Novel Playmates in the Intelligent Era: Characteristics of Child-Robot Interaction and Its Impact on Child Development

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Date: 2023-08-21T00:00:00+00:00

Abstract

With the rapid development of artificial intelligence, interactions between children and robots are becoming increasingly frequent. Research findings in this field can be summarized according to three processes: children's cognition of robots, their interaction with robots, and the impact of such interaction on children's development. In terms of cognition, children are more readily attracted by the anthropomorphic appearance of robots, tend to explore robots based on interest, and perceive robots as living or quasi-living entities. During interaction, children are more willing to accept robots as intimate companions, readily seek emotional comfort and express protective desires toward them, but may also bully robots. Through interaction with robots, children's cognitive and metacognitive abilities, learning interest, as well as social initiative and empathy are enhanced; however, since robots cannot provide appropriate candid criticism and feedback, they may exert negative effects on children's social development. Future research needs to expand its design, methods, and depth, attempt to conduct longitudinal and cross-cultural studies, improve assessment methods, deeply explore the reasons and contexts for children's interaction with robots, and attend to the ethical issues involved.

Full Text

New Playmates in the Age of Intelligence: Characteristics of Children's Interactions with Robots and Their Impact on Child Development

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Abstract
With the rapid advancement of artificial intelligence, interactions between children and robots have become increasingly frequent. Research in this domain can be summarized across three processes: children's understanding of robots, their interactions with robots, and the developmental impacts of such interactions. In terms of understanding, children are particularly drawn to anthropomorphic robot appearances, tend to explore robots based on interest, and often perceive them as living or quasi-living entities. During interaction, children are more willing to accept robots as intimate companions, seeking emotional comfort and protection, though they may also bully robots. Robot interaction enhances children's cognitive and metacognitive abilities, learning interest, social willingness, and empathy. However, because robots cannot provide appropriate reproach and feedback, they may negatively affect children's social development. Future research should expand study designs, methodologies, and depth; attempt longitudinal and cross-cultural studies; improve assessment methods; deeply explore the reasons and contexts for child-robot interactions; and address relevant ethical issues.

Keywords: Children, Robots, Human-Robot Interaction, Child Development

1. Introduction

With the rapid development of Artificial Intelligence (AI) and robotics technology, its influence on human life is becoming increasingly profound. Both physical and virtual robots are being endowed with previously unimaginable capabilities, such as natural language communication, facial and behavioral recognition, and social and emotional interaction. Notably, they continue to flourish in innovative and high-speed ways. Today's living environment is so intelligent that even the youngest children are profoundly affected in how they learn, live, and play. Today's children will grow up as a generation immersed in intelligent technology from an early age, and their relationship with robots will be fundamentally different from that of previous generations (Pashevich, 2022). This raises an important question: Do children interact with robots in the same way as adults? The answer is clearly no. Children's physical and mental development is not yet mature, and they exhibit unique psychological attributes and cognitive characteristics when interacting with robotic products (Langer et al., 2023). Therefore, specialized research on the interaction characteristics between children and robots is particularly necessary.

In recent years, an increasing number of human-robot interaction researchers have begun to focus on children as a special user group, yielding numerous research findings on Child-Robot Interaction (CRI). This paper aims to provide a narrative summary framework, proposing that research in the CRI field can be organized according to three processes: children's understanding of robots, children's interactions with robots, and the impact of these interactions on child development. This process model aligns with Robot Social Presence theory (N. Chen et al., 2023). First, children need to observe and explore robots, establishing initial impressions and forming understanding and attitudes toward robots. Then, children engage in behavioral interactions with robots, such as socializing, cooperating, and teaching, while also developing emotional exchanges like affection, mutual assistance, and attachment, thereby building relationships and trust. Finally, children's interactions with robots shape their cognitive, learning, and social development, ultimately influencing their growth and peer relationship formation.

Following the taxonomy advocated by Onnasch et al. (2021), human-robot interaction research must consider human characteristics, robot characteristics, and contextual features during interaction. This paper will follow this recommendation, examining the roles of children's characteristics (e.g., age, gender, family and educational background, cultural context), robot features (e.g., appearance, degree of anthropomorphism, level of autonomy), and contextual features of their interaction (e.g., presence of caregivers and peers, educational or entertainment purposes) within the aforementioned process model.

This analysis will help understand the processes and characteristics of child-robot interactions and their impact on child development. Simultaneously, it will provide more targeted recommendations for optimizing the design and manufacturing of child-oriented robotic products to better meet the needs of different children and help them achieve better learning and development through robot interaction.

2. Children's Understanding of Robots

Both the Digital Play Framework for describing children's interaction with novelties (Bird & Edwards, 2015) and the Children's Engagement Behaviour Framework (Rennie & Howitt, 2020) propose that epistemic behavior is the starting point when children first encounter something new—children must first understand "What is this thing?" Building on this framework, this paper divides children's understanding of robots as a new object into three processes: observation, exploration, and comprehension. Observation refers to children perceiving robots' external features such as form, color, and movement through their senses to establish initial impressions. Exploration involves children combining their interests and needs to understand robots' working principles, purposes, and behavior patterns through guidance and manipulation. Compared to observation, exploration primarily involves a process of trial and practice, influenced by both external guidance and children's internal motivation and initiative. Finally, comprehension represents a deeper, more internalized process where children integrate information and experiences gathered in the previous two stages to form thorough and comprehensive understanding. For example, children can predict robot behavior in specific situations or understand how robots complete tasks and recognize their capabilities and limitations. Overall, this process of observation, exploration, and comprehension not only forms the foundation of children's understanding of robots but also serves as the prerequisite for further interaction.

The above process of children's understanding of robots finds support in social cognition theory, which posits that people build cognition and understanding of surrounding things through observation and interaction (Gelman, 2009). Children's understanding of robots involves observing robot appearance and behavior, exploring robot characteristics and functions, and gradually forming understanding and attitudes. In this process, children are not passive recipients of robot-related knowledge but actively construct robot-related concepts (Charisi, Malinverni, et al., 2020). Therefore, studying children's understanding of robots is the first step toward better understanding the essence of child-robot interaction.

2.1 Children's Observation of Robots

Children are typically curious about novel things, and robots as an emerging technology often capture their interest. The S-O-R framework for child-robot interaction proposed by van Straten et al. (2020) suggests that robots' visual appearance features are the first information children perceive during the recognition process, often creating a profound first impression. Visual features include many elements, with anthropomorphic features being the first to attract children's attention (Tung, 2016). Anthropomorphic features refer to the degree of similarity between robots and humans. Research has found that 7-14-year-old children's perception of the small humanoid robot NAO fluctuates significantly with changes in anthropomorphism, and appropriate anthropomorphic features can improve children's acceptance of robots (Barco et al., 2020). However, compared to younger children, children over 9 years old exhibit the "Uncanny Valley" effect, finding overly human-like robots creepy (Brink et al., 2019). Thus, for older children, robot anthropomorphism should not be too realistic.

Beyond anthropomorphic features, children also notice overall appearance aspects like color, shape, and gender. Research on 7-year-old children shows they prefer robots with rounded, smooth edges and compact, sturdy bodies, with blue being the preferred primary color—possibly because it is associated with positive emotional states, trust, and stability (Oros et al., 2014). Additionally, different age groups show different gender preferences: 3-8-year-old children follow gender segregation when interacting with gendered robot NAO, preferring same-gender robots, while older children (9-12 years) show no significant gender preference differences (Sandygulova & O'Hare, 2018).

As a novel cognitive object, robots are not silent objects for children to manipulate; they convey social cues. Experiments with humanoid robot Robi and cute chick-shaped robot Keepon show that robots' initial behaviors during first encounters and short-term interactions affect children's perceptions (Haring et al., 2016). Research finds that robots' facial expressions, vocal tone, and behavioral movements greatly influence their social capabilities and children's preferences (Tung, 2016). First, in children's perception of robots, facial expression feedback from robots increases children's positive exploration enthusiasm and makes interaction more enjoyable (Cameron et al., 2018). Studies on 9-14-year-old children find that when humanoid robot Furhat displays happy expressions, children are more likely to perceive it as trustworthy, likable, and capable; when it shows angry expressions, children perceive it as untrustworthy, unlikable, and incapable (Calvo-Barajas et al., 2020). Second, compared to robots using facial interaction, children prefer robots they can physically interact with. Research finds that for 5-6-year-old children, physical and verbal contact with physical humanoid robot NAO improves their mood and enhances their attitude toward robots (Conti et al., 2019). Experiments with 7-year-old children find that extroverted social robot Pepper's use of positive language and brisk, short, higher-pitched tones attracts more attention and affection (Jewell et al., 2019). Finally, robots' behavioral cues also affect children's friendliness. For example, during interaction, humanoid robot Alpha can attract children through eye movements (flashing lights and color temperature changes) and body movements (Dou et al., 2022).

In summary, during children's observation of robots, visual features create profound first impressions. Children prefer anthropomorphic robots, but for older children, excessive anthropomorphism can trigger the "Uncanny Valley" effect. Meanwhile, social cues like facial expressions, vocal tone, and behavioral movements can attract children's attention and generate interest and positive feelings.

2.2 Children's Exploration of Robots

After observing robots' visual features and social cues and establishing initial impressions, children proceed to further exploration, understanding robots' functions and behavior patterns through trial and practice. This exploration typically begins with simple, feasible tasks. In studies, 4-6-year-old children were guided to engage in simple conversations with remote-controlled social robot Tega, such as storytelling. Children found it easier to build relationships with robots when the robots' storytelling level matched their language abilities, and they were more willing to imitate the robots' vocabulary and phrases (Kory-Westlund & Breazeal, 2019a). Similarly, research on initial interactions between 8-13-year-old children and social robot Miko found that relatively easy, highly interactive "out-of-the-box" tasks (e.g., Q&A sessions, races, or ball games) could help children better understand robot functions and characteristics and improve their cognitive acceptance of robot technology (Lee et al., 2022). During this process, children prefer to explore robots based on their own needs and interests rather than following fixed schedules or task flows. Research on 6-11-year-old children found that compared to desktop social robot Haru's "intervention," children preferred autonomous choice in whether to seek robot help when collaborating on tasks (Charisi, Gomez, et al., 2020). This voluntary interaction approach better stimulates children's interest and initiative, thereby enhancing their exploration desire.

The exploration process is influenced by external contexts. The most important contextual factor is adult guidance, as children's initial exploration of robots, especially younger children, almost always occurs with adult accompaniment. Research finds that adults' introduction of robots greatly affects children's exploration behavior: if adults provide positive introductions before mechanical arm robots interact with 5-16-year-old children, children's helping behavior toward robots increases significantly after such introductions. This phenomenon is explained by the "halo effect," suggesting that setting expectations creates positive experiences and anticipation for children when interacting with robots (Beran, Ramirez-Serrano, Kuzyk, Nugent, et al., 2011). Additionally, after 3-7-year-old children hear adults describe social robot Tega as a social partner (rather than a human-like machine), they look at the robot's face and eyes more frequently and become more talkative (Kory-Westlund et al., 2016). Research also finds that during children's first contact with robots, their interaction patterns are influenced by robot portrayals in media and parents' descriptions: if external portrayals are positive, expectations of pleasant interaction extend to actual child-robot interaction; otherwise, children approach robots cautiously (Brunick et al., 2016). After investigating children's interactions with commercial social robots like Amazon Alexa, Google Home, and Cozmo, research found that 3-10-year-old children need robots to provide understanding feedback to remain attractive; hosts and parents play key roles in helping children rephrase or refine their questions, making child-robot communication more positive and smooth (Druga et al., 2017).

Overall, during children's exploration of robots, they learn about functions through simple interactions, further understand robot purposes through autonomous exploration, and under adult guidance, begin to explore robot behaviors to deepen their understanding. Therefore, providing children with appropriate tasks and exploration methods, and creating a positive interaction atmosphere through active guidance, are important ways to promote healthy understanding of robots.

2.3 Children's Comprehension of Robots

After observation and exploration, children gradually form comprehension of robots, developing an understanding of "What is a robot?" Overall, children's understanding of robots is ambiguous yet friendly. Research finds that by age 3, children show strong anthropomorphic tendencies: younger children typically do not view robots as electromechanical devices running computer programs but as living systems, or at least maintain the illusion that robots have lifelike characteristics (Belpaeme et al., 2013). Further research finds that in the cognition of slightly older children (7-10 years), robots are considered neither living nor non-living but as entities with which children may form social relationships (van Straten et al., 2020). A study on free-choice attribution toward robots (versus humans) among 5-7-year-old children found that in morally neutral scenarios, children attribute similar degrees of free choice to robots and humans, whereas adults more readily attribute free choice to humans (Flanagan et al., 2021). These findings reveal that children's understanding of robots is unclear and varies across different ages and cognitive developmental stages.

Why do children hold such understanding? Meta-analysis suggests that cognitive ability differences across age stages are significant, making age the primary factor affecting children's robot understanding (Stower et al., 2021). Piaget's cognitive development stage theory posits that children's cognitive development progresses through sensorimotor, preoperational, concrete operational, and formal operational stages, with qualitative differences in cognition and behavior across stages (蒋柯, 李其维, 2020). Children in sensorimotor and preoperational stages have not yet acquired cognitive skills like conservation and group structure thinking, so younger children generally hold "animism," tending to endow inanimate objects with life and consciousness (Beran, Ramirez-Serrano, Kuzyk, Fior, et al., 2011). Many studies show that younger children struggle to distinguish whether robots are alive, while older children have clearer cognition that strengthens through observing robot operation and interacting with robots (Cameron et al., 2017; Okanda et al., 2021). This leads to younger children in sensorimotor and preoperational stages having insufficient robot cognition, making them more accepting of robots, more willing to interact with them, and more likely to view them as social partners (Burdett et al., 2022).

As age increases, children's cognitive development enters concrete and formal operational stages. During these stages, children's robot understanding becomes more complex. They no longer simply view robots as living entities but begin to understand robots' working principles and functions; they also recognize that robot intelligence is not natural but designed and programmed by humans (Jung & Won, 2018). Simultaneously, older children's social cognition affects their interaction patterns with robots, as they expect robots to exhibit more social behaviors like emotional reactions and humanized communication (Kahn et al., 2012; Kim et al., 2018). Additionally, children at this stage begin to understand robot moral and ethical issues, such as robot rights and human responsibilities toward robots (Woo et al., 2021).

For older children, gender differences begin to influence robot understanding. Experimental research measuring 8-14-year-old children's perceptions of different anthropomorphic robot images found no significant age differences in cognition and attitudes toward humanoid robots, but boys showed significantly greater interest in mechanized-appearance robots than girls, while girls preferred highly anthropomorphic robots (Tung, 2011). Similar measurement studies found that as they grow, 8-11-year-old children show gender differences in friendliness perception toward robots: girls prefer robots with cute or soothing features, while boys prefer war-related robots (Cheng et al., 2017). Further research suggests this may be because girls value intimacy and alliance more than boys in long-term friendship contexts, so girls generally value robots' social qualities more than boys (Kory-Westlund et al., 2018).

In summary, younger children tend to view robots as living systems or endow them with life and consciousness, related to their cognitive abilities and developmental stages. As they age, children's robot understanding becomes clearer. Older children can better distinguish robots from living entities, while gender also begins to influence their robot understanding.

3. Children's Interaction with Robots

After encountering and understanding something new, children's subsequent behavior typically involves interacting, exploring, and playing with it to deeply understand "What can I do with this thing?" (Bird & Edwards, 2015; Rennie & Howitt, 2020). In human-robot interaction, frameworks by van Straten et al. (2020) and Onnasch and Roesler (2021) suggest that human-robot interaction processes can be described through people's socialization with robots and their responses to robots. Moreover, children's interactions with new things can be viewed as a play process (Wynberg et al., 2022). This paper therefore speculates that during the interaction stage, children first engage in game-like social interaction with robots, then develop partner-like emotions and attachment. However, it is worth noting that child-robot relationships are not always harmonious, as children also exhibit negative behaviors toward robots (Yamada et al., 2020).

This child-robot interaction process aligns with embodied cognition theory. Embodied cognition is an important way for children to understand the world. Although AI technology has changed how children interact with traditional objects, unlike adults who primarily understand the world through symbolic systems and abstract thinking, children instinctively still understand the world through personal experience and sensory perception (叶浩生 et al., 2020; 陈巍 et al., 2021). Current social robots are powerful and can effectively simulate human behavior (张钺, 2022). Therefore, when children engage in social interaction with robots, they often treat this interaction as similar to interacting with real people or objects, viewing robots as entities with social attributes. Further, this interaction process enables children to connect with robots and communicate with them on emotional and cognitive levels (Peter et al., 2021). Meanwhile, children attempt to understand and adapt to new technology challenges through their bodies and sensory systems, during which various factors may lead to negative behaviors toward robots. The following sections examine child-robot interaction processes from these three aspects.

3.1 Social Interaction Between Children and Robots

As previously mentioned, children's cognition of robots is less clear than adults', and younger children cannot even distinguish whether robots have life characteristics. However, it is precisely this cognitive ambiguity that prevents children from having adult concerns about privacy, safety, or interpersonal relationships, instead approaching robots with pure curiosity or hedonistic attitudes (Burdett et al., 2022). Because children hold more open attitudes toward robots' use and existence and have higher robot acceptance, robots can serve as children's companions in households and are typically viewed as partners in play scenarios (de Jong et al., 2022; Michaelis & Mutlu, 2017). Many studies find that children form prosocial connections with robots during interaction. For example, 5-year-old children care about how robots view them during interaction and are more willing to share with interactive robot Sota (Okumura et al., 2023). Research on interactions between 5-16-year-old children and arm-faced robots found that children help robots that cannot reach target locations or need to pick up dropped items, and children can distinguish which robots need help and how to help them (Beran, Ramirez-Serrano, Kuzyk, Nugent, et al., 2011). Attribution studies on 3-4-year-old children's help toward small humanoid robot NAO found that young children's sympathy for robots depends on robots' help-seeking behavior rather than anthropomorphic features—that is, regardless of whether children consider robots alive, they are willing to help them, possibly related to children's natural altruistic tendencies (Martin, MacIntyre, et al., 2020; Martin, Perry, et al., 2020). This reason for children forming prosocial connections with robots reveals an important issue in designing child-oriented social robots: robot behavior significantly impacts children during interaction, and if children observe robots as strongly prosocial, they themselves exhibit more prosocial behavior (Peter et al., 2021; Tolksdorf et al., 2020).

Furthermore, research finds that during child-robot interaction, children consider robots good friends rather than toys. For example, compared to playing alone, 8- and 12-year-old children prefer playing with social robot iCat, and children show stronger non-verbal expressive behavior when playing with robots than when playing alone (Shahid et al., 2014). A study investigating different preferences between 10-12-year-old children and parents when interacting with household social robots found that beyond learning and playing with robots, children are more interested in deep social interaction with robots. Children believe robots can listen and empathize, making them more willing to confide in robots, possibly because children perceive robots as providing neutral, trustworthy relationships (Cagiltay et al., 2020). Research also finds that in social interaction, 7-10-year-old children appreciate robot NAO's questions and self-disclosure about personal preferences and fears, leading children to believe robots possess cognitive perspective-taking and empathy (van Straten et al., 2022a). However, increasing interaction frequency and maintaining robot autonomy are crucial during this process. For example, a study on repeated interactions between 9-12-year-old children and a virtual version of social robot Furhat found that compared to first interactions, children's trust in the virtual robot's capabilities and sense of intimacy increased with interaction frequency (Calvo-Barajas & Castellano, 2022). Meanwhile, for 7-10-year-old children, observing that robot NAO's behavior is controlled by remote operators reduces their perception of robot autonomy and anthropomorphism, affecting their trust and social willingness toward robots (van Straten et al., 2022b).

In summary, because children's robot understanding is less complete than adults', they are willing to engage in deep social interaction with robots, making robots potential companions for children. However, children want robots as friends to be familiar, anthropomorphic, and autonomous. Therefore, designing child-oriented social robots requires careful consideration of robot characteristics and behaviors.

3.2 Children's Emotions and Attachment to Robots

As children's interaction with robots deepens, they may develop more and deeper emotions and attachment toward these social partners. First, children exhibit affectionate behaviors like petting and hugging robots, just as they would with real pets or humans. Research on 7-9-year-old children's interaction with robotic dog AIBO found that children showed affectionate behaviors such as petting, scratching, kissing, and hugging, believing AIBO could be a friend. In control experiments with biological dogs, although some children recognized robots lacked biological attributes, many still affirmed AIBO had mental states and social qualities, showing that children's cognition of AIBO as an artificial product did not prevent them from viewing the robotic dog socially (Kahn et al., 2013). Second, children protect robots. Research found that when unfamiliar adults approach small humanoid robot Keepon, 3-year-old children try to hide it, showing protective desire (Kozima et al., 2009). Third, children seek learning from robots. Research found that 7- and 12-year-old children's games and interactions with robots are not simple play; children also learn knowledge and skills from this "friend," indicating considerable emotional identification with robots (Constantinescu et al., 2022). Fourth, children seek emotional communication and comfort from robots, showing attachment. Research found that the vast majority of 10-year-old children (90.2% of the sample) felt better with robotic dog AIBO's company when home alone, while adults held more indifferent attitudes, indicating children's special emotional attachment to robot companions (Weiss et al., 2009). Meanwhile, 4-year-old children show emotional reactions toward robots similar to those toward real living beings, such as closeness, trust, and dependence, and may share stories and secrets with robots, viewing them as confidants (Borenstein & Pearson, 2013). Fifth, children may even feel "jealous" of robots' interactions with others. Research found that in robot caregiving games, children develop attachment to robots; however, when children realize robots give the same responses to other children as to themselves, they feel dissatisfied because they recognize their relationship is not unique (Law et al., 2022).

During the development of emotional and attachment relationships with robots, children show cultural background differences. A study had Dutch and Pakistani 8-12-year-old children play card games with social robot iCat, finding that Pakistani children were more enthusiastic, hugging and touching robots more frequently than Dutch children. Pakistani children also had higher expectations for robots and showed more positive cues. While this relates to Pakistani children having less robot contact and being more positive toward novelties, researchers also considered cultural factors important: Dutch children have clear individualistic tendencies, while Pakistani children are more collectivist, caring more about teamwork and group goals, thus showing more friendly interaction with robots in collective tasks (Shahid et al., 2014). Additionally, when investigating social robots for diabetes self-management, compared to 8-11-year-old Dutch children, 10-14-year-old Italian children held more open attitudes toward robots, using more emotional expressions and expressive vocabulary in interaction texts and showing more physical proximity and frequent touching. Since the age groups were similar, researchers attributed this to Italian culture encouraging outward expressiveness and enthusiasm in social situations (Neerincx et al., 2016). Thus, children's emotional interaction with robots is shaped by their cultural environments.

In summary, due to children's ambiguous cognition and open attitudes toward robots, they exhibit affectionate behaviors, protective desires, learning tendencies, and even emotional communication and attachment during interaction. This process is influenced not only by children's age, robot characteristics, and interaction environment but also importantly by children's cultural contexts.

3.3 Children's Negative Behaviors Toward Robots

Notably, children do not always treat robots as intimate friends. Research evidence shows that children also exhibit negative behaviors toward robots during interaction. A study deploying sensors in an Osaka shopping mall found that when parents were absent and few pedestrians were around, 5-9-year-old children stayed near humanoid robots for longer periods. When more children were present, they were more likely to abuse robots, such as obstructing robot movement, even insulting, hitting, kicking, and/or pushing them. Even when robots asked them to stop, they usually ignored the request until they became bored or their parents intervened (Bršćić et al., 2015). Attribution studies on 5-9-year-old children's abuse of humanoid robots found that most children participated in abuse out of curiosity about robot reactions, without intent to harm; however, some children still abused robots even when considering them human-like entities. This may be due to these children's lack of empathy—they believe robots can perceive their abuse but enjoy the process, just as some children abuse small animals (Nomura et al., 2016). Further research found that other present children may be a prior stimulus for target children's robot abuse, and when other children participate, target children's robot abuse repeats and escalates. Researchers believe that, similar to human bullying, children's robot abuse involves mutual imitation and escalation, possibly caused by desire for peer praise (Yamada et al., 2020). Thus, children's negative behaviors toward robots are influenced by peer pressure and conformity psychology.

Researchers believe that, without external intervention, children's negative behaviors toward robots are "natural." Because children frequently play with robots and seek comfort and companionship, and robots are often designed to act according to children's wishes without their own "temperament," children need not consider robots' social interests and needs. This situation may lead to master-servant relationships between children and robots, potentially resulting in adverse developmental outcomes such as children applying violence or abuse to robots, even viewing robots as their slaves and expecting unconditional obedience. Over time, such master-servant relationships may hinder children from building healthy social relationships with other humans and animals, leading to loneliness and isolation, and children may become over-dependent on robots, losing ability to interact with the real world (Kahn et al., 2013). Therefore, to intervene in children's negative robot behaviors, one approach is to make robots "resist," making children realize robots are not passive servants but have their own will. A statistical model was developed to predict the likelihood of children abusing humanoid robots, enabling robots to escape before abuse occurs; field validation proved this strategy effectively reduces robot abuse incidents (Brščić et al., 2015). On the other hand, parents and other adults should promptly stop children's negative behaviors toward robots, making children realize that insulting and pushing robots is not praiseworthy behavior (Sanoubari et al., 2021).

Overall, because children have not yet developed mature cognitive patterns and judgment abilities, they may view compliant robots as their servants. When peer imitation exists, children can easily be drawn into their surroundings and adopt inappropriate ways to treat robots. In such cases, robots should be designed to respond to children's negative behaviors, while parents should also intervene promptly to ensure children remain friendly toward robots.

4. Impact of Robot Interaction on Child Development

Interaction with the surrounding environment is a crucial influencing factor in children's growth. As an emerging technology, robots have integrated into children's developmental environments and become an important component of their learning and lives (毛忆晨 et al., 2022). As previously mentioned, children often attribute human characteristics to various objects. In this context, social robots serve roles similar to imaginary companions and anthropomorphic objects in children's lives. However, compared to traditional toys or dolls, robots can better simulate the companion role and interact more fully with children. Research shows that children treat robots as knowledgeable and informative conversationalists and information providers, tend to learn from responsively sensitive robots, and robots can adjust based on children's behaviors and reactions (Breazeal et al., 2016). Thus, through rich interaction and feedback, robots' various performances affect child development. The following sections examine the impacts of robot interaction on children's cognitive abilities, learning capacity, and social development.

These three aspects of impact are three sides of the same coin. Cognitive development theory states that children continuously adjust and build their world cognition through environmental interaction, affecting their learning capacity development. Sociocultural theory emphasizes that learning is a social process through which children acquire higher mental functions via interaction and feedback with others (王光荣, 2014). As mentioned, robots can provide interesting, feedback-rich social interaction. In the process of interacting with robots, children can simulate real-world scenarios, exercising problem-solving and decision-making abilities. Meanwhile, robots can help children better explore the world and learn new knowledge and skills through timely feedback and guidance. Additionally, robots can simulate interpersonal interaction, allowing children to practice communication, collaboration, and problem-solving in relatively safe environments, thereby developing interpersonal relationship abilities. Therefore, through robot interaction, children can better progress in cognitive ability, learning capacity, and social development, demonstrating the internal logic of child development.

4.1 Impact on Cognitive and Metacognitive Development

As previously mentioned, robots as interesting and highly interactive novelties can increase children's interest and engagement in exploring them, thereby helping improve children's ability to process, store, and retrieve information—that is, promoting cognitive development (Kálózi-Szabó et al., 2022). First, robots can present information in interesting and engaging ways that help improve children's attention. A study designed five task modules and observed 6-12-year-old children's interaction duration with robot NAO, finding most children showed positive engagement and significantly reduced time completing modules two through four, indicating improved attention (Ismail et al., 2021). Second, robots can patiently and repeatedly provide learning materials to enhance children's memory. Research shows robots can repeatedly present specific words or concepts to help elementary and middle school children encode this information into long-term memory; since robots can provide this information anytime, they can also help children review at appropriate times, further strengthening memory capacity (Chu et al., 2022). Finally, robots can provide an innovative learning environment where children improve problem-solving abilities through exploration and experimentation. By completing tasks with social robots, children must think, plan, and execute solutions; this learning approach improves logical thinking and enhances information processing and problem-solving abilities (Anwar et al., 2019; Neumann, 2020).

Beyond promoting cognitive abilities, robots can also enhance children's awareness and regulation of their own thinking processes—that is, promote metacognitive development. A study developed a social robot project called KindSAR to assist kindergarten geometry teaching. The robot could monitor and record children's performance in game tasks and provide detailed feedback to educators and children. Children first completed tasks with robots and after one week explained task goals and their completion methods to children who hadn't completed the tasks. Scale measurements showed KindSAR's feedback helped children understand their performance, thereby improving test scores in metacognitive knowledge, metacognitive regulation, and emotional and motivational regulation (Keren & Fridin, 2014). Related review studies also indicate robots can promote metacognitive development by providing concrete, learner-centered environments. In robot activities, children must use metacognitive strategies to plan, monitor, and evaluate their learning processes to successfully guide robots through tasks, thereby developing self-monitoring and evaluation metacognitive skills (Özkan & Toz, 2022).

These improvements in children's cognitive and metacognitive abilities form through relationship building during robot interaction. Children often learn and imitate robot behavior (Itakura et al., 2008); the more contact children have with robots before task execution, the more likely they are to repeat robot actions (Sommer et al., 2021). Moreover, children's imitation does not distinguish whether robot behaviors serve purposes; even when knowing more effective strategies exist, children still prefer causally irrelevant actions (Schleihauf et al., 2021). Therefore, interacting with peer-like robots expressing growth mindsets can positively influence children's cognitive patterns. Robots can stimulate children's exploration interest and motivation by demonstrating positive mindsets and behaviors, helping them form more positive, confident thinking patterns. Simultaneously, robots can provide personalized feedback and support to help children overcome challenges and succeed, further consolidating their growth and development mindsets (Park et al., 2017). Additionally, robots can provide a safe, pressure-free interaction environment where children can try new things without risk. This pressure-free environment helps children maintain positivity and curiosity and facilitates faster development of various cognitive skills (Ali et al., 2019).

In summary, because robots can provide interesting, positive, relaxed, and feedback-rich interaction scenarios, children are willing to deeply and persistently focus on exploring robots and completing tasks with them. These interactions can effectively promote children's cognitive and metacognitive development.

4.2 Impact on Learning Ability Development

For children, learning is important content in their growth. Children's learning ability refers to their capacity to master basic knowledge and learning skills, such as language, mathematics, and basic concept understanding. Through specific learning in various subjects, children develop abilities to master basic knowledge and skills, which in turn become the foundation for successfully mastering subject knowledge and shaping thinking patterns (Sommer et al., 2021). Research shows robot interaction can enhance children's learning ability. First, in language ability: after 5-year-old children participated in robot recognition and simple construction courses, their literacy improved, and during robot interaction, children expanded their terminology and used more complex sentences to explain robot behaviors or their own ideas (McDonald & Howell, 2012). Further research also found that compared to traditional digital teaching methods (e.g., tablets), children interacting with small humanoid robot NAO were more willing to participate in storytelling tasks, and language learning benefits increased over time (Konijn et al., 2022). Second, in mathematics ability: research confirms robots' effectiveness as teaching tools for children, particularly in mathematics education. Robot interaction can rekindle children's interest in high-demand cognitive tasks, thereby improving arithmetic test scores (Brown & Howard, 2015). A study designed a robot tutor that, in experiments with 7-9-year-old children, could provide feedback on errors in basic addition and subtraction problems. The robot could automatically detect errors, identify error types, and explain how to avoid them. Because robot tutors respond more quickly and intervene more timely than humans, children's arithmetic abilities improved effectively (Hindriks & Liebens, 2019). Finally, in comprehensive subject ability: researchers designed "Child-Robot Theater," incorporating humanoid robots NAO and Robosapien into traditional STEM education. Participating children were 5-11 years old; in scripts designed by children, robots performed according to roles, significantly improving children's interest in learning programming and robot manufacturing and helping them better understand new technology usage (Barnes et al., 2020). Thus, introducing robot-interactive teaching models provides a good platform for early exposure to new technologies like programming, robot control, and other engineering concepts, thereby improving children's scientific literacy.

In cultivating children's learning ability, robots can serve not only as teachers but also as students. A study utilized the protege effect in teaching, having children play teachers imparting knowledge and skills to humanoid robot NAO, while robots as students dialogued with children. This process requires children to deeply explain learning content and continuously adjust their expression methods to ensure robot understanding. After teaching robots, children received recognition and feedback, enhancing their in-depth thinking and memory of learning content and improving their confidence and task commitment (Jamet et al., 2018). Related theoretical research summarizes four pathways for robots to cultivate children's learning ability: (1) By programming robot behaviors, children can develop computational and logical thinking skills and learn creative problem-solving in practice; (2) Through robot interaction, children can learn how to respond to different situations and challenges in practice, thereby cultivating creative problem-solving abilities; (3) Robots can provide a challenging and motivating environment, encouraging students to try new ideas and methods and promoting creativity development; (4) Robot activities can also promote students' cooperation and communication skills, which are also necessary for creative problem-solving. In practice, these aspects work together to provide a good environment for cultivating learning ability (Gubenko et al., 2021).

In summary, due to their high flexibility, robots can not only accompany children in learning and provide timely feedback on problem-solving errors but also serve as students learning from children's teaching, thereby promoting children's in-depth understanding of knowledge. Thus, robots as a new educational tool provide multiple pathways for promoting children's learning ability development.

4.3 Impact on Social Development

Children's social development refers to their gradual learning of how to build relationships, understand each other, and cooperate with others during growth. As previously mentioned, children receive positive feedback during robot interaction and build unprecedented intimate relationships. Positive psychology suggests that positive experiences and emotions at the internal level lead to patience and tolerance at the behavioral level (翟贤亮, 葛鲁嘉, 2017). Therefore, positive child-robot interaction may promote their social development.

From existing research, first, robot friends can promote children's social willingness and empathy development through playful practice. Research finds that intimate connections between 4-year-old children and robots can promote social skills and empathy development and help alleviate children's loneliness and anxiety (Borenstein & Pearson, 2013). Related research also notes that small humanoid robot Zeno can provide more predictability and clear friendly signals, making it easier for children to view robots as friends and develop their social willingness and imagination during interaction (Elder, 2017). Second, robot friends can help children learn more social skills and promote connections and interactions with real human friends. Research finds that for 6-12-year-old children, social play with household social robots can help develop social skills like eye contact, facial expressions, and verbal communication, and social robots can adjust interactive game difficulty according to children's interests and levels to maintain engagement (Scassellati et al., 2018). Further research also finds that because robot scripts do not allow children to accelerate dialogue pace, this encourages elementary children to maintain rhythm in interaction and learn to listen patiently to others (Smakman et al., 2022). Third, robot friends can also provide emotional support, helping children better understand and cope with complex social situations. Research finds that robot education courses have significant positive impacts on 12-16-year-old children's teamwork and social skills. Social robots can stimulate children's curiosity to promote learning and participation, dialogue with children to encourage them to express thoughts and feelings, and play games with children to help them learn cooperation and sharing (Kandlhofer & Steinbauer, 2016). These findings indicate that positive interaction with social robots can positively impact children's social development.

However, it must be noted that child-robot relationships are more of a friendship simulation (Nyholm, 2020). Social robots merely "imitate" human socio-emotional reactions and behaviors, and this script-based or program-specific feedback cannot demonstrate true goodwill or feelings between friends (Matthias, 2015). This reality indicates that although robots can provide some companionship and interaction, gaps remain between them and real friends. Therefore, emotional bonds between children and robots may damage children's social development (Smakman et al., 2021). First, robots' compliance and obedience may make children prefer interacting with robots over human friends (Sharkey, 2016). Existing research shows that because robots actively feedback children's operational instructions, children growing up in AI environments encounter fewer difficulties in interpersonal relationships, so continuous robot interaction may inhibit children's friendship building with others (Arnd-Caddigan, 2015). Meanwhile, unlike interaction with human friends, children seek comfort and companionship from robots without needing to "adapt" to robots' social interests and needs, presenting an unequal social relationship. Therefore, when children bring this into future interpersonal situations, it may create a series of social problems (Kahn et al., 2013; Sharkey & Sharkey, 2021). The aforementioned children's negative behaviors toward robots are one example: because robots do not oppose or respond to abusive behavior, they may encourage children to conduct cruel experiments on them, leading to desensitization or habituation to these negative behaviors in children with bad habits (Constantinescu et al., 2022).

Thus, social robots can on one hand promote children's social willingness and empathy development, help them learn more social skills, and provide emotional support to assist in understanding and coping with complex social situations, all contributing to social development. On the other hand, because robot friends cannot provide appropriate reproach and feedback like real human friends, child-robot social interaction is unequal, which may distort children's social perspectives.

5. Summary and Outlook

This paper organizes child-robot interaction characteristics and outcomes as shown in Figure 1 [Figure 1: see original paper]. The following sections review typical research methods in this field and the implications of current findings for designing child-oriented robots.

5.1 Summary of Typical Research Methods

In the child-robot interaction research field, existing empirical studies can be divided into descriptive and experimental categories. Descriptive studies typically do not intervene in child-robot interaction processes; researchers mainly collect data through observation and interviews. For example, observing and recording children's views and reactions to robot images (Cheng et al., 2017), conducting interviews to understand children's feelings about interacting with robots (Kahn et al., 2004), or combining observation and interviews by first observing children's robot behaviors then interviewing them to analyze behavioral reasons (Nomura et al., 2016). In such descriptive studies, video recording interaction processes for coding and scoring is also common (Schadenberg et al., 2020). These descriptive studies are non-experimental, often lacking variable control and strict environmental requirements, so open recording results may be disturbed by other on-site environmental factors, such as parents and researchers frequently appearing at study sites, affecting children's robot views and behaviors (Beran, Ramirez-Serrano, Kuzyk, Nugent, et al., 2011; Michaelis & Mutlu, 2017).

Relatively speaking, experimental studies are more common. Researchers prefer experimental designs to understand causal relationships between psychology or behavior in child-robot interaction, controlling relevant variables, conducting random grouping, and comparing experimental and control groups. This causality-centered design provides more systematic and rigorous evaluation (Jung & Won, 2018). Because child-robot interaction processes are relatively complex, researchers in experimental studies often use mixed methods to evaluate interaction details. For example, Shahid et al. (2014) required children to self-report using questionnaires while also using objective measurements from robot sensor data and manually annotating interaction recordings to understand child-robot interaction processes. Cameron et al. (2017) used open-ended questions, interviews, and Likert scale ratings to understand children's robot reactions and thematic analysis for content classification and integration. However, these quantitative data analyses cannot comprehensively assess children's robot understanding processes and comprehension levels, so experimental studies also interview children afterward to obtain subjective descriptions of robot views and feelings to enrich experimental content (Haring et al., 2016). Overall, current experimental studies mostly use cross-sectional designs, considering child-robot interaction status at a single time point, while longitudinal studies on long-term child-robot interaction remain rare. Moreover, laboratory studies may be affected by experimental environments and researcher interventions, thus lacking ecological validity for accurately reflecting children's daily behaviors.

To address existing problems, researchers are making improvements. For example, concerned about children's misunderstanding or bias regarding questionnaire content, Tung (2011) provides detailed explanations and guidance and supervises questionnaire completion, incorporating age-appropriate language and expressions to ensure accurate understanding. Kory-Westlund et al. (2018) suggest four aspects to meet measurement needs for long-term child-robot relationships: (1) Inclusion of Other in Self Task measuring children's emotional investment in robots, requiring children to select from images the one that best represents their relationship with robots; (2) Social-Relational Interview understanding child-robot interaction and relationships, including how children view robots, communicate with them, and whether they consider robots friends; (3) Narrative Description understanding children's ability to comprehend and express their robot relationships, requiring children to tell stories including their robot interactions; (4) Self-Disclosure Task understanding children's willingness to disclose personal information and trust levels, having robots ask private questions like "Who do you most like to play with?" or "What do you most like to do?" These methods help researchers better understand emotional connections, trust levels, and friendship quality changes between young children and robots and provide comparison benchmarks for future research. Kory-Westlund and Breazeal (2019b) note that picture-based scales and behavioral indicators are easier for children to understand, proposing Picture Sorting Task and Social Acceptance Questionnaire to assess children's robot acceptance and related views.

These methods better capture children's perceptions and relationship changes during repeated robot contact and are effective for evaluating long-term child-robot interaction.

5.2 Design Considerations for Child-Oriented Robot Products

Today's children are future masters of the human world, so understanding child-robot interaction processes and characteristics is a necessary prerequisite for designing robots in the right direction to meet children's expectations and needs (Fortunati et al., 2015; 邓士昌 et al., 2022). Classic research suggests product user experience can be divided into three levels: forming first impressions at the visceral level, understanding and using products to meet needs at the behavioral level, and reflecting on product connotations and planning future actions based on experience at the reflective level (Norman, 2004). From these three levels, this paper summarizes design elements for child-oriented robots:

First, at the visceral level, because children typically view robots as novelties and endow them with life characteristics, and children's first impressions are often influenced by robot appearance traits, robot appearance design should arouse children's curiosity and closeness while remaining within acceptable anthropomorphism thresholds. From existing research, robots with bright colors, cute shapes, and soft, comfortable materials better attract children's attention and stimulate imagination.

Second, at the behavioral level, children are active participants who prefer interacting with robots. Unlike adults who mainly understand robots through observation and inquiry, children learn more through continuous interaction (Weiss et al., 2009). Research shows that because children's physical and mental development is still progressing, they tend to learn from robots with rich information content and quick responses (Breazeal et al., 2016). Therefore, child-oriented robot interaction design should be simple, clear, easy to understand and operate, and quick responses and smooth movements can enhance children's engagement and enjoyment (Haas et al., 2016). Moreover, robots should provide personalized interaction experiences according to children's needs and abilities (Park et al., 2019), thereby promoting their exploration and growth.

Finally, at the reflective level, children easily develop emotional attachment during robot interaction and engage in deeper communication accordingly. Current research has noted the formation of social relationships between robots and children, so when robots communicate politely with children, they must be able to express friendliness, respect opinions, and maintain attention (Uluer et al., 2021). Therefore, child-oriented robot design should emphasize emotional connection building, displaying friendly, caring traits to make robots children's partners and friends. Simultaneously, robots should provide rich information and interesting learning experiences to satisfy children's curiosity and thirst for knowledge (Toh et al., 2016). Such design will stimulate children's emotional engagement and memories, promoting their growth and development.

In summary, designing robots to interact with children requires considering children's characteristics at visceral, behavioral, and reflective levels. Through attractive appearance design, simple and easy interaction, and emotional connection building, positive, interesting, and beneficial robot experiences can be created for children. Such robots will become children's companions and learning partners, stimulating their curiosity, creativity, and learning interest.

5.3 Future Research Outlook

Current child-robot interaction research still has some problems; future research needs to explore three aspects further. First, research design expansion. During research, age is found to be an important factor affecting children's robot perception. However, in many studies, interaction differences across ages are discovered during attitude or preference investigations rather than through experiments with strictly age-divided participants. Moreover, many current child studies are single cross-sectional survey results, and children's robot cognition may be due to novelty effects, requiring long-term interaction research. However, due to children's special characteristics, it is difficult to find enough children for sustained participation in long-term studies (Kory-Westlund & Breazeal, 2019b). Meanwhile, current child-robot interaction studies may only select children from limited regions, mostly Western countries, making cross-cultural child-robot interaction research quite rare. This paper suggests future research should conduct more detailed studies on individual child characteristics while attempting longitudinal tracking and cross-cultural comparative studies to obtain more reliable and rich findings.

Second, research method improvement. When studying children's robot views and cognition, traditional questionnaires or interviews cannot fully understand children's thoughts. For a problem, children may have many explanations but, limited by their logical development levels, may only completely express one aspect rather than the whole picture. Moreover, current assessment methods for young children remain limited or inaccurate; many written assessment methods (e.g., Likert scales) are difficult for children to understand, and young children may cause invalid surveys due to attention issues or incomplete question comprehension (Kory-Westlund & Breazeal, 2019b; Nomura et al., 2016). Although researchers propose using picture scales and other behavioral observations to solve these problems, results from showing children robot photos versus movies, animations, or other materials may differ, and perceptions after contacting actual robot entities may differ again (Burdett et al., 2022). Therefore, future research should develop more effective assessment methods aligned with children's cognitive characteristics to evaluate children's responses in child-robot interaction for more accurate results.

Third, research content deepening. Child-robot interaction is not isolated, reminding researchers to examine related issues in specific contexts, such as children's potentially different robot responses in family or peer relationships. For example, children's social presence perception of robots is influenced by interaction environment; using the same robot to explore social presence changes across different contexts helps deepen understanding of child-robot relationships (Y. C. Chen et al., 2023). Meanwhile, current research generally focuses on child-robot interaction patterns in public places like shopping mall halls and classrooms (Bršćić et al., 2015), but what interaction patterns occur in private settings without witnesses remains worth investigating. Furthermore, existing research mostly observes various behaviors children display during human-robot interaction but lacks in-depth exploration of the reasons behind these behaviors. Notably, accompanying children's behavioral interaction with robots raises more ethical issues. Future research and practice should more comprehensively consider children's and robots' characteristics, more reasonably design child-robot interaction patterns, and provide more help for children.

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Note: Figure translations are in progress. See original paper for figures.