in their homes. Roombas were distributed through 30 households and one experimenter visited each household five times during a six-month period. The first visit happened a week before Roomba was introduced, the second visit when families unpacked the robot and used it for the first time, and the other three visits took place respectively, two weeks, two months and six months after Roomba was introduced. During the visits, several methods besides traditional interviews were used to better capture people's routines and acceptance of the robot, such as drawings, probing techniques and checklists of the activities they did with Roomba. Participants were also encouraged to report their experiences with the robot via e-mail. The authors argue that two months are enough for observing stable interactions between robots and households in a domestic environment. They also found that the combination of several data collection methods is extremely useful for capturing people's routines and interaction with the robot, especially in a domestic environment. Based on this study, the first steps for establishing a long-term framework were taken [69]. The framework includes four different temporal steps that contain key interaction patterns experienced while households were accepting the robot: *pre-adoption*, *adoption*, *adaptation*, and *use and retention*.

Fernaeus et al. [16] reported a similar study with Pleo (Fig. 4(c)), a robotic toy dinosaur. Six families took a Pleo robot home for 2 to 10 months (each family decided for how long they wanted to keep the robot). They were also given a video camera to record moments of their interaction with the robot. Most families were interviewed at least two times after having Pleo in their homes. The study is focused on the discrepancy between previous expectations that participants had about Pleo, and how the robot met (or failed to meet) such expectations. Participants' initial expectations were really high due to the price, sophistication and the advertisements about Pleo. However, the robot's behaviour was not attractive enough to keep these expectations so high until the end of the study. After the initial novelty effect, participants did not interact with Pleo in a regular manner. After a while, Pleo was only switched on in special occasions, for example when friends were visiting the home. Even though at first Pleo was treated in a similar way to a real animal, with activities such as petting and choosing a name for the robot, over time, it failed to encourage regular interactions and started being treated as a regular toy. This study reinforces the findings of Jacobsson [31] which reveal that the majority of the blog and forum posts about Pleo only contain a few posts concerning the initial stage of interaction and after that people stop writing about the robot.

With participants from a different age group, Klamer and colleagues [42] conducted a preliminary study to understand how elderly people use social robots at home, and which factors are relevant for people to build a relationship with the robot. A Nabaztag robot (Fig. 4(d)) was programmed to talk about health related activities in a personalised way with the three participants who took part in the experiment. They could answer the robot using yes- and no-buttons installed near the robot. The study consisted in interviewing the participants after 10 days of interacting with Nabaztag at their homes. The interviews contained questions regarding the general use of the robot (usefulness, contrast with initial expectations, etc.), perceived enjoyment while interacting with the robot and other relational factors such as perceived trust, credibility and likeability. Even though the sample size was very limited, the study points out interesting utilitarian and social factors of robots that deserve further attention. For example, the participant who found the robot useful was also the one who named the robot differently and stated that she built a relationship with the robot, which suggests that the utilitarian aspect of the robot is a major determinant for people to establish a social relationship with it.

3.4.1 Discussion

A summary of the studies described above is presented in Table 4. As domestic robots are becoming a reality with the arrival of commercial products such as Roomba, significant progress has been made towards studying people's acceptance of robots in home environments. In fact, the earliest

Table 4 Summary of the long-term studies in home environments

References	Robot	Capabilities	Exp. design	Nr. sessions	Main results
Koay et al. (2003)	PeopleBot	Approach the user in several ways	Subjects: 12 (8 male and 4 female) Measures: proxemic preferences Methods: questionnaire, comfort level device	8 (aprox. 1 hour each)	People's preferences in terms of promixity change over time
Sung et al. (2009, 2010)	Roomba	Vacuum cleaning, move around the house	Subjects: 48 (across 30 households) Measures: acceptance of robot Methods: observation, interviews, probing techniques, activity cards, small questionnaires	6 months	Two months is the time required for observing stable interactions between robots and households. Several techniques should be complemented to really capture people's routines at home
Fernaeus et al. (2010)	Pleo	Animal-like behaviour	Subjects: 6 families Measures: exploratory study Methods: interviews, video recordings and pictures	2–10 months	Initial expectations about Pleo were not met. After the novelty effect, participants played with the robot only occasionally
Klamer et al. (2011)	Nabaztag	Personalised health conversations; users interact using yes- and no-buttons	Subjects: 3 (50–65 years old, females) Measures: usage and acceptance of social robots Methods: interviews	10 days	Utilitarian and social factors seem important reasons for participants to accept social robots in domestic environments

Table 5 Summary of the guidelines for future design of social robots for long-term interaction

Guideline	Recommendations
Appearance	– Select embodiment according to the robot's purpose and capabilities – Functional embodiments well suited for home or office environments – Animal-like embodiments create less expectations of robot's social capabilities
Continuity and incremental behaviours	– Routine behaviours (e.g., greetings and farewells) – Strategic behaviours (e.g., recalling previous activities and self-disclosure) – Incremental addition of novel behaviours over time
Affective interactions and empathy	– Understand the user's affective state (and react accordingly) – Display contextualised affective reactions
Memory and adaptation	– Identify new and repeated users – Remember aspects of past interactions and recall them appropriately – Use information about the user to personalise the interaction

study presented in this section [43] was not performed in users' own homes, but in a home-like environment. More recently, the existing long-term studies in domestic environments so far used commercial robots, as research robots are still not stable enough to run out of laboratory conditions for extended periods of time without supervision. However, commercial robots still have limited capabilities, causing a gap between people's initial expectations and what they really experience after the initial interactions with the robot. These were consistent findings in some of the studies presented here, for example in [68] and [16]. On the other hand, as suggested in the Robot House study [43], even when the novelty effect fades away people allow robots to come closer to them in later interactions. This result highlights that there is potential for social robots in home environments, as long as they are capable of engaging users over extended periods of time. To do so, the robot's functionality (in other words, how it can assist users in their home routines), appears to be a major determinant.

Evaluating users' subjective experiences with a social robot in their home requires more original data collection methods than in any other environment. Quantitative measures such as the number and duration of the interactions or video recordings are usually not suitable in this case (unless when controlled by the families as in the Pleo study). Therefore, researchers have to come up with novel ways to gather user information while keeping users' privacy. A good example on how to overcome this can be found in [68], where traditional interviews were complemented with other methods such as drawings, probing techniques and checklists of the user activities.

The framework proposed by Sung et al. [68] is particularly relevant not only to domestic settings, but also to the field of long-term human-robot interaction in general. The temporal steps identified in their study (*pre-adoption*, *adoption*, *adaptation* and *use and retention*) are similar to those reported in HCI long-term studies (for example, see [38]), which suggests that several methodologies and practises employed in HCI for measuring user experience over time can be applicable to HRI.

4 Guidelines for Future Design

Based on the analysis of the work presented earlier, and taking inspiration from theoretical research on human social relationships, in this section we provide a set of directions where we consider that future research is needed to improve the design of social robots for long-term interactions. Some of these guidelines are also the main research directions of projects that aim to build robots capable of engaging users for extended periods of time such as LIREC[9] and ALIZ-E[10].

A summary of these guidelines is presented in Table 5. This preliminary set of guidelines aims to help researchers with the goal of developing social robots for long-term interaction. This proposal should not be understood as final, but rather as an initial specification that requires further investigation and refinements. Additionally, we would like to stress that these are guidelines that we consider relevant for long-term human-robot interaction, and thus may not represent the entire needs of the HRI field in general (discussed, for example, in the work of Kahn et al. [32]).

4.1 Appearance

Embodiment can play an important role in the first impressions and future expectations that people create about

[9] http://lirec.eu/

[10] http://www.aliz-e.org/

a robot. Several authors have investigated the effects of appearance in social robots. For example, Lohse et al. [50] concluded in a web survey that participants consider the robot's appearance more relevant than functionality, especially in domestic robots. In a study using static images of robots, DiSalvo and colleagues [13] found that the facial features of several robotic heads influenced significantly the perception of humanness in those robots. A study by Hayashi et al. [24] also concludes that "if a robot's appearance and behaviour is less human-like, people would expect less cognitive human-likeness", which at least for now is desirable given the limited autonomous capabilities of robots. Despite the substantial recent advances in the android science [55], human appearance is not always desirable as suggested in Mori's theory of the uncanny valley [53]. Moreover, as argued by Dautenhahn [10], "anthropomorphism might raise false expectations regarding the cognitive and social abilities that the robot cannot fulfil". This is especially true in long-term interactions, since it is more likely that these "flaws" become visible over time. For example, in the "roboceptionist" study [22], the human-like face of the robot (displayed in a computer screen) created very high expectations in users, namely in terms of the robot's dialogue capabilities. Since these expectations were not met, the amount of time that users spent interacting with the robot decreased day after day. On the other hand, the animal-inspired embodiments used in the studies of the health-care domains proved to be more effective, as people seem expect less from a robot with an animal shape form.

Therefore, the choice of the robot's appearance must take into account not only its behavioural and social capabilities, but also the application domain where the robot will operate and its function. While animal-inspired embodiments are well suited for health and therapy related scenarios, as they elicit care-taking behaviours from humans, functional embodiments are more appropriate for work environments or domestic settings, where the ways in which the robot can assist users are a major determinant.

4.2 Continuity and Incremental Novel Behaviours

To maintain a social relationship, humans perform a series of activities in order to keep the relationship in a satisfactory condition. Several researchers separate these activities between routine and strategic behaviours. While routine behaviours are those who "people engage in for other reasons which serve to maintain a relationship as a side effect" [7], strategic behaviours are those which "individuals enact with the conscious intent of preserving or improving the relationship" [65]. Greetings and farewells, or performing everyday tasks together, are examples of routine behaviours relevant for the maintenance of social relationships. Examples of strategic behaviours include relational communication (e.g., talking about the relationship or recalling past activities together), performing planned activities together and self-disclosure (revealing personal information as a mechanism to give and receive advice that increases trust and intimacy) [14].

Some of these strategies of relationship maintenance were successfully applied in the works presented in the previous section, namely greetings and farewells [22, 39, 61] and self-disclosure [34, 36]. Regarding the latter, even when the confiding of personal information is not the most appropriate behaviour, the addition of novel behaviours over time can contribute in a positive way to engage users in long-term interactions. These mechanisms are important for keeping users interested in the interaction. As such, they are of particular relevance in application domains such as Education or Public Spaces, where users usually have more freedom to abandon the interaction if they wish.

4.3 Affective Interactions and Empathy

The display of emotions and other non-verbal behaviours by social robots has been one of the features extensively used in the studies presented earlier [30, 41, 44, 47], especially in the most recent ones. Also in the field of virtual agents, this subject has been receiving considerable attention over the last few years. For example, the main goal of the SEMAINE project[11] was to build an Autonomous Sensitive Artificial Listener [63] based on emotional and non-verbal interaction capabilities. However, in HRI, one of the capacities that remains nearly unexplored is the capacity to understand, adapt and respond more appropriately to the user's affective and motivational states. In other words, the ability to empathise with users [26].

Hoffman defines empathy as "an affective response more appropriate to someone else's situation than to one's own" [26]. Such affective response may include an emotional display in tune the affective state of the person we are empathising with, but also prosocial actions that can, for example, reduce the other's distress [56]. It is believed that empathy facilitates the creation and development of human social relationships [2], as it increases similarity, fondness and affiliation [12]. Moreover, many authors also highlighted the central role of empathy in learning [3, 59], which makes this capability very important for social robots developed for educational domains.

Previous short-term studies using empathic robots yielded promising results, showing that the presence of empathic behaviours has a positive effect on user's perception of the robot [45, 58]. Taking this into account, it is expected that empathy might as well play an important role in social robots for long-term interaction. In fact, some researchers

[11] http://www.semaine-project.eu/

even consider the awareness of the user's affective state more important than the actual display of emotions by the robot. While discussing the desired features of future artificial companions (robots or virtual agents), Pulman [57] argues that "a Companion which behaved in the same way whatever our emotional state would be thought of as insufficiently aware of us. But this may not mean that the Companion itself has to express emotions: all that is necessary to achieve this is the ability to recognise our own displays of emotion".

4.4 Memory and Adaptation

Another relevant aspect that remains nearly unexplored is memory. Although some robots in the survey were able to identify different users and call them by their names [35] (for more details on how this mechanism was implemented in the robot please refer to [33]), which can be considered a simple kind of memory, there are still many challenges that need to be addressed. Recently, researchers have been investigating computational models of memory to be included in social robots or virtual agents that will interact with users for extended periods of time [25, 48], but the actual benefits that memory can bring are still unclear. Nevertheless, they anticipate that memory will give users the impression of behavioural coherence and plausibility, and therefore it might positively influence the perception of intelligence and quality of the interaction with the robot [48].

Memory will definitely make social robots more flexible and personalised to particular users, regardless of the application domain in which they are supposed to operate. As stated by Dautenhahn, "rather than relying on an inbuilt fixed repertoire of social behaviours, a robot should be able to learn and adapt to the social manners, routines and personal preferences of the people it is living with" [10]. To achieve this, social robots need to remember aspects of the past interactions with users. However, as shown by Koay et al. [43] in the proxemics preferences study, this can be done in simple ways without requiring complex perceptual capabilities by the robot. Simple preferences regarding proxemics or even related to the type of the responses employed by the robot (e.g., the amount of interruptions, how users like to be addressed, etc.) should be enough for users to feel comfortable with the interaction and increase their trust and sense of control towards the robot. These small adaptations will ultimately lead to personalisation [9], one of the features often mentioned as relevant in social robots or agents that will interact with users for extended periods of time.

5 Other Open Issues

Being such a new area of research, there are many open questions that need to be addressed in the near future. This section is dedicated to more general issues related to long-term interaction studies. We start by discussing relevant factors for defining "long-term interaction", followed by some considerations regarding the experimental design methods in these studies. We end this section by providing some references to relevant ethical discussions in this area.

5.1 How Long Should "Long-Term" Be?

A question that naturally arises when developing social robots for long-term interaction is related to the notion of temporality: how often should a robot interact with the same users so that the interaction can be considered as "long-term"? Some authors argue that two months is the answer [35, 68], while in Human-Computer Interaction there are reports of longitudinal studies lasting five weeks [38]. We believe that more than providing an exact number of days, weeks or months, it is more important to look at the actual number of interaction sessions with the robot during that period, and to the length of each session (an interaction of 5 minutes is certainly different from an interaction of an hour). Moreover, there are other factors that should be considered, such as the number of users interacting with the robot at the same time and the complexity of the robot's behaviour. Concerning the number of users interacting with the robot at the same time, we argue that if the robot interacts with a group of users, users need more time for the novelty effect to fade away, since the robot will be switching its attention by the different users. As for the complexity of the robot's behaviour, if the repertoire of the robot is more limited, it is more likely that the novelty effect will fade away more quickly.

Taking this into account, an interaction can be considered as "long-term" when the user becomes familiarised with the robot to a point that her perception of such robot is not biased by the novelty effect anymore. However, the novelty effect may wear out more quickly in some cases than others, depending on factors such as the length of each interaction session, whether the user is "sharing" the robot's attention with other users or not, and also on the complexity of the robot's behaviour. We consider that the point where participants become familiarised with the robot is the minimum required for the interaction to be considered as "long-term". This does not necessarily mean that the interaction should end there. Instead, it means that from that point on, the study should be analysed from a long-term interaction perspective.

But how can we determine the point that the novelty effect wears out? In other words, when does user's familiarisation with the robot become stable? Familiarisation (or habituation) is a research topic used in psychology to study children's perceptual capabilities and their ability to differentiate different stimuli. Fennel [15] defines habituation as the "progressive reduction of an organism's behaviour in response to a repeated stimuli". This research has been motivated by Hunter and Ames' multifactor model of children's preferences for novel and familiar stimulus [29]. According to this model, children first show no preferences, then they prefer familiar stimulus and finally they start showing preferences for novel stimulus, following an U-shaped function. One relevant aspect in this model is that the preferences for novel stimulus indicate that the familiar stimulus was completely assimilated and, as a consequence, there is a change in the patterns of interaction. Taking this model as an analogy to long-term interaction in HRI, we can say that the novelty effect wears out when users get familiarised with the robot and start preferring novel behaviours. As in psychology research, behavioural metrics can be used to measure the end of the habituation phase, for example, searching for significant differences in the amount of time that users spend looking at the robot [15].

5.2 Experimental Design Considerations

One of the most prominent challenges when conducting long-term interaction studies is the time and effort required to analyse large amounts of data. Not only because one needs to collect data from several interaction sessions, but also because, since usually the number of subjects is limited (also due to time restrictions and because of the difficulties in recruiting participants for long-term studies), qualitative methods are more valuable, yet again more time consuming. For these reasons, most of the existing long-term studies are exploratory, and the data collection methods reflect the exploratory nature of these studies: video observation and interviews are often preferred to other quantitative methods such as questionnaires. However, when video material is collected, a deep analysis of all the interactions is usually not carried out because video annotation is very time consuming. For example, in the Keepon study [44], only the first 15 from 30 sessions were analysed, and the results of the Paro studies collected in the nursing homes are not available yet.

Ganster et al. [20] stressed the importance of using appropriate research methods for analysing long-term interactions, stating that methods and instruments that have been applied successfully in short-term studies might not be appropriate for long-term interactions. They provide a set of objective and subjective measurements that could be used successfully in this case (e.g., keeping diaries, task-accomplishments and change of performance, physiological methods, eye tracking or the analysis of audio and video material), arguing that a combination of different types of methods would bring value both in terms of data quality and reliability. Additionally, it is important to collect data through all the interaction sessions—and not only from the first and last sessions. This can help to determine at which point of the interaction the user's attitudes towards the robot has changed (if there was a change). In general, when selecting measures (and the amount of times they are collected) for longitudinal studies, there are several aspects that need to be balanced. These aspects include not only the advantages and disadvantages of the measures in terms of data quality and reliability, but also the amount of time and costs required to collect and analyse such data.

Considering these issues, below we summarise a set of guidelines that can be useful in the design of future long-term interaction studies:

– *Sample size*: the number of participants should be reasonable considering the number of interaction sessions, the data collection methods and the number of people allocated to analyse the data. For example, if only one person is assigned to work on the data analysis, there is no point in collecting videos of 10 sessions from 100 participants, since it is not feasible for a single person to analyse such large amounts of data.
– *Number of interaction sessions*: also due to the reasons mentioned above, the number of interactions should take into account the factors mentioned in the previous section. In other words, it should be enough to capture the changes on people's perception of the robot after the "novelty effect".
– *Control conditions*: the use of one (or more) control conditions should be done only if extremely necessary. As we can see from the related work presented in this paper, most of the long-term studies do not have a control condition. This happens not only because it doubles the amount of data to be analysed, but also because user's experience over time can already be considered a strong independent variable.
– *Data collection methods*: they should be adequate to both the environment where the study is taking place and the type of users that will interact with the robot. While video recordings may be appropriate for studies in public spaces, they are not very suitable for domestic settings. In the same way, interviewing very young children or elderly people might not be the best option. Nevertheless, qualitative measures are often preferred to quantitative measures, mainly due to the issues of sample size.

5.3 Ethical Issues

Another issue that has been receiving increasingly more attention in the last few years concerns with the ethical questions raised by having social robots in our daily lives. In other words, what are the ethical implications of interacting with robots for extended periods of time?

When humans interact with something (either with another human or an object) on a regular basis, they start creating bonds with that entity. This phenomenon happens in early childhood [1] but also in our adult life [77]. We often hear about people getting attached to their mobile phones and other personal objects. This issue can be magnified if these artifacts have some life-like abilities, as observed with the Tamagotchi in the late 90's [8]. Robots share our physical space, and so it is expected that people might get attached to them as well, especially if they are endowed with human-like capabilities.

Other aspects such as the security of users when interacting with the robot without any experimenter supervision, especially when the target users are children, or the protection of the data collected during the long-term studies (keeping the privacy of users), should also be taken into consideration. For a more detailed discussion on the ethical issues raised by having robots interacting with people over repeated interactions please consult [49, 73] and [17].

6 Conclusions

In this paper, we have presented a comprehensive survey on social robots designed for long-term interaction, with the respective long-term interaction studies carried out with those robots. We also highlighted open areas for future research and provided a discussion of general issues that are emerging in this field.

The studies we have analysed show that, in the last few years, significant research has been made towards understanding how users interact with robots over repeated interactions, and also on how such robots can be improved to engage users in the long-term. However, this is a very recent area, which means that most of the presented studies are exploratory and were performed with a limited number of users. The purpose of the majority of the experiments was to gain familiarity with the environment where the robot would be placed, and to better understand the nature of the situations that may happen after repeated interactions. Even though evidence suggests that people are willing to accept and interact with robots for extended periods of time, there is still a lot of work that needs to be done. We believe that, in the next few years, many new results will arise, contributing to the development of this field.

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References

1. Ainsworth M (1969) Object relations, dependency, and attachment: a theoretical review of the infant-mother relationship. In: Child development, pp 969–1025
2. Anderson C, Keltner D (2002) The role of empathy in the formation and maintenance of social bonds. Behav Brain Sci 25(1):21–22
3. Aspy D (1974) Toward a technology for humanizing education
4. Banks MR, Willoughby LM, Banks WA (2008) Animal-assisted therapy and loneliness in nursing homes: Use of robotic versus living dogs. J Am Med Dir Assoc 9(3):173–177
5. Beran TN, Ramirez-Serrano A (2011) Can children have a relationship with a robot? In: Akan O, Bellavista P, Cao J, Dressler F, Ferrari D, Gerla M, Kobayashi H, Palazzo S, Sahni S, Shen XS, Stan M, Xiaohua J, Zomaya A, Coulson G, Lamers MH, Verbeek FJ (eds) Human-robot personal relationships. LNCS, vol 59. Springer, Berlin, pp 49–56
6. Bhamjee S, Griffiths F, Palmer J (2011) Children's perception and interpretation of robots and robot behaviour. In: Akan O, Bellavista P, Cao J, Dressler F, Ferrari D, Gerla M, Kobayashi H, Palazzo S, Sahni S, Shen XS, Stan M, Xiaohua J, Zomaya A, Coulson G, Lamers MH, Verbeek FJ (eds) Human-robot personal relationships. LNCS, vol 59. Springer, Berlin, pp 42–48
7. Bickmore T, Picard R (2005) Establishing and maintaining long-term human-computer relationships. ACM Trans Comput-Hum Interact 12(2):327
8. Bloch L, Lemish D (1999) Disposable love: the rise and fall of a virtual pet. New Media Soc 1(3):283–303
9. Castellano G, Aylett R, Dautenhahn K, Paiva A, McOwan P, Ho S (2008) Long-term affect sensitive and socially interactive companions. In: Proc of the 4th international workshop on human-computer conversation
10. Dautenhahn K (2004) Robots we like to live with?!—A developmental perspective on a personalized, life-long robot companion. In: 13th IEEE international workshop on robot and human interactive communication. ROMAN 2004. IEEE, New York, pp 17–22
11. Dautenhahn K, Werry I (2004) Towards interactive robots in autism therapy: background, motivation and challenges. Pragmat Cogn 12(1):1–35
12. De Vignemont F, Singer T (2006) The empathic brain: how, when and why? Trends Cogn Sci 10(10):435–441
13. DiSalvo C, Gemperle F, Forlizzi J, Kiesler S (2002) All robots are not created equal: the design and perception of humanoid robot heads. In: Proceedings of the 4th conference on designing interactive systems: processes, practices, methods, and techniques. ACM, New York, pp 321–326
14. Duck S (1998) Human relationships. Sage, Thousand Oaks
15. Fennell C (2011) Habituation procedures. In: Hoff E (ed) Research methods in child language: a practical guide. Wiley-Blackwell, New York
16. Fernaeus Y, Håkansson M, Jacobsson M, Ljungblad S (2010) How do you play with a robotic toy animal?: A long-term study of pleo. In: Proceedings of the 9th international conference on interaction design and children. ACM, New York, pp 39–48
17. Floridi L (2010) Artificial companions and their philosophical challenges. In: Wilks Y (ed) Close engagements with artificial companions. Key social, psychological, ethical and design issues. Benjamins, Philadelphia, pp 23–27
18. Fong T, Thorpe C, Baur C (Collaboration) (2003) Dialogue, human-robot interaction. Robot. Res. 255–266
19. François D, Powell S, Dautenhahn K (2009) A long-term study of children with autism playing with a robotic pet: taking inspirations from non-directive play therapy to encourage children's proactivity and initiative-taking. Interact Stud 10(3):324–373
20. Ganster T, Eimler S, von der Pütten A, Hoffmann L, Krämer N (2010) Methodological considerations for long-term experience with robots and agents. In: Proceedings of EMCSR 2010
21. Giusti L, Marti P (2006) Interpretative dynamics in human robot interaction. In: The 15th IEEE international symposium on robot and human interactive communication. ROMAN 2006. IEEE, New York, pp 111–116

22. Gockley R, Bruce A, Forlizzi J, Michalowski M, Mundell A, Rosenthal S, Sellner B, Simmons R, Snipes K, Schultz A, Wang J (2005) Designing robots for long-term social interaction. In: 2005 IEEE/RSJ international conference on intelligent robots and systems. IROS 2005. pp 1338–1343
23. Hanna L, Risden K, Alexander K (1997) Guidelines for usability testing with children. Interactions 4(5):9–14
24. Hayashi K, Shiomi M, Kanda T, Hagita N (2010) Who is appropriate? A robot, human and mascot perform three troublesome tasks. In: RO-MAN, 2010. IEEE, New York pp 348–354
25. Ho WC, Dautenhahn K, Lim MY, Vargas P, Aylett R, Enz S (2009) An initial memory model for virtual and robot companions supporting migration and long-term interaction. In: The 18th IEEE international symposium on robot and human interactive communication. RO-MAN 2009, pp 277–284
26. Hoffman M (2001) Empathy and moral development: implications for caring and justice. Cambridge Univ Press, Cambridge
27. Horvath A, Greenberg L (1989) Development and validation of the working alliance inventory. J Couns Psychol 36(2):223
28. Houston-Price C, Nakai S (2004) Distinguishing novelty and familiarity effects in infant preference procedures. Infant Child Dev 13(4):341–348
29. Hunter M, Ames E (1988) A multifactor model of infant preferences for novel and familiar stimuli. Adv Infancy Res 5:69–95
30. Hyun E, Yoon H, Son S (2010) Relationships between user experiences and children's perceptions of the education robot. In: Proceeding of the 5th ACM/IEEE international conference on human-robot interaction. ACM, New York, pp 199–200
31. Jacobsson M (2009) Play, belief and stories about robots: a case study of a pleo blogging community. In: The 18th IEEE international symposium on robot and human interactive communication. RO-MAN 2009. IEEE, New York, pp 232–237
32. Kahn P, Ishiguro H, Friedman B, Kanda T, Freier N, Severson R, Miller J (2007) What is a human? Toward psychological benchmarks in the field of humanrobot interaction. Interact Stud 8(3):363–390
33. Kanda T, Hirano T, Eaton D, Ishiguro H (2003) Person identification and interaction of social robots by using wireless tags. In: Intelligent robots and systems. IEEE/RSJ international conference on IROS 2003. Proceedings, vol 2. IEEE, New York, pp 1657–1664
34. Kanda T, Hirano T, Eaton D, Ishiguro H (2004) Interactive robots as social partners and peer tutors for children: a field trial. Hum-Comput Interact 19(1):61–84
35. Kanda T, Sato R, Saiwaki N, Ishiguro H (2007) A two-month field trial in an elementary school for long-term human–robot interaction. IEEE Trans Robot 23(5):962–971
36. Kanda T, Shiomi M, Miyashita Z, Ishiguro H, Hagita N (2010) A communication robot in a shopping mall. IEEE Trans Robot 26(5):897–913
37. Kapoor A, Burleson W, Picard RW (2007) Automatic prediction of frustration. Int J Hum-Comput Stud 65(8):724–736
38. Karapanos E, Zimmerman J, Forlizzi J, Martens J (2009) User experience over time: an initial framework. In: Proceedings of the 27th international conference on human factors in computing systems. ACM, New York, pp 729–738
39. Kidd C, Breazeal C (2008) Robots at home: understanding long-term human-robot interaction. In: Intelligent robots and systems. IEEE/RSJ international conference on IROS 2008. IEEE, New York, pp 3230–3235
40. King WJ, Ohya J (1996) The representation of agents: anthropomorphism, agency, and intelligence. In: Conference on human factors in computing systems: common ground. CHI '96. ACM, New York, pp 289–290
41. Kirby R, Forlizzi J, Simmons R (2010) Affective social robots. Robot Auton Syst 58(3):322–332. Towards autonomous robotic systems 2009: intelligent, autonomous robotics in the UK
42. Klamer T, Ben Allouch S, Heylen D (2011) "Adventures of harvey"—use, acceptance of and relationship building with a social robot in a domestic environment. In: Akan O, Bellavista P, Cao J, Dressler F, Ferrari D, Gerla M, Kobayashi H, Palazzo S, Sahni S, Shen XS, Stan M, Xiaohua J, Zomaya A, Coulson G, Lamers MH, Verbeek FJ (eds) Human-robot personal relationships. LNCS, vol 59. Springer, Berlin, pp 74–82
43. Koay K, Syrdal D, Walters M, Dautenhahn K (2007) Living with robots: investigating the habituation effect in participants' preferences during a longitudinal human-robot interaction study. In: The 16th IEEE international symposium on robot and human interactive communication. RO-MAN 2007. IEEE, New York, pp 564–569
44. Kozima H, Michalowski M, Nakagawa C (2009) A playful robot for research, therapy, and entertainment. Int J Soc Robot 1:3–18
45. Krämer N, Bente G (2010) Personalizing e-learning. The social effects of pedagogical agents. Educ Psychol Rev 22(1):71–87
46. Lee K, Nass C (2005) Social-psychological origins of feelings of presence: creating social presence with machine-generated voices. Media Psychol 7(1):31–45
47. Leite I, Martinho C, Pereira A, Paiva A (2009) As time goes by: long-term evaluation of social presence in robotic companions. In: The 18th IEEE international symposium on robot and human interactive communication. RO-MAN 2009. IEEE, New York, pp 669–674
48. Lim M, Aylett R, Ho W, Dias J, Vargas P (2011) Human-like memory retrieval mechanisms for social companions. In: Proc of 10th int conf on autonomous agents and multiagent systems. AAMAS 2011, pp 1117–1118
49. Ljungblad S, Nylander S, Nørgaard M (2011) Beyond speculative ethics in hri?: Ethical considerations and the relation to empirical data. In: Proceedings of the 6th international conference on human-robot interaction. HRI '11. ACM, New York, pp 191–192
50. Lohse M, Hegel F, Wrede B (2008) Domestic applications for social robots-an online survey on the influence of appearance and capabilities. J Phys Agents 2(2):21–32
51. Matarić M, Eriksson J, Feil-Seifer D, Winstein C (2007) Socially assistive robotics for post-stroke rehabilitation. J NeuroEng Rehabil 4(1):5
52. Michaud F, Salter T, Duquette A, Mercier H, Lauria M, Larouche H, Larose F (2007) Assistive technologies and child-robot interaction. In: AAAI spring symposium on multidisciplinary collaboration for socially assistive robotics
53. Mori M (1970) The uncanny valley. Energy 7(4):33–35
54. Moshkina L, Arkin R (2005) Human perspective on affective robotic behavior: a longitudinal study. In: International conference on intelligent robots and systems. IROS 2005. IEEE, New York, pp 1444–1451
55. Nishio S, Ishiguro H, Hagita N (2007) Can a teleoperated android represent personal presence?—A case study with children. Psychologia 50(4):330–342
56. Preston S, De Waal FE (2002) Its ultimate and proximate bases. Behav Brain Sci 25(1):1–20
57. Pulman S (2010) Conditions for companionhood. In: Wilks Y (ed) Close engagements with artificial companions. Key social, psychological, ethical and design issues. Benjamins, Philadelphia, pp 29–34
58. Riek LD, Paul PC, Robinson P (2010) When my robot smiles at me: enabling human-robot rapport via real-time head gesture mimicry. J Multimodal User Interfaces 3(1–2):99–108
59. Rogers C (1975) Empathic: an unappreciated way of being. Counseling Psychol 5(2):2–10
60. Rosenthal S, Biswas J, Veloso M (2010) An effective personal mobile robot agent through symbiotic human-robot interaction. In: Proceedings of the 9th international conference on autonomous agents and multiagent systems, vol 1. IFAAMAS, pp 915–922

61. Sabelli A, Kanda T, Hagita N (2011) A conversational robot in an elderly care center: an ethnographic study. In: Proceedings of the 6th international conference on human-robot interaction. ACM, New York, pp 37–44
62. Salter T, Dautenhahn K, Bockhorst R (2004) Robots moving out of the laboratory—detecting interaction levels and human contact in noisy school environments. In: 13th IEEE international workshop on robot and human interactive communication. ROMAN 2004, pp 563–568
63. Schroder M, Bevacqua E, Cowie R, Eyben F, Gunes H, Heylen D, ter Maat M, McKeown G, Pammi S, Pantic M, Pelachaud C, Schuller B, de Sevin E, Valstar M, Wollmer M (2011) Building autonomous sensitive artificial listeners. In: IEEE transactions on affective computing
64. Severinson-Eklundh K, Green A, Hüttenrauch H (2003) Social and collaborative aspects of interaction with a service robot. Robot Auton Syst 42(3–4):223–234
65. Stafford L, Dainton M, Haas S (2000) Measuring routine and strategic relational maintenance: scale revision, sex versus gender roles, and the prediction of relational characteristics. Commun Monogr 67(3):306–323
66. Stiehl WD, Breazeal C, Han KH, Lieberman J, Lalla L, Maymin A, Salinas J, Fuentes D, Toscano R, Tong CH, Kishore A, Berlin M, Gray J (2006) The huggable: a therapeutic robotic companion for relational, affective touch. In: ACM SIGGRAPH 2006 emerging technologies. ACM, New York
67. Stubbs K, Bernstein D, Crowley K, Nourbakhsh I (2005) Long-term human-robot interaction: the personal exploration rover and museum docents. In: Proceeding of the 2005 conference on artificial intelligence in education. IOS Press, Amsterdam, pp 621–628
68. Sung J, Christensen H, Grinter R (2009) Robots in the wild: understanding long-term use. In: Proceedings of the 4th ACM/IEEE international conference on human robot interaction. ACM, New York, pp 45–52
69. Sung J, Grinter RE, Christensen HI (2010) Domestic robot ecology. Int J Soc Robot 2(4):417–429
70. Takayama L, Ju W, Nass C (2008) Beyond dirty, dangerous and dull: what everyday people think robots should do. In: Proceedings of the 3rd ACM/IEEE international conference on human robot interaction, HRI ’08. ACM, New York, NY, USA, pp 25–32
71. Tanaka F, Cicourel A, Movellan J (2007) Socialization between toddlers and robots at an early childhood education center. Proc Natl Acad Sci 104(46):17,954
72. Turkle S, Taggart W, Kidd C, Dasté O (2006) Relational artifacts with children and elders: the complexities of cybercompanionship. Connect Sci 18(4):347–362
73. Vargas P, Fernaeus Y, Lim M, Enz S, Ho W, Jacobsson M, Ayllet R (2011) Advocating an ethical memory model for artificial companions from a human-centred perspective. In: AI & society, pp 1–9
74. Wada K, Shibata T (2006) Robot therapy in a care house-its sociopsychological and physiological effects on the residents. In: Robotics and automation. IEEE international conference on ICRA 2006. Proceedings. IEEE, New York, pp 3966–3971. 2006
75. Wada K, Shibata T (2006) Robot therapy in a care house-results of case studies. In: The 15th IEEE international symposium on robot and human interactive communication. ROMAN 2006. IEEE, New York, pp 581–586
76. Wada K, Shibata T (2007) Living with seal robots—its sociopsychological and physiological influences on the elderly at a care house. IEEE Trans Robot 23(5):972–980
77. Wallendorf M, Arnould EJ (1988) “My favorite things”: a cross-cultural inquiry into object attachment, possessiveness, and social linkage. J Consum Res 14(4):531–547

Iolanda Leite is a PhD candidate at Instituto Superior Técnico, Technical University of Lisbon. Her research interests concern with the role of empathy and adaptive behaviour in long-term human-robot interaction. She worked as a research assistant in EU-funded projects LIREC (Living with Robots and IntEractive Companions, FP7) and MINDRACES (from Reactive to Anticipatory Cognitive Systems, FP6). Currently, she is an intern at Disney Research, Pittsburgh.

Carlos Martinho is Assistant Professor at Instituto Superior Técnico, Technical University of Lisbon, and Senior Researcher in the Intelligent Agents and Synthetic Character Group at INESC-ID. His research interests include autonomous agents, synthetic characters, social robotics and user adaptation, with a focus on the creation of believable behaviour designed for interaction experiences. He has co-authored over 80 papers on these subjects and worked in more than 10 EU-funded and international projects related to his field of research.

Ana Paiva is an Associate Professor in the Department of Computer Science and Engineering of Instituto Superior Técnico, Technical University of Lisbon. She is also the group leader of GAIPS (Intelligent Agents and Synthetic Character Group) at INESC-ID. Her main scientific interests lay in the area of Autonomous Agents, Embodied Conversational Agents and Robots and Multiagent Simulation Systems. Prof. Ana Paiva has been researching in the area of artificial intelligence for the past twenty years, having also taught at IST during that period.