Applications of Social Robots in Children with Autism Spectrum Disorder

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Abstract

One of the core symptoms of children with Autism Spectrum Disorder (ASD) is impaired social interaction. Early intervention is crucial for the development of social skills in children with ASD; however, traditional psychological intervention methods suffer from numerous limitations, including time-consuming processes, high costs, and shortages of professional rehabilitation therapists. With the advancement of artificial intelligence technology, social robots have been widely applied in intervention research targeting the social abilities of children with ASD. This entails reviewing the feasibility of social robots in ASD interventions, analyzing the current research status of social robots in social interactions with ASD children, and exploring the advantages and challenges regarding experimental environments and methodologies in social robot interventions for ASD children. Future research on social robots for children with ASD may consider developing in aspects such as exploring the characteristics of both human and robot agents to create novel social scenarios, uncovering the psychological processes underlying human-robot interaction through the integration of multimodal and brain science technologies, and constructing closed-loop systems for social robots by focusing on advancements in artificial intelligence technology.

Full Text

Preamble

The Application of Social Robots in Children with Autism Spectrum Disorder

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Abstract

Social interaction impairment constitutes one of the core symptoms of Autism Spectrum Disorder (ASD) in children, and early intervention is crucial for the development of their social capabilities. Traditional psychological intervention methods suffer from numerous limitations, including time-intensive requirements, high costs, and a shortage of professional rehabilitation therapists. With advances in artificial intelligence technology, social robots have been widely applied in intervention research targeting the social abilities of children with ASD. This paper examines the theoretical and practical feasibility of social robots in ASD intervention, analyzes the current state of social robot applications for improving social interaction in children with ASD, and further discusses the advantages and challenges of social robots in terms of experimental environments and methodologies. Future research on social robots for children with ASD may consider exploring new social scenarios based on the characteristics of both human and robot agents, revealing the psychological processes of human-robot interaction through multimodal and brain science technologies, and constructing closed-loop systems for social robots by leveraging developments in artificial intelligence.

Keywords: social robots, autism spectrum disorder, human-robot interaction, social skills

1. Introduction

Autism Spectrum Disorder (ASD) is a pervasive neurodevelopmental disorder characterized primarily by social interaction impairments and restricted or repetitive behaviors and interests, with social interaction deficits representing its core symptom (Genovese & Butler, 2023). The etiology of ASD involves both genetic and environmental factors, and there is currently no cure (Holeva et al., 2022). Traditional psychological interventions are predominantly behavior-based, yet these approaches demand substantial time, effort, and financial resources, imposing a heavy burden on families and society (Leaf et al., 2022). In recent years, with the development of artificial intelligence, social robots have been widely employed in interventions for children with ASD, demonstrating effectiveness in ameliorating their social interaction impairments (Chevalier et al., 2020). Based on the feasibility of social robots in ASD intervention, this paper reviews the current research status of social robot applications for improving social skills in children with ASD, analyzes the advantages and challenges of social robot interventions, and proposes potential directions for future research, aiming to provide new insights for social robot-based interventions.

2. Feasibility of Social Robots in ASD Intervention

Social robots are tools that help people improve their social abilities through social interaction, with their primary focus being the achievement of effective human-robot interaction (Alabdulkareem et al., 2022). Current research on social robot interventions for children with ASD reveals widespread issues such as diverse robot types and inconsistent usage standards, making it difficult to evaluate the feasibility and effectiveness of social robots for improving social skills in this population. Therefore, this paper begins by classifying social robots and, based on an understanding of robot types and application scenarios, further discusses the preferences of children with ASD for social robots and their influencing factors, thereby providing references for researchers in designing and selecting different types of social robots.

2.1 Classification of Social Robots in ASD Intervention

This study classifies social robots along two dimensions: flexibility and human-likeness (see [Figure 1: see original paper]). Flexibility primarily references the robot's degrees of freedom (DoF), with mobility serving as a secondary consideration (Kumazaki et al., 2020). Degrees of freedom refer to the minimum number of coordinates required for a robot to complete movements. Human-likeness is categorized based on limb completeness and facial realism, allowing robots to be divided into humanoid and non-humanoid robots (see). Among the numerous humanoid robots, the Nao robot has been widely applied in ASD interventions due to its high flexibility and human-likeness, offering unique advantages for various social skill training programs (Alabdulkareem et al., 2022).

2.2 Preferences of Children with ASD for Social Robots

Research examining preferences for social robots among children with ASD indicates that, regarding non-humanoid robots, these children show preferences for robots designed with cartoonish or animal-like appearances. For instance, one study asked children with ASD to rank their preference for six social robots and found that both children with ASD and typically developing (TD) children most preferred the Keepon robot, suggesting that simple, exaggerated cartoonish appearances can better capture children's attention. Additionally, children with ASD least preferred the Pleo animal robot but showed some preference for the Probo robot (an animal robot with a screen on its abdomen) (Peca et al., 2014), possibly because robots combining mechanical elements possess certain visual appeal for children with ASD (Cabibihan et al., 2013).

Regarding humanoid robots, children with ASD demonstrate preferences for both appearance and technology. One study found that four children with ASD showed significantly higher scores in gaze, touch, and proximity when interacting with a "robot" (an actor wearing a standard robot costume) compared to interacting with a human (Robins et al., 2006). Another study revealed that eight children with ASD rated a humanized Nao humanoid robot (dressed in human clothing covering its torso and limbs) higher than a standard Nao robot in terms of general emotion and average interest (van Straten et al., 2018). Further research also found that, compared to their typical peers, adolescents with ASD exhibited higher levels of self-disclosure when interacting with the CommU humanoid robot (Kumazaki, Warren, et al., 2018). Meanwhile, one study discovered that individuals with ASD scoring higher on the autism quotient scale (IQ > 100) preferred the Actroid-F humanoid robot over mechanical-element humanoid robots and mascot robots (Kumazaki et al., 2017), with these individuals explaining their preference by citing the robot's advanced technology. However, current research suffers from limitations including small sample sizes, limited robot varieties, and high participant heterogeneity, preventing consistent conclusions about robot preferences.

Furthermore, robots with appearances closely resembling humans may trigger the "uncanny valley" effect in typical individuals. In 1970, Japanese robotics expert Mori proposed the "uncanny valley" effect, wherein robots that appear human-like but not perfectly so may evoke feelings of unease, causing emotional responses to drop sharply, though these responses recover as the robot's appearance becomes highly similar to humans. This effect has been validated in monkeys (Steckenfinger & Ghazanfar, 2009), human infants (Lewkowicz & Ghazanfar, 2012; Matsuda et al., 2012), and healthy adults (Saygin et al., 2012). Consequently, designers often create robots that do not resemble real humans to avoid this effect.

However, the emotional responses of individuals with ASD to humanoid robots do not entirely align with the uncanny valley effect. Based on the uncanny valley effect, researchers have proposed an emotional curve model for individuals with ASD (see [Figure 2: see original paper]) and conducted numerical simulations of robot-assisted intervention effects. This model uses the mechanical and human-like degrees of robot appearance as the horizontal axis and positive/negative emotional responses (calculated values) as the vertical axis (Ueyama, 2015). Positive emotional responses facilitate learning, while negative responses hinder it. As shown in [Figure 2: see original paper], individuals with ASD may not experience an "uncanny valley" effect with humanoid robots but rather an "uncanny cliff": when robots become more human-like to a certain extent, they do not evoke negative emotions; however, when humanoid robots become indistinguishable from real humans, they may trigger social avoidance and subsequent negative emotions in individuals with ASD. Empirical research has also found that while the Kasper humanoid robot triggers the uncanny valley effect in typical individuals, children with ASD show positive behaviors such as active social engagement and frequent touching toward it (Dautenhahn et al., 2009). Additionally, the difference in the point at which typical individuals and those with ASD begin to experience negative emotions (the different intersection points of the two emotional curves with the horizontal axis, indicated by the blue shaded area) suggests that individuals with ASD may have lower perceptual sensitivity to humanoid robots compared to their typical peers. This low sensitivity can be explained by the Intense World Theory, which posits that social information triggers hyper-reactivity in the amygdala of individuals with ASD. When confronted with abundant social information (such as multiple facial expressions and body movements), these individuals easily experience emotional stress and anxiety, manifesting social avoidance behaviors to alleviate these negative emotions (Fan et al., 2020; Markram & Markram, 2010). Humanoid robots, while retaining certain human-like elements, simplify the complexity of facial expressions and body movements. Compared to real humans, they reduce the influx of social information, thereby alleviating negative emotions to some extent. Therefore, the low sensitivity of individuals with ASD to humanoid robots may be attributed to robot appearance and technology.

2.3 Factors Influencing Preferences for Social Robots in Children with ASD

Factors such as gender, intelligence, and symptom presentation may influence preferences for social robots among children with ASD. For example, one study suggested that boys and girls differ in their categorization of robots, with boys classifying the Kaspar humanoid robot as human and girls viewing it as a toy (Coeckelbergh et al., 2016). Additionally, IQ affects intervention outcomes, with research indicating that children with ASD and lower IQ interact more with the Keepon robot but benefit less from robot intervention (Kozima et al., 2009). Furthermore, children with ASD with lower visual sensitivity more easily process social cues from robots, while those with higher auditory sensitivity require quieter robots (Chevalier et al., 2021). Beyond these factors, internal and external factors such as age, individual experience, and growth environment may also influence preferences for social robots, though researchers have rarely explored these variables. Therefore, further empirical research is needed to investigate these potential influencing factors when selecting social robots for intervention.

2.4 Theoretical Hypotheses on the Feasibility of Social Robot Intervention

The feasibility of social robots as tools for intervening in social deficits among children with ASD can be understood through relevant psychological hypotheses. Based on the New Ontological Category (NOC) hypothesis and social motivation theory, social robots represent both a new entity and a social reward for children with ASD, suggesting they may serve a transitional role in intervention.

The NOC hypothesis posits that children perceive social robots as a new entity distinct from humans (Kahn et al., 2013; Zhang et al., 2019). For instance, one study demonstrated that preschool children believe the Robovie humanoid robot possesses mental states (has feelings), can be a trusted social being and friend, and should be treated fairly and protected from psychological harm (Kahn et al., 2012). Another study found that while 5-year-olds could clearly identify the non-humanoid Dash robot as inanimate, both 3- and 5-year-olds believed the Nao humanoid robot might possess life (Goldman et al., 2023). These findings suggest that children may perceive humanoid robots as a new ontological category.

Moreover, social robots function not only as intervention tools but also as social rewards during intervention. Social motivation theory suggests that individuals with ASD have deficits in social motivation, manifesting as impaired social orienting, abnormal reward brain circuits, and lack of social maintenance strategies (Wang et al., 2021). Regarding social orienting, research has found that children with ASD look at the Nao robot more than at rehabilitation therapists (E. Bekele et al., 2014), and Damm et al. (2013) observed more gaze toward robot faces. These findings indicate a possible attentional bias toward social robots in individuals with ASD. In terms of social reward, studies show that social robots evoke children's curiosity, and children with ASD may actively participate in experiments due to a "novelty effect" (Croes & Antheunis, 2021). For social maintenance, Scassellati et al. (2018) found that children with ASD showed higher engagement during interactions with social robots, maintaining consistent engagement throughout a 40-day intervention. Thus, social robots can serve as social rewards to motivate social engagement in children with ASD.

3. Research Status of Social Robots in Social Interaction for Children with ASD

Children with ASD exhibit social interaction impairments, including deficits in joint attention, difficulty initiating social interactions, delayed language and non-verbal ability development, empathy deficits, and challenges with motor imitation. Research on social robot interventions has demonstrated certain effectiveness in improving social skills in children with ASD. This section elaborates on the current intervention research from five aspects.

3.1 Joint Attention

Joint attention (JA) forms the foundation for developing social and early cognitive abilities and plays a critical role in the development of children with ASD (Sano et al., 2021). Also known as shared attention, JA involves the ability to display and coordinate information between objects and people through gaze, vocalization, and gestures to share attention with others (So et al., 2020).

Social robot interventions for JA in children with ASD have shown improvements such as increased gaze and enhanced JA skills. Research has found that children with ASD show increased gaze toward the Nao robot compared to humans, and their attention to the Nao robot does not diminish over time (E. T. Bekele et al., 2013). Additionally, after intervention using the Jibo robot, JA skills improved in children with ASD (with reduced robot prompting), and their social communication abilities were enhanced (Scassellati et al., 2018). Following CommU robot intervention, children with ASD also performed better on JA tasks in human interactions (Kumazaki, Yoshikawa, et al., 2018). Moreover, after children with ASD mastered JA skills, removal of the Nao robot still maintained some treatment effects (Wang, 2019). Furthermore, previous research has found that high-level stimuli from the Nao robot (gaze, pointing, vocalization) elicited higher JA scores than low-level stimuli (gaze, pointing) (Warren et al., 2015).

3.2 Self-Initiations

Self-initiations represent the ability to actively initiate social interactions, a capacity that children with ASD rarely possess or lack entirely (Koegel et al., 2003). Self-initiations can be divided into two types: functional self-initiations, such as seeking help, objects, or information; and social self-initiations, such as seeking social information or making comments (Verschuur et al., 2019). Research has found that after robot-assisted intervention, self-initiation abilities (Huskens et al., 2013) and general social skills improved in children with ASD (Boccanfuso et al., 2017). Additionally, the robot-assisted pivotal response training group showed greater growth in functional self-initiations compared to the pivotal response training alone group, though no difference was observed in social self-initiations (De Korte et al., 2020).

3.3 Language and Non-Verbal Communication

Language and non-verbal communication impairments in children with ASD manifest in two main aspects: difficulty initiating conversations, participating in dialogues, and responding to others' communication requests; and challenges in understanding non-verbal behaviors (such as body language, gestures, and facial expressions) and integrating them into social interactions (Eigsti et al., 2011). Research has found that children with ASD produce more language when interacting with robots compared to adults (Kim et al., 2013), and further studies have shown that social robot interventions can increase verbal duration in children with ASD (Srinivasan et al., 2016). Additionally, when children with ASD adopt the robot's perspective, their understanding of non-verbal communication improves, and their communicative expressiveness is enhanced (Kumazaki et al., 2019).

3.4 Empathy

Empathy can be divided into cognitive empathy and emotional empathy, with children with ASD lacking both cognitive and emotional empathy abilities (Baron-Cohen, 2000). At the cognitive empathy level, they have difficulty recognizing others' emotional states (i.e., theory of mind deficits); at the emotional empathy level, they struggle to synchronize with others' emotions (Dziobek et al., 2008; Maliske et al., 2023). Some research suggests that theory of mind training may improve empathy abilities in children with ASD (Holopainen et al., 2019). Additionally, some children with ASD can attribute false beliefs to robots, meaning they can infer the robot's mental states (Zhang et al., 2019), suggesting that robot-based empathy interventions could consider approaches from theory of mind training. Moreover, research has found that interpersonal synchronization may promote emotional empathy. For example, children with ASD show interpersonal desynchronization when interacting with humans but demonstrate interpersonal synchronization (significant heart rate increase) and improved emotional sensitivity when interacting with robots, indicating that robots may enhance emotional expression in children with ASD (Giannopulu et al., 2018; Giannopulu et al., 2020).

3.5 Motor Imitation

Imitation plays an important role in the development of cognitive, language, and social skills in children with ASD. Gestures are spontaneous hand movements for communication (Bono et al., 2004), such as waving goodbye or wiping sweat from the brow. Although research findings on delayed gesture function development in children with ASD are inconclusive, studies have found that individuals with ASD may selectively delay the development of communicative gestures (e.g., waving hello) (Stieglitz Ham et al., 2010). So et al. (2018) demonstrated that the Nao robot can improve early gesture development delays in children with ASD, enabling them to reach typical developmental levels after robot intervention. Additionally, children with ASD produce more gesture imitation behaviors under robot intervention than human intervention, and their gross motor imitation skills improve after robot intervention, maintaining imitation abilities three months post-intervention (Conti et al., 2021). Furthermore, gesture imitation can trigger language imitation behaviors; for example, research has found that gesture actions in children with ASD under robot intervention are more likely to be accompanied by language imitation, such as saying "come here" while making the corresponding gesture (So et al., 2018).

4. Advantages and Challenges

4.1 Advantages of Social Robots

The advantages of social robots manifest in two aspects. First, advantages in ASD intervention include increased child engagement, enhanced attention, strengthened positive emotional arousal, and greater parental understanding and cooperation. For example, social robots can improve engagement during interventions, with children with ASD maintaining consistent engagement from beginning to end (Barnes et al., 2021). Robots also attract more attention from children with ASD, who show greater interest in and longer gaze duration toward robot faces (Damm et al., 2013). Social robots have short-term positive arousal effects on emotions, can alleviate social avoidance, and induce proactive social interaction behaviors (Huang, 2018). Additionally, research has found high parental acceptability and compliance with robot interventions.

Second, social robots possess inherent advantages such as predictability and self-disclosure. Predictability refers to the ability to quickly and accurately learn to anticipate a robot's future behavior, which is crucial for maintaining children's learning states. When robot behavior is highly predictable, children with ASD may increase visual attention to the robot's activity location and gradually join interactions, potentially producing positive learning effects, particularly for visually-based tasks (Schadenberg et al., 2021). Self-disclosure involves the communication of self-related information. Appropriate robot self-disclosure can enhance children's emotional evaluation of robots, and children with ASD can achieve greater self-disclosure when interacting with simple CommU robots compared to human interactions (van Straten et al., 2022).

4.2 Advantages of Intervention Methods

Compared to traditional intervention methods, social robots provide stable social output with less behavioral uncertainty and can continuously cooperate with therapists or parents to complete target behavior training for children with ASD. One study found that children with ASD (ages 3-8) could adhere to robot-assisted treatment protocols (average adherence rate of 85.5%), showed positive emotional ratings after treatment (86.6% of sessions rated as positive), and parents rated the added value of robots at an average of 84.8 points (on a 0-100 scale) (van den Berk-Smeekens et al., 2020). Another study showed that after robot intervention, children with ASD demonstrated improved abilities in making non-verbal requests to humans, understanding behavioral requests, and increased tendency for social interaction compared to children receiving conventional treatment (Ghiglino et al., 2021). Additionally, parental presence did not significantly affect interactions between children with ASD and social robots (Amirova et al., 2022), indicating the potential for robots as alternative or adjunctive interventions.

4.3 Challenges from Experimental Environments

Robot intervention experiments are typically conducted in homes, rehabilitation institutions, and laboratories. However, data collection primarily relies on audio, video, and performance recordings, while experiments often contain noise (Kouroupa et al., 2022), which may affect intervention implementation and outcome evaluation. For example, when social robots are used for home interventions, equipment placement in participants' homes may be interrupted by siblings, friends, or neighbors, affecting participant performance. Changes in equipment positioning during experiments also increase interference in visual feature extraction, impacting intervention effect evaluation. Moreover, since robot-assisted intervention systems are not designed for multi-agent interaction, they may fail to capture all individuals in the environment, reducing internal validity. Additionally, high attrition rates due to factors such as distance to rehabilitation institutions result in small sample sizes, affecting the reliability and generalizability of findings.

4.4 Limitations of Experimental Methods

Despite advantages of social robots and intervention methods, certain limitations exist in technical requirements, cost investment, and skill generalization. First, at the technical level, the effects of social robots cannot be measured independently and require multimodal data collection combined with other technologies. However, experiments predominantly employ audio/video coding, performance measures, and electrodermal activity, with limited use of brain science equipment such as functional magnetic resonance imaging or event-related potentials, lacking exploration at the neural mechanism level and failing to reveal the psychological processes of human-robot interaction. Second, considering cost, maintainability, and adaptability, robot interventions remain unsuitable for long-term clinical application. Although initial costs are high, long-term technological improvements and standardized mass production may reduce costs, with corporate profits balancing out as the industry rapidly develops. Therefore, social robots maintain long-term development potential for ASD intervention applications. Finally, whether children with ASD will increasingly prefer interacting with machines over humans during long-term robot intervention, and whether social skills learned in experimental settings can generalize to real-world environments, require further empirical exploration.

5. Summary and Outlook

In summary, social robot interventions for social skills in children with ASD demonstrate certain feasibility and effectiveness. First, social robots may function as "transitional objects" in intervention, though their feasibility must fully consider children's preferences for social robots and influencing factors, with intervention research conducted on the basis of further standardizing robot design and selection criteria. Second, analysis of existing research not only enriches our understanding of social robot interventions for social skills in children with ASD but also provides directions for future studies. Finally, based on the synthesis and analysis of current research, future intervention studies may consider the following directions.

5.1 Exploring Human-Robot Characteristics and Developing New Social Scenarios

Although social robot interventions have achieved certain effectiveness in improving social skills in children with ASD, the interaction characteristics and performance patterns between these children and social robots have not been fully explored. First, aspects such as robot appearance, movement, self-disclosure, and intervention duration affect social skills training. Research indicates that early intensive behavioral intervention of 25 hours per week is effective (Mottron, 2017), yet few studies have investigated optimal intervention duration for social robots. Furthermore, current research seldom addresses training in language knowledge, life skills, and other areas, and whether factors such as age, gender, and symptom severity moderate intervention effects require more empirical investigation. Future research could develop humanoid robots specifically for children with ASD and incorporate diverse interactive modalities. For example, in robot performance, humanoid robots could utilize dance, music, yoga, and games to mobilize children's enthusiasm and initiative; in robot design, human-likeness requires careful consideration, with researchers developing both universally applicable and specially customized robots and exploring appropriate scenarios for different robots to achieve effective maintenance and generalization of learned skills across contexts.

Additionally, beyond social abilities, repetitive behaviors represent another important intervention target. Based on previous research, the effects of social robot interventions on repetitive behaviors in children with ASD vary. Some studies observed reduced repetitive behaviors after robot intervention (Pennisi et al., 2016), while others found that repetitive behaviors and negative emotions might increase during robot intervention (Srinivasan et al., 2015). Therefore, future research could consider using social robots to intervene in repetitive behaviors and other deficits while exploring new social scenarios.

5.2 Combining Multimodal and Brain Science Technologies to Reveal Psychological Processes

Although research on social robot interventions for social skills in children with ASD continues to develop, investigators have paid limited attention to the psychological processes underlying these interactions. Future research should incorporate advanced technologies such as multimodal and brain science methods into experimental design. First, social robots can combine multimodal data to enhance analysis of behavioral phenomena. Multimodal data identification includes visual information, auditory information, speech, semantics, pragmatics, heart rate, and other data that help reflect psychological changes underlying human-robot interaction behaviors. Second, brain science technologies such as Functional Near-Infrared Spectroscopy (FNIRS), Event-Related Potentials (ERP), and Task-based Functional Magnetic Resonance Imaging (T-FMRI) can be employed during human-robot interaction to collect real-time data and reveal the neural mechanisms of these processes. Moreover, to prevent stereotypical behaviors during human-robot interaction, future social robots could incorporate functions to predict and identify such behaviors, enabling timely alerts for therapists to interrupt them. Additionally, Resting-state Functional Magnetic Resonance Imaging (rs-FMRI) could be collected before and after robot intervention to analyze structural and functional characteristics of brain regions and improvements in whole-brain functional connectivity, revealing the neural mechanisms of intervention effects from an imaging perspective. In summary, technological support is essential for research, and social robot interventions should emphasize integration with artificial intelligence and brain science technologies.

5.3 Leveraging AI Technology Iteration to Construct Closed-Loop Systems

Although artificial intelligence technologies such as machine learning and supervised learning have been applied in adaptive robot systems, social robots still lack sufficient active learning capabilities and cannot engage in real-time interaction based on environmental changes. Research indicates that technologies such as Virtual Reality (VR), Mixed Reality (XR), and Extended Reality (MR) may improve cognitive abilities in children with ASD, including attention, memory, and executive function. However, due to intolerance of headsets, experiments can only include high-functioning children with small sample sizes, and these new technologies have limitations including restricted application scenarios, high participant requirements, and low completion rates (Chen et al., 2022; Shahmoradi & Rezayi, 2022). Social robots could combine modern AI technologies (such as computers and tablets) to construct closed-loop human-robot interaction systems that enable long-term, coherent interactive content. Closed-loop systems, also known as adaptive robot systems, refer to robots that can not only react autonomously but also adjust output modes in real-time based on behavioral feedback. Furthermore, algorithm innovation in AI is crucial, as current personalized algorithms used in social robots are overly simplistic and lack adaptive models that can prioritize needs and preferences, making it difficult to maximize the potential of robot-assisted interventions. Therefore, AI technology holds promising applications for measuring and intervening in the performance of children with ASD during robot interventions.

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