Bond formation with pet-robots: An integrative approach

Marta Díaz-Boladeras

Abstract
The challenge of long-term interaction between humans and robots is still a bottleneck in service robot research. To gain an understanding of sustained relatedness with robots, this study proposes a conceptual framework for bond formation. More specifically, it addresses the dynamics of children bonding with robotic pets as the basis for certain services in healthcare and education. The framework presented herein offers an integrative approach and draws from theoretical models and empirical research in Human Robot Interaction and also from related disciplines that investigate lasting relationships, such as human-animal affiliation and attachment to everyday objects. The research question is how children’s relatedness to personified technologies occurs and evolves and what underpinning processes are involved. The subfield of research is child-robot interaction, within the boundaries of social psychology, where the robot is viewed as a social agent, and human-system interaction, where the robot is regarded as an artificial entity. The proposed framework envisions bonding with pet-robots as a socio-affective process towards lasting connectedness and emotional involvement that evolves through three stages: first encounter, short-term interaction and lasting relationship. The stages are characterized by children’s behaviors, cognitions and feelings that can be identified, measured and, maybe more importantly, managed. This model aims to integrate fragmentary and heterogeneous knowledge into a new perspective on the impact of robots in close and enduring proximity to children.

Keywords Child-Robot Interaction · Bonding · Robotic Pets · Companion Robots · Attachment · Robot-Based intervention

Introduction
One primary goal of current robotics research is to develop companion robots that are able to engage children in close physical and affective proximity in contexts such as healthcare (Dawe et al., 2019; González-González et al., 2021; Kidd & Breazeal, 2008; Westlund et al., 2018) and education (Ahmad et al., 2017; Belpaeme et al., 2018; Mubin et al., 2013; Toh et al., 2016). Given that learning and behavioral change can take weeks or months to achieve, a robot companion must be able not only to display smart social and affective behavior but also to engage users beyond the initial novelty, thus sustaining long-term interactions (Belpaeme et al., 2012; Castellano et al., 2009).

However, there is an ongoing debate in the field of Human-Robot Interaction (HRI) on the current capacity of robots to sustain rewarding long-term interactions, not only due to technological limitations but also to a lack of tested theories and models on HRI change over time (Kaplan 2005a; Krämer et al., 2011; Nalin et al., 2012).

Although the literature on companion robots provides valuable insights and encouraging results, the potential and drawbacks of their use as social partners for children in therapeutic and learning contexts are far from clear (Melson et al., 2009). In this context, the HRI community has pointed out the need to understand how robots attract interest and maintain it over time (Castellano et al., 2009; Fernaeus et al., 2010), as well as the emotional effects that this relationship elicits (Rosenthal-von der Pütten et al., 2013; Rosenthal-von der Pütten et al., 2014). There is a lack of knowledge of the conceptual frameworks, models and techniques that can
characterize, explain and measure the relationship between children and robots more effectively.

The accumulated knowledge on the factors associated with the adoption by children of social robots is still fragmentary, heterogeneous and lacking in a well-established, common theoretical basis (de Jong et al., 2021). According to (van Straten, Peter, et al., 2020; van Straten, Kühne, et al., 2020; Westlund et al., 2018), a model of the underlying determinants and processes of long-term child-robot relationships is still under construction.

We therefore assume that the complex dynamics of children bonding with artificial pets would benefit from an overarching integrative approach. Hence, this study presents a conceptual tool that comprehensively integrates the different processes involved. Its main novelty is that it broadens the current perspective of the phenomenon by integrating models and findings drawn from related fields, specifically from human-animal bonding and attachment to daily objects. The motivation is to gain an understanding of the bonding process arising from sustained interaction between children and artificial pets in order to inform educational and healthcare programs.

The remainder of the paper is organized as follows: Sect. 2 reviews relevant studies and models on bond formation; Sect. 3 characterizes the child-pet robot dyad; Sect. 4 formulates the framework; Sect. 5 highlights ‘Credible Attachment’ as the most important factor that drives bond formation; Sect. 6 discusses the limitations, unresolved issues and future research paths, and finally, Sect. 7 summarizes the main conclusions.

Related studies

This section brings together three perspectives that address the same questions when exploring the lasting association and emotional involvement between children and objects, robots and pets: Why are certain things allowed to cohabit with us? How can an object or animal find a “niche” in children’s lives over time? What motivates a child to maintain long-term interest in non-human entities?

Given the multifaceted essence of the child-pet robot dyad, our proposal is grounded on knowledge from three fields: (i) affective and long-term HRI, i.e. a pet robot as a companion, (ii) human-animal bonding, i.e. a pet robot as a pet; and (iii) attachment to inanimate entities, i.e. a pet robot as an everyday object. We have particularly sought to identify models and studies in the literature by authors from backgrounds other than HRI that have also specifically investigated relatedness with social robots.

Child-Robot Interaction (CRI) and long-term HRI

To better understand the potential of pet robots as therapeutic partners, Melson et al. (Melson et al., 2009) carried out two cross-sectional developmental studies with the puppy robot AIBO (see Fig. 1a). The first compared observations of and interviews with 80 pre-schoolers of 3–5 years of age during a 40-minute play session with AIBO and a stuffed dog. The second compared observations and interviews with 72 children of 7–15 years of age who played with AIBO and an unfamiliar but friendly living dog (Melson, Kahn, Beck, Friedman, et al., 2009). The main findings are twofold: first, children attribute biological essences to pet robots, and second, the way children and teenagers reason about pet robots differs ostensibly from their interactions with them, which brings into question the use of only self-reporting measures.
Also, from a development perspective and without making any claims for generalization, Pitsch (Pitsch & Koch, 2010) identified the following stages in a preliminary study based on the observation of children playing with the pet robot Pleo (see Fig. 1b): (i) first intuitive approach, handling an inanimate object, (ii) socialization into appropriate treatment, experiencing the robot as an animate object, (iii) exploring and experimenting with the robot and developing interactional patterns, and (iv) experiencing the robot as a polyfunctional object with which it is possible to interact in different symbolic worlds.

More recently, de Jong et al. (de Jong et al., 2021) proposed and tested a quantitative model of children’s intentions to adopt a social robot at home based on the Theory of Planned Behavior. From a survey of 570 children aged eight to nine, the authors found that up to 82% were willing to adopt the robot at home after watching a video clip, before ever interacting with the robot in real life. What the authors call the ‘tentative model’ identifies and quantifies the influence of distal and proximal factors on children’s intent to adopt (for further details of this model, see 4.3.1 First Impression).

Though not specifically targeting children, another insightful empirical-based model of long-term acceptance of domestic robots is de Graaf’s research into what prolongs interaction with a robot over time, as well as identifying the reasons for discontinuation (M. de Graaf, Allouch, & Van Dijk, 2017). Drawing from a longitudinal real-world study in which the rabbit-like Karotz (or Nazbatag) was introduced to 70 people’s own homes for periods of up to six months, the author collected users’ evaluations over time, and their reasons for usage, refusal and abandonment through questionnaires and interviews. Going beyond models that explain the initial acceptance of technology, this research focuses on the factors that foster sustained, rewarding usage, formulating six phases of the acceptance process: expectation, encounter, adoption, adaptation, integration and identification. Moreover, the authors propose three different user profiles depending on the moment when and reasons why participants stop using the robot: resisters, rejecters and discontinuers. Acceptance factors and motives for non-use are measured and analyzed to produce a useful map of challenges for the long-term use of personal domestic robots to inform robot design and implementation.

Finally, the Domestic Robot Ecology framework provides an insightful perspective to explain how utilitarian robots (i.e. the Roomba Vacuum Cleaning Robot) shape relationships in the domestic environment. The model highlights the contextual conditions for adoption and sustained use. Four phases are identified, namely pre-adoption, adoption, adaptation, and use/retention. Drawing from the data gathered in up to 5 follow-up visits to 30 households over six months, the authors propose a four-stage model to describe the patterns of interaction and subjective experience over time, and ultimately offer interesting recommendations for satisfactory long-term usage of domestic robots (Fink et al., 2013; Sung et al., 2010; Weiss & Hannibal, 2018).

**Human-animal bonding**

Researchers and developers have identified some connection between robots and our experiences with animals (Miklósi & Gácsi, 2012). The ethological approach suggests that HRI should be viewed as a particular case of inter-specific interaction and that human-animal interaction can therefore provide an especially insightful model for the relationship between children and pet robots. The observation of natural social systems in which humans interact with non-humans can be interesting in at least four key areas: analyzing the emotional link that child owners form with their pets; understanding the reasons for and dynamics of adoption in a family environment; identifying the most appreciated features of pets among their owners (Konok et al., 2018; Melson, 2003); and designing social behaviors in pet robots that can forge lasting relationships (Faragó et al., 2014).

The biophilia hypothesis (Kellert & Wilson, 1993) contends that there is an innate evolutionary-based predisposition among children to care about living things, including but not limited to animals. In particular, the attachment behaviors of pets seem to elicit an emotional response in the human counterpart that is the essential driver of engagement in care-giving activities that go beyond other utilitarian effort/reward mechanisms. In addition, the playful behavior of pets supports gratifying interaction, which is another pillar for lasting associations. Both care-giving and play can be rewarding depending on individual variables such as age, altruistic-selfish dispositions, expectations, attitudes towards animals and previous experience (Barco Martelo, 2013) and can be unevenly distributed between the members of a family.

An understanding of how and why human families accept animals into their homes and love them would probably shed light on the chances of other creatures –robots-socializing with us for long periods in a similar way (Konok et al., 2018).

**Attachment to everyday objects**

It is a fact that only certain everyday objects remain in our homes for long periods, sometimes for our entire lifetime. The degree of consumer-product attachment can be defined as the strength of the emotional bond that a consumer experiences with a durable product that is considered to be special and typically means a lot to that person, not as a product.
category but as product specimen (i.e. irreplaceability). Consequently, the owner/consumer is unlikely to dispose of the product and will experience emotional distress if it is lost (Schifferstein & Zwartkruis-Pelgrim, 2008).

From the perspective of a product designer, Kaplan (Kaplan, 2005a) proposed a data-driven model to explain our experience over time with everyday things, both living and artificial. This study introduced the concept of value profiles, which capture in a single hypothetical curve the evolution of the experienced value. This typically unfolds through three stages: immediate value (the first minutes of interaction with the object, which are enough to cause excitement or disappointment); short-term interaction (lasting over a month); and long-term interaction over many months or even years.

Following this model, objects conform to four different types: type (a) with high immediate value followed by a progressive drop (e.g. fashionable clothes); type (b) where experienced value increases slowly because of the necessary training and adaptation, eventually reaching a peak when users master the technology and slowly become obsolete with new technological advances (e.g. computers); type (c) which reach their optimum almost immediately and stay at that level with very little risk of obsolescence or lassitude (e.g. corkscrews); and type (d) where the experienced value keeps increasing over time (e.g. notebooks).

Kaplan concludes that given that the very essence of a companion robot is to remain valuable -engaging our interest and dedication over extended periods of time, they should necessarily be type d) objects, whose value increases over time. This profile corresponds to objects of high historical capacity, versatile functionality and orientation towards social interaction. Hence, a companion robot should be appealing at first sight, meet or exceed our expectations in the short term, and keep increasing in value in the long-run.

These three approaches (socialization with robots, human-animal bonding and attachment to objects) shed light on different facets of the bonding between children and pet robots but present certain limitations when focusing solely on long-term relationships, which suggests the need to incorporate other perspectives. Kaplan’s outstanding model of relationships between pets and their owners does not focus specifically on children and neither does it highlight the role of the social context in this process. The insightful studies and findings by Melson (Melson, Kahn, Beck, Friedman, et al., 2009) and Pitsch (Pitsch & Koch, 2010) are based on children’s views of and behaviors towards pet robots after a single encounter and do not capture the interaction dynamics over time. De Graaf’s long-term study does not specifically investigate children in the process of robot acceptance, and the device chosen for the study performs the role of a domestic assistant, and hence the evaluation is weighted more towards perceived utility than the emotional experience of adoption.

Finally, although the provided contributions are insightful, knowledge about human-animal bonds cannot be transferred directly to child-robot relationships because a living dyad is a dynamically changing and mutually adapting system that is extremely difficult to generalize to a human-robot social system, which should instead be analyzed “on its own terms” (Melson, 2014).

With regard to the reviewed literature, the novelty of the framework proposed herein is that it integrates insights from related disciplines in current knowledge of child-robot interaction, in order to thus generate a broader perspective of the processes involved.

**Children and pet-robots**

**Robotic pets**

Robotic pets or pet-robots are robots to be regarded as artificial life forms, being one of many sophisticated emulations of the natural world that have been made possible by advances in interactive computing (Melson, Kahn, Beck, Friedman, et al., 2009). Robotic pets are a subclass of companion robots that are deliberately designed to mimic aspects of their biological counterparts, such as cats and dogs, and hence foster interaction patterns that are characteristic of our experiences with these animals. Robotic pets therefore share a similar kind of autonomy, situatedness and physicality to real-life ones (Kaplan, 2005a).

According to the well-supported biophilic hypothesis (Kellert & Wilson, 1993), i.e. the natural predisposition of humans to affiliate with life, these zoomorphic animated devices are highly appealing and their hybrid animate and inanimate nature presents both adults and children with mental, social and moral challenges (Melson et al., 2009; van Straten, Peter, et al., 2020).

As opposed to other robots that help with a wide array of tasks, robotic pets provide no utilitarian service to their users. All these seals, dogs, cats, dinosaurs, elephants and other creatures might be deemed useless robots (Kaplan, 2005b), but they can nevertheless offer the affiliative disposition that is the essence of companionship. A robotic pet should be adorable and enable social HRI. And when it comes to interaction with children, it must be able to initiate, participate in, and collaborate with that interaction. In other words, the child and the robotic pet should be able to play together (Belpaeme et al., 2012).

Such artificial pets have been deployed in recent decades on different programs, including therapy, with promising results (see interesting reviews in (Abbott et al., 2019;
However, some zoomorphic robots such as Karotz\(^1\), I-Cat\(^2\), Probo\(^3\) and Huggable\(^4\) perform task-oriented roles, such as tutors, helpers or therapy assistants, so despite their animal-like shapes, they cannot be considered robotic pets. These robots usually feature cartoon-like anthropomorphism, including speech and human-like social skills (e.g. facial expressions and gestures). This study focuses on robots that evoke, but do not necessarily simulate, the appearance, behavior and communicative channels of real-life animals, and that tend to elicit among their users a similar response to that of pet owners (Fig. 2).

### The owner-pet social system

Pets’ social affiliative behaviors fit especially well in the human world and have been the basis of the success of human-dog cohabitation for thousands of years (Faragó et

---

\(^1\) [https://robots.nu/es/robot/karotz](https://robots.nu/es/robot/karotz).

\(^2\) [https://www.trendhunter.com/trends/philips-cool-icat-robot-cat](https://www.trendhunter.com/trends/philips-cool-icat-robot-cat).

\(^3\) [http://probo.vub.ac.be/](http://probo.vub.ac.be/).

\(^4\) [https://www.media.mit.edu/projects/huggable-a-social-robot-for-pediatric-care/overview/](https://www.media.mit.edu/projects/huggable-a-social-robot-for-pediatric-care/overview/).
al., 2014; Miklósi & Gácsi, 2012). The owner-pet social system is an instance of interspecies relationships (i.e. associations between non-conspecific biological entities) (Kovács et al., 2011). More particularly, the owner-pet relationship is an association between humans and a subservient species that is defined by complementary roles based on a core asymmetry. In other words, domestic animals cannot survive without human supplies but humans do not need the company of animals. From a pet’s perspective, the association with humans is indispensable, but from the human perspective keeping a pet is a choice and in our modern societies can be considered an act of consumption, a commodity.

Based on this primary asymmetry, the questions that arise are: Why do humans decide to cohabit with animals and commit not negligible emotional and financial resources over time to satisfy their needs? How do pets obtain resources from humans that they are not capable of obtaining otherwise? What core affiliation between humans and their animals do robotic pets emulate?

The affiliation of pets with humans serves the critical function of obtaining resources -nurture, care and attention- to satisfy their basic needs. In return, humans obtain social warmth, which is the core functionality of pets in our societies. In fact, compared with interpersonal relationships, interactions with pets can even be viewed as more predictable, stable, and secure. Pets tend to be considered more emotionally available, submissive, and eager to please than humans (Zilcha-Mano et al., 2011).

The relationship between humans and their pets is therefore determined by the interdependent roles of master (i.e. owner or keeper) and animal defined by three features: hierarchy, uniqueness and bi-directional connectedness. Hierarchy is expressed through obedience and submission, uniqueness makes the owner a master among other humans, and connectedness is the gratifying experience of closeness and emotional involvement (Kovács et al., 2011).

In terms of the social mechanisms supporting the human-dog relationship, we highlight (i) attention giving and getting, (ii) display of attachment behaviors such as proximity seeking and greeting, (iii) soliciting of resources, (iv) human monitoring and low monitoring, (v) non-verbal communication such as gaze and touch, (vi) shared attention (Dahl, 2014), (vii) individual recognition, (viii) alignment of emotions (Dahl, 2014; Faragó et al., 2014; Miklósi, 2008), (ix) rule learning and following, and (x) the ability to understand and predict human intentions (Miklósi, 2008). All these mechanisms and social skills (see Table 1) serve to form the essence of dog-human association: individualized attachment to the owner displayed as a unique affiliative performance different from other behaviors the dog displays to anyone else (Kaplan, 2005b; Miklósi & Gácsi, 2012).

Meanwhile, the child–pet relationship has been termed a flexible alliance that takes many forms and fulfills some of the important developmental functions that are present in human–human relationships. The benefits of relatedness with animals have been recurrently reported, and include satisfaction of needs to nurture and be cared for, to support and derive support from, to play with, and to secure companionship, among others (Melson, 2003). Parents also cite increased responsibility and “fun” as benefits that animal companions confer on their children (Melson & Fine, 2010).

Interestingly, in their relationships with their parents-and by extension with adults in general- children take the role of the needy, dependent partner and parents/adults the complementary role of what Bowlby (Sable, 1995) calls “stronger and wiser” caregivers. In contrast, in their relationship with pets, child owners serve as parental, caregiving figures (Zilcha-Mano et al., 2011). The opportunity to nurture others is a basic human need, even in childhood. And since pets are dependent on human care for survival and optimal development, they motivate children to learn about and practice appropriate nurture of another being.

Regarding social support, there is evidence that many pet-owning children derive emotional support from their pets. They are as likely to talk to their pets about sad, angry, happy, and secret experiences as they are with their siblings. Elementary school children considered ties with pets to be the most likely to last “no matter what” and “even if you get mad at each other” (Furman, 1989).

**Child-robotic pet dyad**

Children, for reasons that are not fully understood, respond much more readily and strongly to social robots than adolescent or adult users. They present a more positive attitude and engage more easily in playful interaction with robots (Ros et al., 2011).

Myers ((Myers, 2007) in (Kahn et al., 2006)) states that animals appear to be optimally discrepant others in early childhood, whereby they offer children just the right amount of similarity to and difference from the human pattern. We can go further and state that robotic pets present an exciting double otherness with respect to humans. Not only are they a different species to humans, but they also differ from us through being artificial as opposed to biological beings. What remains to be demonstrated is whether—and how—this double otherness is an obstacle or an opportunity for gratifying, smooth and useful cohabitation.

Children’s interactions with robotic pets seem to involve a graceful merger of smart electronic devices with a similarity to their beloved animal buddies. Robotic pets appeal to children because they are both machines and a reflection of their real-life analogue. These two essences reinforce...
each other, whereby a child’s wonder for smart technology is applied to one of the most valuable things in their lives. The fascination raised by the dual nature of robotic pets challenges their cognition with regard to the animate and inanimate worlds in different ways depending on the stage of their development.

We might also expect children to be more sensitive than adults to the physical behavior of robots and nonverbal interaction with them, given the importance that movement and physical activity have for their behavior, interactions, learning, and physical and cognitive development (Nalin et al., 2012). There is a propensity among children to attribute life-like characteristics, such as beliefs, desires and intentions, to inanimate creatures and to maintain this illusion during interactions (Belpaeme et al., 2013). In addition, children’s inclinations towards pretend play introduces an imaginative element to their encounters with robots in the form of a practice that is sometimes referred to as performed belief within the field of pervasive gaming (Jacobsson, 2009), whereby the user projects feelings and attributes onto objects through pretense or metaphor. This process is similar to the deliberate suspension of disbelief (i.e. the state we enter when immersed in an absorbing novel, play, or movie).

As manifestations of children’s socio-cognitive development, perceptions and emotions towards interaction with robots evolve as they grow older. (Kahn et al., 2006; Matellán & Fernández, 2014; Pitsch & Koch, 2010) investigated whether young children accord to robotic pets some measure of (a) animacy (b) emotion, desire or intention, (c) friendship and companionship and (d) moral standing.

Melson’s developmental studies with young children and teenagers (Melson et al., 2009) revealed that hybrid cognitions and behaviors towards robotic pets emerged during play sessions. The robotic dog was treated as a technological artifact that also embodied attributes of living animals, such as mental states, being a social other, and moral standing. And most interestingly, children’s reasoning about robotic pets differs ostensibly from their interactions with them. From these findings, Kahn postulates that robotic pets seem to blur children’s foundational ontological categories, such as animate vs. inanimate (Kahn et al., 2006; Pitsch & Koch, 2010). Indeed, (Kahn et al., 2006) make the stronger proposition that this technological genre will emerge as a new ontological category, especially in young children as they construct categories of knowledge based on interaction.

Similarly, Pitsch (Pitsch & Koch, 2010) bases her model on the cognitive dimension, inferring attributions and perceptions from behavioral analyses at the interactional surface. The ways in which users categorize and reinterpret a robot system step by step during and from interaction with that system, and how they attempt to establish coordinated sequences of action, play a central role in this approach.

From our perspective, the crux of the matter with regard to the potential of robotic pets is children’s ability to attribute biological essences to them despite knowing that they belong to the inanimate world. When asked, children generally do not attribute life-like essences to a robot, but often treat it “as if” it was animate, attempting reciprocal play and expecting autonomous responses to their invitations to socialize (Díaz-Boladeras, 2017; Melson, Kahn, Beck, Friedman, et al., 2009; van Straten, Kühne, et al., 2020).

This dual nature -which is not perceived as an insurmountable logical issue at certain stages of development- is one of the key factors of the attraction that robotic pets exert on children.

Framework of child-pet-robot bonding

Approach and Scope

Bonding is the socio-psychological process of establishing affective links with social partners. It is the basis of different relationships, including companionship. From our perspective, bonding with robotic pets is a dynamic process that is expressed through specific cognitions, emotions and interactive behavior that are contingent to the different phases that unfold across multiple interactions separated in time (Díaz-Boladeras, 2017; Nalin et al., 2012).

To delimit the construct, we differentiate bonding here from two closely related concepts: attachment and interaction. Social bonding includes but is not limited to attachment in its restricted meaning as the primary bond that infants establish with a main caregiver who provides the basic needs of nurture, protection and company (Ainsworth, Blehar, Waters, & Wall, 1978). Meanwhile, in HRI, the term attachment is used often to refer to any kind of social rapport or emotional involvement. In a stricter sense, it is “an enduring affectional bond of substantial intensity” (Armsden & Greenberg, 1987) that is not usually considered healthy when it is with a robot (Huber et al., 2016).

In turn, human-robot bonding has a more restricted meaning than the overarching concept of human-robot interaction, and encompasses any specific communicative act between the individual and the robot in a particular social situation (Krämer et al., 2011). As opposed to the generic concept of interaction, bonding is defined as the emotional relatedness that unfolds over time, almost equivalent to the concept of relationship formation defined by Van Straten (van Straten, Peter, et al., 2020).

We can identify two dimensions to characterize and evaluate bonding: engagement and social rapport. Engagement has been defined as “the value that a participant in an interaction attributes to the goal of being together with the other
participant(s) and continuing the interaction” (Castellano et al., 2009) and may include, although not necessarily, the expression of a positive feeling by the user. While engagement is observable (e.g. time spent together, joint activity, attention, search for proximity, absorption, behavioral alignment and so on), social rapport has to be reported and/or inferred more interpretively from behavior (e.g. willingness to be close, sorrow on separation, missing the robot when absent, enjoying interaction, emotional contagion) (Krämer et al., 2011). Moreover, when people experience social rapport, they are other-involved and form cohesiveness with each other, including a shared sense of friendliness and care through the expression of mutual attentiveness (Perugia et al., 2020).

Neither of these two dimensions of bonding—engagement and social rapport—can cover the complexity of the concept alone. While a child can be absorbed in interaction with a robot for hours, if the interest comes from a technological curiosity we cannot say that a bond is established unless we can also identify emotional involvement with the agent.

Our approach highlights three key features of bonding: its social dimension, its behavioral expression and its dynamic essence. We assume that the specific family context decisively influences the formation of bonds with robotic pets—like any process in children’s lives—since family dynamics, particularly parent-child relationships, always modify and shape children’s other relationships (Melson, 2003). Parents are always important stakeholders in any child’s decision, and the family environment is even more influential when it comes to pet adoption and the use of robots as social companions at home (Fernaeus et al., 2010; Kidd et al., 1992). Also, and in a similar fashion to children’s relationships with real pets, their interactions with robotic pets are embedded in many other contexts, such as school, neighborhood and community, which influence the quality of the contact (Melson & Fine, 2010) and the “creation of significance” beyond the robot’s physical and functional characteristics (Giusti & Marti, 2006).

Complementary to other models that focus on how users think about robots over time (M. M. A. De Graaf, Allouch, & Van Dijk, 2016; Fior et al., 2010; van Straten, Kühne, et al., 2020; Westlund et al., 2018), our framework focuses on how children interact with them. We assume that children’s relatedness to robotic pets is instantiated within and through the interaction, shaping and reshaping its significance and value over time (Pitsch & Koch, 2010).

The Rationale of the Framework: Stages, Challenges and Intervention

From the antecedents reviewed in Sect. 2, the framework proposes a novel perspective based on assumptions on the nature of the processes involved and offering an inclusive overarching narrative of their dynamics.

The key assumptions of our framework are: (i) use and adoption are social context dependent processes that unfold over time and in specific stages, (ii) these stages feature recognizable patterns of use, interaction, perceptions and affect, (iii) the process faces specific challenges that facilitate or hamper closeness, (iv) the process towards an enduring relationship can be managed through design and/or intervention, and (v) it is important to not only investigate the forces that foster closeness (i.e. the impetus forward), but also to understand those that impede progress (i.e. challenges).

From these main assumptions, the framework proposes three stages to encompass recent findings and knowledge on bond formation in a single narrative: first encounter, short term interaction and relatedness. In Fig. 3, the loops represent the three stages of bonding, and the shaded area represents previous experience and individual user variables. The yellow arrows indicate the discontinuation of use/relatedness that can occur at any moment of the process.

First encounter

Any social robot faces a great trial: meeting the user for the first time. The first in person encounter is an unrepeatable episode in the flow of the interaction. This is the precise moment when, without any previous experience, this particular robot is presented to the child for the first time.

This first encounter, considered the cornerstone for both short-term engagement and long-term interactions, is the setting for two important events: the first impression and the initial interaction. If the child approaches the robot, engages in interactive behavior and shows connectedness and motivation to keep interacting (Nalin et al., 2012)—what de Jong (de Jong et al., 2021) calls the intention to adopt—there is a transition to the next stage. If not, the bonding process ends.

First impression

When the user meets a robot for the first time, after just a few minutes he/she will have formed their first opinion about it (i.e. immediate value, (Kaplan, 2005a) and will be able to develop a coherent mental model of its functions (Powers & Kiesler, 2006). Although perceptions of robots change over sessions due to different process like familiarization, some key dimensions of a child’s first impression persist throughout all interaction, influencing their willingness to
To gain a better understanding of the development of emotional attachment on first contact, Weiss (Weiss et al., 2009) investigated the initial reactions of 129 children and 18 adults during a single session of voluntarily free play with the robot dog AIBO in a play area in a shopping mall. Interaction was evaluated both through observation and self-reporting following Norman’s three-level model of user experience: emotional, behavioral and reflective (Norman, 2004). They found that children who felt more attracted on an emotional level were more tolerant of the difficulties on the behavioral level of interaction, revealing interesting relationships between the different levels.

In the development of long-term sociality, the main outcome of the first impression is the intention to keep interacting with and to remain close to the robot. In our framework, we group the main factors influencing the intention to remain connected or to adopt the robot into three overarching categories: children’s individual variables, the robot’s affordances and situational variables. Children’s individual variables of particular interest include their attitude towards animals and also towards technology, and their familiarity interact with the robot over extended periods of time. The first impression is composed of judgments about the robot’s expertise and personality, an initial mental model of its performance, and a primary attitude on an emotional level.

In their experimental study (Paetzel et al., 2020) with 49 adult participants in three different sessions, Paetzel et al. found that the perceived warmth of a robot and judgments about its competence remain stable from the first session. In particular, the perceived competence was determined in the first two minutes of conversation and after that remained stable across sessions. This finding suggests that a robot’s competence is basically judged on its initial appearance.

Regarding the emotional dimension of the first impression, (Calvo-Barajas et al., 2020) studied the emergence of trustworthiness by manipulating the facial expressions of a humanoid robot in terms of gender-likeness, emotional intensity and valence in an experiment with 129 children. Their results showed that a few seconds are enough for children to form a trait inference on likability and competence based on the robot’s emotional expressions.

To gain a better understanding of the development of emotional attachment on first contact, Weiss (Weiss et al., 2009) investigated the initial reactions of 129 children and 18 adults during a single session of voluntarily free play with the robot dog AIBO in a play area in a shopping mall. Interaction was evaluated both through observation and self-reporting following Norman’s three-level model of user experience: emotional, behavioral and reflective (Norman, 2004). They found that children who felt more attracted on an emotional level were more tolerant of the difficulties on the behavioral level of interaction, revealing interesting relationships between the different levels.

In the development of long-term sociality, the main outcome of the first impression is the intention to keep interacting with and to remain close to the robot. In our framework, we group the main factors influencing the intention to remain connected or to adopt the robot into three overarching categories: children’s individual variables, the robot’s affordances and situational variables. Children’s individual variables of particular interest include their attitude towards animals and also towards technology, and their familiarity

Fig. 3 Representation of bond formation dynamics: the thoughts inside the bubbles represent children’s negative perceptions and feelings; in capitals the robot’s capacities and performance that drive the process, in plain letters children’s psychological states that boost the process. (Source: author, inspired by Senge, 1999)
with robots. Robots’ affordances include their appearance or embodiment (e.g. size, shape, texture, aesthetics) and basic skills (e.g. movements, orientation, vocalizations). Finally, among the situational variables we highlight the task or context in which the interaction develops, the role taken by/attributed to the robot (Deng et al., 2019) and the way the robot is introduced to the child (i.e. like a toy, like an animal, turned on or off, by its name).

With robots—as with any object—appearance matters (Sciutti et al., 2014) and based on the cues embodied in it, users generate expectations about its social competences (Díaz et al., 2011; Fernaeus et al., 2010; Jacobsson, 2009; Paepcke & Takayama, 2010; Sciutti et al., 2014). Therefore, robot design should convey clear messages about the type and context of usage, and more importantly, it should trigger the right kind of expectations. Following Lohse (2010); Kaplan (2005a), we consider that the design of successful everyday robots implies a fine-grained understanding of our expectations in the first encounter with them.

As a dynamic cognitive process, expectations -beliefs about a future state of affairs, subjective estimates of the likelihood of future events- can be biased (Lohse, 2010) and unrealistic. Cultural and societal expectations with regard to robotics are higher than more mundane technology, involving a combination of misleading beliefs and naive fantasies. However, the most important feature from our perspective is that expectations can be influenced (i.e. through design) and managed (i.e. providing information or prompts), and the sooner the better to take advantage of the well-known primacy effect of impressions and to avoid misleading and frustrating interaction. This process of building expectations usually begins before the interaction starts, and even before the first encounter, based on media content, direct experience and personal beliefs (de Jong et al., 2021; Fink et al., 2013; Sung et al., 2010).

Initial interaction

In this first stage, the challenge is to appeal to children and encourage them to interact, rather than respond with wariness or reluctance. As evidenced by observations, children seem fascinated by the responsiveness and realism of the bioinspired performance of robotic pets (Díaz-Boladeras, 2017; Fernaeus et al., 2010; Weiss et al., 2009). However, very young children can be wary of their sudden movements and sounds. In their exploratory case analysis with 8 small children, 3 teenagers and 2 adults, (Pitsch & Koch, 2010) observed withdrawal behaviors in a 3-year-old girl, who shrieked and backed off when the Pleo robot suddenly turned its head towards her and produced a growling sound. This response is interpreted by the authors as an expression of experiencing Pleo as an animate object. (Scheffler & Pitsch, 2020) give some recommendations for the design of robot pre-beginnings (i.e. non-verbal behaviors prior to the actual interaction) and opening strategies (i.e. first communicative moves) for a successful first exchange.

Compared to adults, there is consistent evidence that children are prone to engage easily in some form of exploration and testing of the behavior of the robot from the outset. Meanwhile, adults are less keen to spontaneously interact with it, skipping this experimental phase to directly make comments about the machine (Kaplan, 2005a).

In de Jong’s experiment (de Jong et al., 2021), children’s intentions to adopt after watching a video of the Cozmo robot were measured on a 4-item Likert scale. They found that most children (82.1%; n = 468) reported an intention to adopt the robot by scoring above 3. A hedonistic attitude had by far the largest association with adoption intention in the model, showing that children focus on social and entertainment aspects when interacting with robots.

To summarize, in this initial phase the relevant practical aspects that are useful to inform robot design and robot-based interventions are that the robot needs to be appealing at first sight; to look nice and harmless; to exhibit a primary performance that elicits attributions that are consistent with the role of a pet; to create exciting but realistic expectations; to arouse curiosity, and to provoke wonder, surprise, amazement and emotional appeal. Moreover, a robot’s affordances need to foster smooth and enjoyable interaction not only with children but also with their social environment.

The desirable outcomes at this stage are positive judgments with regard to the robot’s likability and competence (Calvo-Barajas et al., 2020) and willingness to continue interacting or the intention to adopt under the terms described by (de Jong et al., 2021), and to thereby advance to the short-term interaction loop.

Short-Term Interaction

Subsequent encounters between the child and the robotic pet may differ greatly from the initial exchanges and each episode increases or decreases the probability of forging a lasting relationship.

Typically in this stage (i) the robot is evaluated against the expectations raised in the previous phase, (ii) the robot’s capabilities and limitations are learned (Fink et al., 2013; Sung et al., 2010), (iii) interactional patterns with the robot are developed (Pitsch & Koch, 2010) and, eventually, (iv) affective behaviors appear or are consolidated.

Springer
Lacking a driving force to use the robot. Being displeased or feeling discontent with Losing the earlier increased interest in the robot. A state of disappointment or disillusion regarding (the use of) the robot. Losing the earlier increased interest in the robot. Lacking a driving force to use the robot. Being displeased or feeling discontent with a sought need that the robot should fulfill. The act of or the perceived need to rely on others to be able to (properly) use the robot. The replacement of applications or the complete use of the robot with another device. Foreseeing or experiencing barriers to use the robot.

Table 2 Coding Scheme of reasons for non-use (De Graaf et al., 2017)

| Code                      | Definition                                                                 |
|---------------------------|-----------------------------------------------------------------------------|
| Disenchantment            | A state of disappointment or disillusion regarding (the use of) the robot. |
| End of novelty            | Losing the earlier increased interest in the robot.                         |
| Lack of motivation        | Lacking a driving force to use the robot.                                   |
| Need not satisfied        | Being displeased or feeling discontent with a sought need that the robot should fulfill. |
| Reliance on others        | The act of or the perceived need to rely on others to be able to (properly) use the robot. |
| Replaced by another device| The replacement of applications or the complete use of the robot with another device. |
| Restrictions and issues   | Foreseeing or experiencing barriers to use the robot.                        |

Evaluating against expectations

Actual usage of the robot is compared with expected functionality or utility and -as studies on long-term interaction have pinpointed- the main risk is disappointment or disenchantment when participants’ expectations are not met (see Table 2). As opposed to helper robots, where disappointment is more likely to stem from a perceived lack of utility, in the case of robotic pets the expectancy is associated to the robot’s hedonistic value. The robot needs to be experienced as an alternative to a living pet, which is an extremely difficult challenge to actually achieve.

Confronted with this fantasy, complaints and disappointment often arise from the expectation of more obvious and salient dog-like activity, such as walking, fetching objects and responding to sounds, as opposed to the more subtle forms of interaction that robotic pets actually perform (Fernaeus et al., 2010). The challenge in this stage is to sustain momentum and keep children engaged and interested when the novelty effect wears off.

Development of interactional skills

This is the phase of acquiring the social skills to interact smoothly and satisfactorily with robotic pets; getting to know both their physical and their psychological capabilities (Kaplan, 2005a); exploring their potentiality and limits; figuring out procedures and mechanisms; identifying social and technological patterns (i.e. their favorite food); understanding cause-effect relationships; and adapting to the robot. In the study by (Nalin et al., 2012), 13 children from 5 to 12 years of age interacted with a NAO robot in a series of play sessions held every one or two weeks to evaluate how their perceptions, engagement and enjoyment evolved. The behavior was video-recorded and analyzed using an ad hoc coding scheme. The preliminary results showed that most children were quick to adapt to the robot’s behaviors in terms of timing, speed and tone and speech, verbal input formulation, nodding and gestures in response to the robot’s own behaviors, even if there is no clear need for them to do so.

Engagement and enjoyment are reinforced when the dyad successfully generates meaningful exchanges in an owner-pet context (e.g. feeding/eating), what (Pitsch & Koch, 2010) call interactional responsive conduct. When these “attempts to establish contingent interaction with the system” result in successful interaction, the loop of rewarding experiences with the robot is reinforced.

However, interaction is sometimes too effortful and even frustrating. This is when restrictions and problems appear, the second reason (after disenchantment) why adult participants gave up using the robot in this phase of the adoption process (de Graaf et al., 2017) (see details of this study in Sect. 2.1, Child-Robot Interaction (CRI) and Long-Term HRI). However, children are enthusiastic enough to forgive mistakes and repetitive behavior, and to help and connect with the robot for more time. But in order to achieve longer-term interaction, such interest and motivation must be fed by reciprocating adaptation on the part of the robot (Nalin et al., 2012).

Affective involvement

Positive affect and emotional involvement with regard to the robot are eventually developed in this phase and materialize in such behaviors as taking care of the pet’s needs and expressing affection by petting, touching and talking kindly. Melson et al. (Melson et al., 2009) in their content analysis of 6,438 posts on Internet forums by 182 owners of the AIBO puppy robot found that up to 59% of adults spoke of social rapport being established with the robotic pet, including communication, emotional connection, and companionship.

Typical observed behaviors that appear in this stage are individualization and personalization, such us giving nicknames, creating a special place for the robot, assigning things to it and taking it to show to friends and relatives. Owners very commonly decide on a gender and choose a name. Naming is an important event in the socialization process that is related to individualization, bonding and family integration. In his qualitative study based on virtual ethnography analyzing the blogging practices of owners of a Pleo robot, (Jacobsson, 2009) showed that a common practice during personalization is accessorizing the pet with different items. These episodes of socialization are experienced as particularly joyful.

Affection and social rapport can also be manifested in substantial contact (i.e. body to body), such as carrying, cuddling, stroking, hugging and holding against the breast (see Fig. 2a). (Heerink et al., 2012) investigated the
occurrence of social behaviors in the free play of 28 school-
children aged 8 to 12 years with Pleo. Analyses of observed
behaviors using an ad hoc coding scheme showed that the
two most prevalent behaviors were clearly social: petting
the robot and showing it objects to engage in interaction.
Aligned with these results, (Díaz-Boladeras, 2017) used a
similar method with 12 children aged between 11 and 12
to report a prevalence of 57% of prosocial behaviors in the
categories of attempts at reciprocity and giving affection
(Heerink et al., 2012; Díaz-Boladeras, 2017). (Fernaeus et
al., 2010) carried out a qualitative long-term exploratory
study in which a Pleo robot was placed in six family homes
for a period of 2 to 10 months. Both personalization and
affectionate behaviors were observed, including petting,
tickling and touching.

This process of individualization and emotional involve-
ment could lead to conflicts if the robot has to be replaced
because owners feel attached to the particular individual
and prefer it to a new one (Jacobsson, 2009).

In this phase, the main strategies to boost the willingness
to remain engaged are support for the owners’ natural ten-
dency to individualize and personalize the robot; exciting
technological curiosity once the initial novelty fades, and
promoting opportunities to include the robot in play and
fantasy games and thus engage new participants in collab-
rative games.

To summarize, according to the processes character-
ized in this phase the main challenges are disenchantment,
restrictions and maintenance issues, end of novelty, unsat-
sified needs, reliance on others and replacement with new
devices (see Table 2). The desirable outcome of this phase
is well-established and gratifying practices and emotional
bonds, which lead to the next stage.

Relationship

In our framework, this last stage of bond formation is
strictly a long-term relationship. There is no general agree-
ment in HRI literature on the minimum duration or the num-
ber of interactions that define a relationship as long-term.
However, a common opinion in the field is that a long-term
relationship begins when the user becomes so familiarized
with the robot that their perception of it is no longer biased
by the novelty effect (Baxter & Belpaeme, 2014; Leite et al.,
2013). Interestingly, the novelty effect may wear off more
quickly in some cases than others depending on contextual
factors such as the availability of the robot (i.e. continuous
vs. scheduled), the number and duration of interaction ses-
sions, the social situation (e.g. individual vs. group encoun-
ters), and also on the complexity of the robot’s behavior, for
those with limited abilities and capacity for interaction can
cause the novelty to fade more quickly (Leite et al., 2013).

More in-depth discussion of the delimitation of long-term in
HRI can be found in (Belpaeme et al., 2012; de Graaf et al.,
2017; Fernaeus et al., 2010; Karapanos et al., 2009; Matel-
lán & Fernández, 2014; Nalin et al., 2012; Sung, J., Chris-
tensen, H. I., & Grinter, 2009; Tanaka & Kimura, 2009). In
our framework, we prefer to delimit the phases in terms of
behavioral change (i.e. the intensity and frequency of use)
rather than the number of encounters or time span.

In this phase, participants -called retainers in de Graaf’s
model- do not interact as regularly with the robotic pet as
previously. They only play for short periods of time and
then set it aside with their other toys, or even ignore it com-
pletely except for on special occasions such as when friends
visit (Fernaeus et al., 2010). Empirical evidence shows that
even though participants engage in nurturing and playful
activities with robotic pets and experience social rapport
for a period of 2 to 10 months. Both personalization and
affectionate behaviors were observed, including petting,
tickling and touching.

activities with robotic pets and experience social rapport
towards them, this is not always enough to maintain their
interest, and the metaphor of caring for a real-life creature
decays. In this phase when usage is consolidated, children
are already familiarized with the robot and will most prob-
ably prefer novel behaviors and experiences (Leite et al.,
2013). The main two reasons reported by discontinuers in
the long-term study with the Karotz robot were the robot’s
lack of adaptability and its lack of enhanced sociability (i.e.
richer interaction and initiative in communication).

The dynamics modeled by the framework suggest two
main strategies to deal with the challenge of discontinuity
after previous adoption: expanding the robot’s capabilities
and exploiting social facilitation and gamification. In the
two next sections, specific implementations of these strate-
gegies are exposed briefly.

Maturation and learning

Change and novelty are the essence of attraction and these
can be provided by the progressive development of both
natural and artificial creatures. A robot’s range of skills
should be able to expand over time. Such a capacity has
been confirmed to encourage human–robot social bonding
(van Straten, Peter, et al., 2020).

One highly effective way of engaging users is to link the
maturation of creatures (i.e. the natural expansion of their
capabilities) in some manner with the way the user takes
care of them. In this self-reinforcing iteration, the more the
user interacts with their robot, the more the robot’s behavior
changes. Most of the existing virtual or physical pets (e.g.
AIBO or Pleo) have a predefined maturation program which
slows down when their owner fails to interact with them.

(Konok et al., 2018) suggests, according to gathered
evidence, that robotic pets are more engaging when their
behavior is modifiable through training. Future robots living
in the human environment should learn new skills by means
of teaching/training by the user -rather than by reprogram-
ing- as real pets do in human-animal interactions.

Pervasiveness

Another way to expand a robot is by endowing it with ubiq-

uity to complement the physical anchoring, whereby it is

located in different devices –such as smartphones or table-

lets-, in a process of teleportation or metamorphosis (Lar-
rriba et al., 2015). Robots like Pleo often fail to engage users

for extended periods of time, especially in comparison to

the enormous success of virtual pets in video games (Díaz-

Boladeras, 2017). Taking inspiration from pervasive gaming

technology where the player’s experience benefits from a

combination of real and virtual game elements, (Dimas et

al., 2010) proposed the extension of Pleo’s identity to mul-

tiple interfaces –pervasive Pleo- to thereby create a virtual

representation of the robot on a mobile device. This pro-

vides a supplementary modality of interaction that enables

the robot to overcome some of its limitations such as battery

life and the lack of transparency of its internal states.

Credible attachment: The tie that binds

We cannot agree more with Kaplan’s (Kaplan, 2005b) cat-

ergorical claim that in order to establish rewarding rela-

tionships with their owners, robotic pets must display artificial

attachment. In our framework, perceived attachment sup-

ports the engagement, interaction and rewarding experi-

ences that are necessary to sustain the willingness to remain

connected.

Recent comparative studies of what makes a hetero-spe-

ific companion a lovable social partner (Konok et al., 2018)

show that most of the most liked qualities and reported

advantages of dogs (i.e. love, faithfulness and kindness)

were related to attachment, companionship or the emotional

support that owners get from their dogs (Zilcha-Mano et al.,

2011). The behavioral descriptions that participants gave of

these categories were very similar to the scientific descrip-

tion of attachment, which is well defined and measured by

the Strange Situation procedure devised by Ainsworth (Ain-

sworth et al., 1978) to assess the quality of infants’ attach-

ment to their mothers or main care givers. This test has been

adapted to measure dogs’ attachment to their owners (Topál

et al., 1998) and has also been claimed to be applicable to

measure the naturalness of the affiliative behavior displayed

by a robotic pet, as a sort of Turing test (Kaplan, 2001).

Tentatively, to ground the construct of attachment in

terms of interactive behavior, we identify the follow-

ing social mechanisms that a robotic pet should deploy to

perform credible attachment: social awareness, individual-

ization, contingency, autonomy, and emotional alignment.

First of all, to establish the expected special relationship,

the robotic pet should be able to recognize and discriminate

its owner as the object of selective attachment and inter-

act in an individual-specific way through distinguishable

behaviors. One of these behaviors supporting owner-pet

connectedness is for the latter to perform continuous low

monitoring of its owners’ movements and activities, appear-

ning aware, attentive and ready to interact when the owner

wishes to (Melson, 2014).

It also seems necessary for social robots to feature a

certain degree of autonomy to create the perception of life-

likeness. They should act proactively (Melson, 2014), as if

having their own goals that emerge as a function of inner

states -varying their behavior in response to similar situa-

tions- and getting as close as possible to having a personal-

ity. Importantly, in Konok’s comparative studies (Konok et

al., 2018), the respondents reported that the main difference

between robots and dogs -and the advantage of the latter- is

that dogs have a personality and emotions. However, over-

autonomy can be interpreted by the user as disconnection, a

lack of interest in the users’ needs or even selfishness, and

can become a reason for disaffection and rejection (de Graaf

et al., 2017).

Moreover, robotic pets should be able to interact in a

timely manner and perform in response to people’s actions

by deploying socially situated, appropriate and prompt reac-

tions to their owners’ actions. These should closely match

the interaction suggested by the life-like appearance of the

device. As opposed to low-tech toys and dolls, the expec-

tations with regard to robotic pets are associated to their

actual performance, rather than the projections of our own

imagination (Fernaeus et al., 2010).

Last, but not least, sociability involves the capacity of

smart emotionality, whereby robots detect and react to their

users’ emotions in appropriate, socially acceptable ways

(von Scheve, 2014). Showing empathy with and respons-

iveness to their users’ needs can induce the key features of

attachment (Konok et al., 2018; Weiss & Hannibal, 2018).

This emotional alignment involves the two basic capabili-

ties of exhibiting readable emotional behavior and recogniz-

ing users’ moods and emotions.

Discussion

Limitations

As a conceptual representation, the framework presented

herein is based both on evidence from previous studies

and on assumptions from the selected theoretical models.
Therefore, it is by nature open to discussion, especially in terms of its internal coherence and its consistence with the findings in the field.

With regard to its scope, the framework is mostly supported by studies with three popular zoomorphic robots: the cartooned bio-inspired baby dinosaur Pleo, the puppy robot AIBO, and the little rabbit-like Koro. However, the presented dynamics of bond-forming with robotic pets are aimed to be general and applicable to different platforms taking the role of robotic pet. At a lower level, an effort should be made to identify for each platform the specific mechanisms to deploy the functions involved in the dynamics of bonding, according to their particular affordances and intelligence.

We consider that some patterns of the conceptual framework can also be applied to the formation of relationships with social robots through the adoption of different roles to that of pets. Some of the social dimensions of human-robot rapport such as likability, friendliness, closeness and likeness are commonly relevant to the formation of relationships, regardless of the nature that the robot embodies -human or animal- or the role it takes. However, two specific features of the owner-pet social situation limit the generalization of the framework to interaction with other robots: its core asymmetry and the prevalence of non-verbal communication. In contrast, when a child interacts with a robot on an equal standing (e.g. a playmate, a peer learner) or with a robot that adopts an authoritarian role (e.g. a teacher assistant, a therapist) other dimensions of social rapport become more prominent than attachment, such as trust and anthropomorphism (van Straten, Kühne, et al., 2020).

Despite the evidence that attitudes towards pets and robots are strongly culture dependent, most of the studies considered in the present work do not clearly specify the participants’ culture, socio-economic status, or ethnicity. Hence, we cannot count out the existence of bias in the findings, and therefore the present framework lacks corroboration of sociocultural generalizability. Further work is required not only in the form of comparative studies but also examining by default the effect of these demographic and social variables, even in exploratory studies.

Challenges and further research

Despite the growing interest in CRI and the number of remarkable contributions to the field, most empirical research is constrained to initial exposure to robots, which is probably enough for many applications and services where the interaction is expected to be brief and non-repeated (e.g. a museum guide) but is insufficient when robots are expected to cohabit with humans in their close environments (Dautenhahn, 2007; Matellán & Fernández, 2014). Though necessary, studies in the field of social robots that spend long periods of time interacting with humans are labor, time, and equipment intensive, and involve important challenges such as the deployment of robots that are robust enough to be studied outside the laboratory for extended periods of time without expert supervision (de Graaf et al., 2017; Weiss & Hannibal, 2018).

Another important challenge is to keep developing adequate instruments to measure the outcomes of child-robot relatedness in its three expressions: cognitions, behaviors, and affects, including adaptations of available instruments or ad hoc production (van Straten, Kühne, et al., 2020). Multi-technique designs seem to be the most promising approach to capture the multifaceted nature of CRI and to deal with the fact that children’s judgments about robots often diverge from the observed behaviors. Behavioral studies are extremely rich and pertinent in children behavior research. However, they imply the construction of ad hoc category systems and coding schemes for every single platform in order to register the interactive behavior and to carry out the tedious and discouragingly time-consuming hand coding of the video data (Díaz-Boladeras, 2017; Mwangi et al., 2018; Perugia et al., 2020; Pitsch & Koch, 2010).

Also, regarding methodology design, we consider that in social HRI the focal unit of study is the child-robot dyad, and this assumption implies systematic, timely and detailed observation, coding and reporting of the concurrent behavior of the autonomous robot during interaction. A large number of studies omit this information. A highly promising though challenging approach to investigation of how children engage in sequences of action with a robot is the application of conversational analyses, where any behavior unit draws its meaning from the flow of the interaction in a particular scenario, with detailed descriptions of the context (Pitsch & Koch, 2010).

Another of the most challenging issues in HRI research is that interactive behaviors with robots are extremely platform dependent. This affects the comparability of results. The HRI community investigates children’s interaction with diverse platforms with a huge range of appearances, affordances and competences, and which present substantial differences to each other, affecting communication and interaction.

And last but not least, we appreciate the extremely valuable efforts of a large number of CRI studies that have contributed to the academic and social debate on the possible detrimental psychological and developmental impact of interacting with robots (de Graaf, 2016). Judgments about the desirability of children forming relationships with robots vary greatly, even more when the exposure involves highly repeated interactions for extended periods of time (Huber et al., 2016; Leite et al., 2013; van Straten, Kühne, 2013).
et al., 2020). Many concerns and ethical implications arise with regard to children being exposed to personified technology, both as participants in studies and as target users in robot-based interventions, including the treatment of deception and possibly unhealthy attachment to the robot. Therefore, more evidence-based knowledge and critical reflection is needed to inform the decisions of such stakeholders as parents, educators, health practitioners and politicians on the beneficial and detrimental effects of artificial partners in children’s lives.

**Conclusion**

We view the formation of child-robot bonds as a socio-psychological process that unfolds over time. This process conforms to identifiable patterns of interactive behaviors with and perceptions and feelings towards the robot. These patterns are context and platform dependent and highly influenced by individual and situational variables.

The framework presented herein aims to represent how children’s perceptions of robots evolve across multiple interactions separated in time, as well as their subjective experience and the way they interact.

Our framework assumes that the key mechanism driving bond formation is the robot’s ability to deploy credible attachment behaviors—proximity seeking, resource soliciting and affect expression—that elicit complementary nurturing and play behaviors in children. Beyond the novelty effect, self-reinforcing processes such as learning and evolution can keep children engaged in rewarding interaction with the robot over time.

Robots’ affordances and behaviors need to be carefully designed to enhance their appeal, while situational variables need to be managed throughout the process in order to expand the robot’s potential and thus maximize the experienced value.

Children easily engage in imaginative play, whereby they interpret robot behavior, attributing meaning to events, utterances and movements, inferring moods, affective states and intent. The naturalness and credibility of emotional expressions support these attempts and assumptions, which are heavily dependent on life-likeness, whereby robots are conceptualized as intentional agents whose behavior is influenced by states, beliefs, desires, roles, genres and learning.

Moreover, the versatility of robotic pets—always according to the platform’s affordances—allows diverse modalities of interaction and individual and group play, satisfying different needs such as company, technological curiosity, entertainment and social facilitation both for normatively developed children and for children with special needs and their families.

We assume that the experienced value of a robotic pet for children lies in the experience of rewarding closeness that provides both warmth and enjoyment. Closeness as the essence of companionship enriches interaction and opens a new avenue for pretend play that can offer beneficial effects to children (e.g. alleviating loneliness, giving comfort) that other kinds of relatedness with a robot could not provide. We believe that the ability to generate this closeness is the strong point of a robot companion and particularly of robotic pets as a powerful resource in healthcare and education.

The framework presented herein aims to integrate different perspectives from related fields and to articulate the findings and unresolved issues. Despite the existence of valuable antecedents and the growing interest, further research is required to gather more evidence about the bonding process and its impact on children, not only for a deeper understanding of its dynamics but also to inform solid judgments with regard to the ethical implications.

**Funding** Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. No funding was received to assist with the preparation of this manuscript.

**Data availability** Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

**Statements and declarations**

**Conflicts of interest** The author declares no conflict of interest.

**Ethical statement** The Author declares that the reported research does not involve human participants, their data or biological material.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

**References**

Abbott, R., Orr, N., McGill, P., Whear, R., Bethel, A., Garside, R., & Thompson-Coon, J. (2019). How do “robopets” impact the health and well-being of residents in care homes? A systematic review of qualitative and quantitative evidence. *International Journal of Older People Nursing, 14*(3), 1–23. https://doi.org/10.1111/opn.12239

Ahmad, M., Mubin, O., & Orlando, J. (2017). A Systematic Review of Adaptivity in Human-Robot Interaction. *Multimodal
Melson, G. F. (2003). Child Development and the Human-Companion Animal Bond. *American Behavioral Scientist*, 47(1), 31–39. https://doi.org/10.1177/0002764203255210

Melson, G. F. (2014). Building better robots. *Interaction Studies Social Behaviour and Communication in Biological and Artificial Systems*, 15(2), 173–179. https://doi.org/10.1075/is.15.2.02mel

Melson, G. F., & Fine, A. H. (2010). Animals in the Lives of Children. *Handbook on Animal-Assisted Therapy*. Fourth Edi. https://doi.org/10.1007/978-0-12-381453-1-0012-1

Melson, G. F., Kahn, P. H., Beck, A., Friedman, B., Roberts, T., Garrett, E., & Gill, B. T. (2009). Children’s behavior toward and understanding of robotic and living dogs. *Journal of Applied Developmental Psychology*, 30(2), 92–102. https://doi.org/10.1016/j.appdev.2008.10.011

Melson, G. F., Kahn, P. H., Beck, A. M., & Friedman, B. (2009). Implications for the human-animal bond and for human relationships with personified technologies. *Journal of Social Issues*, 65(3), 545–567. https://doi.org/10.1111/j.1540-4560.2009b.01613.x

Miklösi, Á. (2008). “Communicative interaction in specific collaborative tasks” - Lirec-D.7.1-Ethogram of dog-human interaction.pdf. Retrieved April 6, 2015, from http://dl.lirec.eu/deliverables/Lirec-D.7.1-Ethogram-of-dog-human-interaction.pdf

Miklösi, Á., & Gácsi, M. (2012). On the utilization of social animals as a model for social robotics. *Frontiers in Psychology*, 3(March), 1–10. https://doi.org/10.3389/fpsyg.2012.00075

Moerman, C. J., van der Heide, L., & Heerink, M. (2019). Social robots to support children’s well-being under medical treatment: A systematic state-of-the-art review. *Journal of Child Health Care*, 23(4), 596–612. https://doi.org/10.1177/1367493518803031

Mubin, O., Stevens, C. J., Shahid, S., Mahmud, A., Al, & Dong, J. J. (2013). A Review of the Applicability of Robots in Education. *Technology for Education and Learning*, J(1), https://doi.org/10.2316/journal.209.2013.1.209-0015

Mwangi, E., Barakova, E., Diaz-Boladeras, M., & Catalá, A. (2018). Dyadic Gaze Patterns during Child-Robot Collaborative Gameplay in a Tutoring Interaction. *RO-MAN 2018–27th IEEE International Symposium on Robot and Human Interactive Communication 856–861

Myers, O. G. (2007). The significance of children and animals: Social development and our connections to other species. Purdue University Press

Nalin, M., Baroni, I., Krujiff-Korbayova, I., Canamero, L., Lewis, M., Beck, A., & Sanna, A. (2012). Children’s adaptation in multi-session interaction with a humanoid robot. *Proceedings - IEEE International Workshop on Robot and Human Interactive Communication*, (November 2017), 351–357. https://doi.org/10.1109/ROMAN.2012.6343778

Norman, D. A. (2004). Emotional design. *Ubiquity*, 2004(January), 1–1. https://doi.org/10.1145/985600.966013

Paepcke, S., & Takayama, L. (2010). Judging a bot by its cover. *Proceeding of the 5th ACM/IEEE International Conference on Human-Robot Interaction - HRI ’10*, 45. https://doi.org/10.1145/1734454.1734472

Pactz, M., Perugia, G., & Castellano, G. (2020). The Persistence of First Impressions The Effect of Repeated Interactions on the Perception of a Social Robot. *HRI ’20: Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction March*, 73–82. https://doi.org/10.1145/3319502.3374786

Perugia, G., Diaz-Boladeras, M., Catala-Mallofle, A., Barakova, E. I., & Rauterberg, M. (2020). ENGAGE-DEM: A Model of Engagement of People with Dementia. *IEEE Transactions on Affective Computing*. https://doi.org/10.1109/TAFFC.2020.2980275

Pitsch, K., & Koch, B. (2010). How infants perceive the toy robot Pleo. An exploratory case study on infant-robot-interaction. *Proceedings Second International Symposium on New Frontiers in Human-Robot Interaction*, (April), 80–87
