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An approach of designing a child-height-assisted robot with semi-autonomous enhances social reciprocity for children with autism spectrum disorders

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Abstract

Individuals with autism spectrum disorder (ASD) often face significant challenges in social reciprocity, which involves the mutual exchange of social cues and interactions. This study investigates the potential of using a child-height assistive robot named Rudolf to enhance the social reciprocity skills of children with ASD. The research focused on two main questions: how the robot's semi-autonomous functions influence the enhancement of social reciprocity and how its customizable features elicit and improve these skills. Rudolf was specifically designed to engage children with ASD in a structured, supportive environment, offering tailored interactions to practice social reciprocity. A multiple-probe design was employed over three months to evaluate the robot's impact on the social skills of three participants with ASD. The study revealed significant improvements in the children's social reciprocity, with participants demonstrating increased engagement, trust, and interaction within the robot-assisted environment. The customizable functionalities of Rudolf were particularly effective in eliciting and reinforcing interactive behaviors. This research highlights the potential of assistive robots, like Rudolf, in addressing the unique social challenges faced by individuals with ASD. The findings suggest that such robots, when designed with customizable, child-centered features, can significantly enhance social skills in this population. The study contributes to the development of tailored assistive technologies that improve social integration and overall quality of life for children with ASD.

Keywords

inclusive education, social skills, autism, personalized learning, assistive technology, technology perspectives

Highlights

- Exploring how a specifically designed robot influences social reciprocity in children with ASD, and assessing the interactive dynamics between this robot and the target population.
- A tailored mechanical figure, a child-height robot with semi-autonomous, has been developed with functionalities specifically designed for children with ASD.
- The robot's operating platform includes capabilities such as movement, hugging, waving hands, speaking, and making facial expressions to interact with children with ASD.
- A multiple-probe design and a three-month-long experiment were conducted to investigate changes in the social skills performance of three participants with ASD.
- The results indicated:
  - The participants demonstrated enhanced social reciprocity skills, promoted collaboration, displayed experience sharing with the researcher, and showed predictability and trust in the robot's interactions.
  - The Rudolf robot environment proved beneficial in increasing predictability,

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motivating, and encouraging social reciprocity practices, and facilitating eye contact.

➢ The customizable functionality of the robot's design allowed for tailored interactions based on individual skill levels.

People with autism spectrum disorder

The diagnostic criteria for autism spectrum disorder (ASD) highlight deficits in social interaction and repetitive behaviors, with a lack of social reciprocity being a critical criterion for an ASD diagnosis (American Psychiatric Association, 2013). Individuals with ASD demonstrate limited structured interactions involving reciprocal behaviors in real-life situations (Chasson & Jarosiewicz, 2014; Volkmar & Klin, 2000). Individuals with ASD often face significant challenges in social reciprocity, which refers to the mutual exchange of social interaction, including the ability to share interests, take turns, respond appropriately to social cues, engage in mutual communication, commonly experience, and build meaningful relationships (Baker van Ommeren et al., 2012; Schwartz et al., 2021; Gengoux et al., 2019). Children with ASD often struggle to express their wants and needs, fulfill others' desires, and engage in solitary or group activities (Gates et al., 2017). This population encounters difficulty in modulating behaviors based on social contexts and demonstrating socio-emotional reciprocity (Baker van Ommeren et al., 2012; Chasson & Jarosiewicz, 2014). They often face challenges in understanding and responding to others' emotions (Marino et al., 2020), expressing empathy, fostering friendships, engaging in conversations, and establishing mutual attention (Engle et al., 2011; Garcia-Garcia et al., 2021; Kurnicki & Stanczyk, 2020). Consequently, those with ASD frequently find it difficult to maintain enduring social relationships, encountering obstacles in the realm of interpersonal and affective skills (Hyman et al., 2020). Developing complex social reciprocity skills could help children with ASD enjoy social interactions and increase their motivation to engage socially, thereby enhancing their social reciprocity (Chasson & Jarosiewicz, 2014).

Improving social reciprocity is not only crucial for increasing social interactions but also plays a significant role in enhancing the overall quality of life for individuals with ASD (e.g., developing social networks and interpersonal relationship) (Kasari et al., 2011). Research also indicated that the ability to engage in reciprocal social exchanges is associated with better social integration and participation in community and educational settings (Baker van Ommeren et al., 2012; Gates et al., 2017). By improving these skills, individuals with ASD may experience increased motivation to engage in social activities, leading to a more fulfilling and socially connected life. The benefits extend beyond mere social interactions, as improved social reciprocity can also lead to better academic performance, increased participation in collaborative tasks, and more opportunities for personal growth and independence (Attwood, 2013). Heasman and Gillespie (2019) highlighted the positive impact of social engagement in activities like play and education on the cognitive and social development of children with ASD. Such activities can help build engagement with others, foster collaborative actions, companionship, affection, intimacy, trust, turn-taking skills, and empathy, all of which are crucial for developing social reciprocity (Attwood, 2013; van Ommeren et al., 2012; Kasari et al., 2011). Gates et al. (2017) focused on group-based social skills intervention programs for youths with ASD to enhance social interaction, resulting in modestly effective social skills interventions in this population. Furthermore, encouraging children with autism to collaborate is essential, as it can lead to increased social interaction and higher levels of social engagement (Ben-Sasson et al., 2013). The lack of agency for interaction is a critical concern for children with ASD, as providing agency could enhance play experiences and create opportunities for future skill development (Spiel et al., 2019). Given the profound impact that enhanced social reciprocity can have on the lives of individuals with ASD, it is imperative to explore innovative approaches to support the development of these skills.

Robotics and ASD

The use of robots has played a crucial role in enhancing the development of social skills by providing a structured and supportive environment. These robots can engage children with ASD in a structured and supportive environment, thereby promoting social reciprocity and improving their ability to interact with others meaningfully (Scassellati et al., 2012; Szymona et al., 2021). Robots, capable of emulating human-like functions, can significantly contribute to enhancing social reciprocity among individuals with ASD, making them particularly valuable in eliciting specific behaviors targeted in interventions (Szymona et al., 2021). This effectiveness arises from the robots' ability to provide repeated instructions, engage in kind conversations, increase user attention levels (Lee, 2020), and offer physical touch, precise gestures, and operating platforms (Kurnicki & Stanczyk, 2020; Romanyuk et al., 2020; Szymona et al., 2021). Chung (2021) utilized robot-based social interaction to enhance social communication and interaction, promote socialization, and reduce behavioral problems. This approach employed an applied behavioral analysis (ABA) time-series analysis to investigate the impact of social robots on the social skills of children with ASD. The study findings indicated continued improvement among participants with ASD, even after the robot was withdrawn during the maintenance phase. When working with children who have ASD, the shape, size, and aesthetics of robots should be carefully considered (Qidwai et al., 2020). Robots used with this population can have various characteristics, including humanoid or non-humanoid forms. The human-like, anthropomorphic robot "NAO" is an autonomous, programmable humanoid robot capable of performing various functions. In a study by Qidwai et al. (2020), the NAO robot was used as a companion for teaching and therapeutic purposes. Fifteen participants with ASD, aged 7–11 years, engaged in activities such as exercising, singing, explaining, and playing to interact with the robot. In educational and mediational contexts, interactions can involve a triad of participants: children with ASD, an adult confederate, and an interactive partner. A robot can take on the role of an interactive partner or mediator in relationships, enhancing children's engagement through role-playing in therapy-like scenarios involving the therapist and the child with ASD (Huijnen et al., 2016).

Specifically, the customized humanoid social robot, Kaspar, was developed to interact tactilely with children with ASD (Wood et al., 2021). Researchers designed touch sensors for Kaspar, enabling it to distinguish and respond to gentle touches. This study explored how recognizing the human body by touching the Kaspar robot increased body awareness in children with ASD and promoted a relationship with the robots. The results demonstrated that children with ASD were able to share objects of interest with the researcher and engage in gentle touching of the Kaspar robot. Some assistive robots are designed to resemble animals or lack human-like features such as hands and feet, making it challenging for them to display certain behaviors (Belpaeme et al., 2018). The robotic toys are employed as social mediators for children with various needs. Bharatharaj et al. (2017) and Chernyak & Gary (2019) improved children with ASD's social-emotional development and developed sensitivity to physical contact using the therapeutic robot KiliRo or dogs. The study results showed that these animal-like robots could improve the sense of touch in this population. However, humanoid robots, robotic toys, and small robots may have limitations in providing interactive experiences for children, such as eye contact, body gestures, and initial physical interactions. In this context, some children tend to participate in fewer interactions when the robots closely resemble humans, possibly because such human-like appearances remind them of the stress associated with human interaction (Qidwai et al., 2020). Therefore, it is crucial to investigate the design mechanisms and features of robot development that can effectively support social reciprocity for these children.

The Current Work

This study aimed to utilize an assistive robot with semi-autonomous actions, designed at child height and capable of imitating humanoid behaviors, to examine its impact on social reciprocity among children with ASD. It also focused on investigating the interactive dynamics between the assistive robot and children with ASD, exploring which aspects of the robot's design could facilitate social reciprocity. The robot was intended to demonstrate interactive behaviors and provide human-like feedback to engage this population. To achieve this, a robot named *Rudolf* was created and developed with specific functions, including a mechanical figure equipped with a programmed operating platform (refer to Beran & Ramirez-Serrano, 2010).

The Design Process of *Rudolf*: The Hardware, Software, and Functionality

A mechanical figure robot of tangible construction, referred to as a child-height *Rudolf*, was custom-designed to meet the particular needs of the children with ASD selected for this study. The *Rudolf,* is able to be movable and capable of providing immediate responses and executing specific behaviors to motivate the participants' attention (refer to (Belpaeme et al., 2018; Marino et al., 2020). The tangible considerations related to human-like behaviors (e.g., emotions, mobility, and speaking), humanoid appearance (e.g., a head with two eyes and one mouth, two hands, body, and moving), and a favored cartoonish appearance can attract children's motivation, attention, and engagement (Qidwai et al., 2020; Welch et al., 2010). All speaking sounds of *Rudolf* were programmed in advance for use at a suitable time.

Rudolf was constructed using a hardware frame and manufactured by the Department of Mechanical Engineering at the university (Figures 1 and 2). For presenting the facial expressions of the robot, the designed facial expressions were installed on an iPad on the robot's symbolic head (The hat on the deer's head was movable). To simulate human behavior, the designs of two moveable hands (one hand with an infrared sensor in the right palm), moving functions, and speaking were considered in the robot design. A mini-PC was connected to a chip-on-board (COB), which was designed to control the robot's body. All its functional parts are connected to a programmable logic controller (PLC) platform that can be controlled by the operator. The executing functions of *Rudolf* were preprogrammed by a researcher using a graphical user interface (GUI). The GUI was programmed in LabVIEW (National Instruments Corporation) to operate *Rudolf*. Each child's performance during the experiment was observed/recorded via a camera using Debut Video Capture Software (NCH Software).

Regarding modularity and adaptability in the robot's design, both autonomous and semi-autonomous actions were implemented, with each module being extendable as needed. For the autonomous actions of *Rudolf*, a clickable red button was placed on the shoulder, and an infrared sensor was installed in the palm for sensory stimuli. When the infrared sensor was activated, *Rudolf* raised its right hand and said, "Well done! Give me five!" When the shoulder-based red button was pressed, *Rudolf* was programmed to respond, "What is the matter?". Semi-autonomous actions included

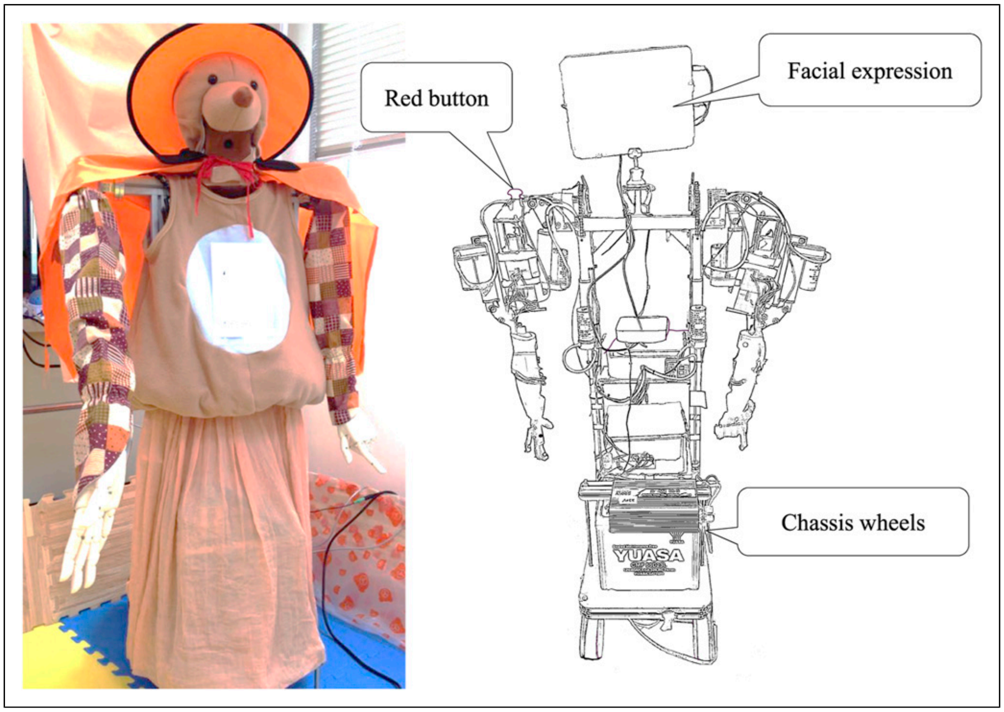

Figure 1. The robot playmate - Rudolf.

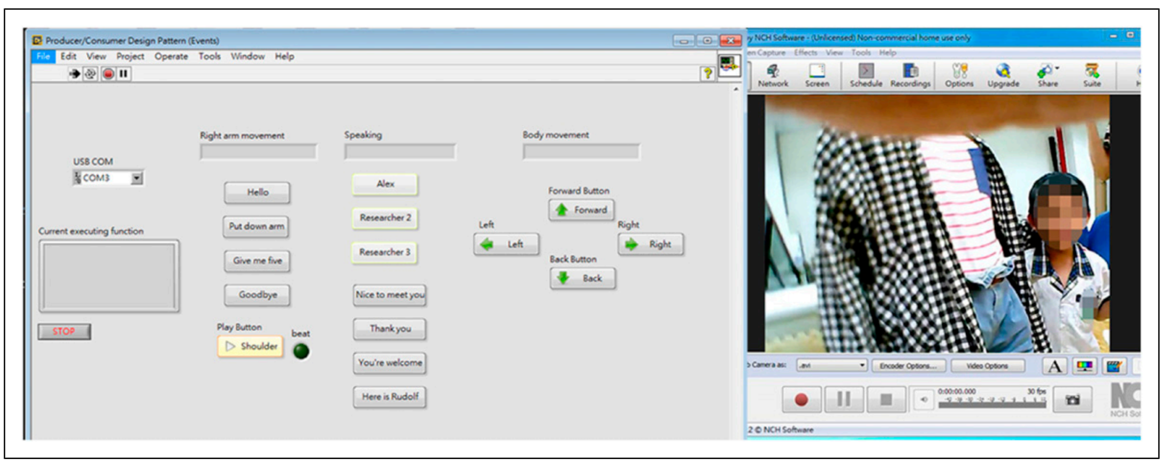

Figure 2. The interface of robot- interaction- system.

moving the right arm up and down, waving to greet, and clapping. Additionally, a menu in the GUI was designed, featuring options such as 「arm-behavior」 and 「chassis-wheels」.

- The menu item 「arm-behavior」 includes three toolbars: 「Arm & Speaking」, 「Gestures of Body Language」, and 「Voice」. Each toolbar contains different buttons:
  - ➢ The toolbar 「**Arm & Speaking**」 comprises four buttons: 「**Hello**」, 「**Put Down Arm**」, 「**Give Me Five**」, and 「**Goodbye**」**.** For example, if the 「**Hello**」 button is clicked, the robot will raise its right hand and say, "Hello, I'm *Rudolf*." If the 「**Put Down Arm**」 button is clicked; *Rudolf* will lower its right hand.
  - ➢ The toolbar item 「**Gestures of Body Language**」 contains the buttons 「**Welcome**」, 「**Cheering**」, 「**Hugging**」, 「**Waving a Hand**」, 「**Shaking a Hand**」, and 「**Putting the Head Down**」. For instance, when the 「**Welcome**」 button is pressed, the robot's arms will open to present a "welcome" sign to participants. The arms will remain open for 5 seconds before closing slightly, and the front arm will be used for hugging for 5 seconds.

- ➢ The toolbar item 「**Voice**」 includes 「**Child's Name**」 and 「**Verbal Instructions**」. The 「**Child's Name**」 button allows the robot to call out each child's name. The 「**Verbal Instructions**」 button includes phrases such as "You are doing well!", "You can try it again," "Go! Go!" "Hello," "Goodbye," and "Give me a high five." Speech and sound effects are delivered in a boy's voice using a computer and pre-recorded sentences from a speaker embedded in *Rudolf*'s body. All communications and behaviors of the participants were recorded through a webcam set into *Rudolf*'s neck.
- The 「Chassis Wheels」 window controls *Rudolf*'s movement and consists of four buttons: 「Forwards」, 「Backwards」, 「Turn Left」, and 「Turn Right」. These buttons are used for moving closer to or away from participants. When the Forwards, Backwards, Turn Right, or Turn Left buttons are pressed, *Rudolf* will continue moving in the desired direction until the buttons are released.

The *Rudolf* robot was specifically designed with robustness in mind, prioritizing both sturdiness and safety. Its body, made of stainless steel, was covered with clothing that had no sharp edges, and the robot was programmed to move slowly to ensure a safe interaction with children. The design of the robot—including its mechanism, functions, appearance, safety features, semi-autonomous capabilities, and modular behavior—was carefully reviewed and validated by two experts in ASD. One of these experts is a special education professional working in a primary school, and the other is a university expert who is also a parent of a child with ASD. Their combined professional expertise and personal experience ensured that the system effectively met the safety and efficacy requirements for children with ASD (Cabibihan et al., 2013). Thus, the research questions involved:

- How does the use of a child-height assistive robot with semi-autonomous functions, specifically designed to engage children with ASD, influence the development of social reciprocity skills in this population?
- How did the robot-based environment impact the participants' performance in areas such as joint engagement, turn-taking, eye contact, experience sharing, and cooperation in tasks, among children with ASD?
- How do the robot's customizable functionalities elicit and enhance social reciprocity skills?

Methods

This small-scale observational study involved children with ASD and utilized a multiple-probe design across baseline, intervention, and maintenance phases—a method recognized as one of the most comprehensive single-case research designs for individuals with ASD (Gast & Ledford, 2014). This approach incorporated repeated and structured teaching scenarios, systematic sequential observations of targeted behaviors, and reinforcement strategies. The study began with an initial probe to establish each participant's baseline performance, providing a foundation for measuring and analyzing their progress throughout the intervention. From baseline to maintenance, the researchers observed each participant's performance at different time points. This approach allowed for the exclusion of alternative explanations for the observed behavioral changes, while also minimizing unnecessary measurements and reducing potential frustration for the participants during the experimental process (Lerman et al., 2013; Slocum et al., 2022).

To ensure the teaching content's suitability for each participant, the first participant underwent three sessions in the baseline phase and was required to maintain stable performance in the targeted behaviors. Once the first participant's performance stabilized, the second participant began their first session. This process was then repeated for the third participant, and so on. The procedure followed for the third participant was similar to that adopted for the second participant. In addition, the experimental study received approval from the Institutional Review Board (IRB) to ensure that research involving participants with ASD was conducted ethically and with appropriate safeguards.

Participants

The three children included in this study (see Table 1; for ethical considerations, pseudonyms were used for all participants) were recruited from a region of the local autism society. Parental permission was obtained for each child, and the children themselves also agreed to participate by signing a consent form. The Wechsler Abbreviated Scale of Intelligence III (WASI; Wechsler, 1999) was used to evaluate the verbal IQ (VIQ), performance IQ (PIQ), and full-scale IQ (FSIQ) scores of the three participants, all of whom scored above 50. The participants used basic verbal expressions and were able to articulate their needs. Parents were required to complete a Social Skill Checklist (SSC) regarding their child's performance, which included questions about social reciprocity. The SSC contained eight items related to social reciprocity, and each participant was involved in at least three of these items. Additionally, the parents signed a consent form to confirm their children's participation in the experimental study. The

Table 1. Participant's Information.

Participant[a]	Age	Gender	VIQ	PIQ	FSIQ	ASD Diagnosis
Daniel	7	Male	78	81	87	Moderate
Joseph	9	Female	82	86	81	Mild
Matthew	11	Male	75	57	56	Moderate

[a]Note: Autism Spectrum Disorder(ASD).

below provides each participant's information, and social challenges.

- Participant 1**:** Daniel (7 years, 11 months), FSIQ: 87; PIQ:81; VIQ: 78.
  Grade Level: First grade, mainstream school.
  Social Challenges:
  ➢ Difficulty in building social relationships with peers.
  ➢ Struggles with following game rules and often resorts to attention-seeking behavior by attacking others.
  ➢ Lacked making eye contact, sharing with others, and cooperative partner/tasks, as identified in the SSC.
- Participant 2: Joseph (9 years 9 months), FSIQ: 81; PIQ: 86; VIQ: 82.
  Grade Level: Third grade, mainstream school with special training courses
  Social Challenges:
  ➢ Difficulty in taking turns, often interrupts communication, and exhibits unstable emotions.
  ➢ Lacked making eye contact and sharing with others, according to the SSC.
- Participant 3: Matthew (11 years 7 months), FSIQ: 56; PIQ:57; VIQ: 75.
  Grade Level: Sixth grade, special school
  Social Challenges:
  ➢ Struggles with using language to express needs, difficulty in building peer relationships, and has echolalia.
  ➢ Lacked sharing with others, as noted in the SSC.

All participants engaged in 12–15 sessions (comprising three phases) for 3 months. An experimental analysis of the targeted behaviors (joining a group, turn-taking, making eye contact/gazing, displaying experience sharing, and displaying cooperative/partner tasks) was conducted using systematic observations (researchers A, B, and C).

Teaching Contents

All teaching scenarios focused on social awareness, the appropriate interpretation of and response to interpersonal cues, and the motivation to interact with others to develop social reciprocity (Constantino et al., 2003). These skills, which are related to joint attention, interpersonal interaction, and friendship development, aimed to provide participants with opportunities to engage in various social scenarios and learn relevant reciprocal skills during different social events (Attwood, 2013; Mundy, 2003; Rollins et al., 1998). Thus, the skills related to joint engagement (JE) were emphasized, demonstrated through actions such as welcoming others to join activities or saying 'Hello' to everyone. (e.g., by clicking the red button on the researcher or the robot); Turn-taking (TT) involved waiting quietly for others' communication or actions, whether from the researcher or the robot. Making eye contact/gazing (EC) required maintaining eye contact for more than 5 seconds with the researcher or the robot. Experience sharing (ES) was demonstrated by offering an object or reward to the researcher or the robot upon task completion. Cooperative partner/tasks (CP/T) showcased the ability to collaborate effectively with the researcher or the robot as a team. The four designed tasks, which included social events such as playing baseball, assembling puzzles, engaging in chess, and interacting with toy roller coaster cars, were structured to emphasize social collaboration and reciprocal interactions. The social scenarios encompassed activities such as deciding who would select the ball, chess piece, or car color first based on dice roll scores, taking turns to shoot a ball, assembling a puzzle piece with the researcher, addressing incidents like the accidental crushing of a puzzle piece or the hiding of a chess piece or toy car, and following the guidance of the researcher or robot, among other interactions. Each participant went through four stages—'Greeting,' 'Task 1,' 'Task 2,' and 'Farewell'—during the baseline, intervention, and maintenance phases. The baseline and maintenance sessions involved human-partner intervention, where researchers followed the teaching process to interact with each participant. The intervention session utilized a robot-assisted environment, with *Rudolf* playing the role of an assistive partner (similar to one of the researchers) to complete tasks with the participants with ASD. Researcher A provided instructions, while Researcher B and Researcher C/the robot acted as assistive partners, offering hints, task rules, guidance, or encouragement. Each 'Greeting' session began with a self-introduction. Each game had unique rules and instructions, which were communicated by the researcher or the robot. Participants were encouraged to seek help from the researcher or *Rudolf* when encountering difficulties. Immediate prompts and feedback from the researcher were provided to address any unsuitable behaviors and provoke interactions with the robot (Yaw et al., 2011). At the end of each session, participants received a 'Goodbye' from the researchers or *Rudolf* and reciprocated the farewell. Social events related to targeted behaviors were presented (e.g., how to respond if the researcher got hurt). Finally, upon completing each task, participants were prompted to engage in a 'Give me five!' interaction with the researcher or the robot.

Measurements

This study developed the skills of reciprocity and sharing (SRSS) scale, to measure changes in the participants' targeted skills following the experiment's implementation (Table 2). The scale was developed because existing measures did not fully capture the specific social reciprocity behaviors targeted in the study, particularly within the context of robot-assisted interactions with children with ASD. The scale was tailored to assess key behaviors like joint engagement, turn-taking, eye contact, experience sharing, and cooperation, ensuring relevance to the intervention. The scale focused on five key behaviors, which were assessed using 12 picture-based questions verbally communicated by the researcher in each phase. The rule of the teaching contents was designed to follow the process of guided instructions in each task, and a hint was provided after 5 seconds of waiting. Upon task completion, the participant received an award in the form of stamps or stickers. After completing two tasks and collecting ten stamps or stickers, the children were rewarded with a reinforce (e.g., cookies, or a toy car). All measurements and teaching contents were based on early social communication scales (Mundy, 2003), building interpersonal skills (Attwood, 2013), joint attention skill scale (Cheng & Huang, 2012), and evidence-based practice (Zervogianni et al., 2020). These measurement items were thoroughly reviewed by a panel of professors specializing in in special education, along with two special education teachers, to ensure social validity, clarity, and suitability for application among these children. These items of measurement were in detail by a panel of educators, working in the field of special education with 15 years of experience, and two special education teachers, to ensure the social validity, clarity, and suitability for application among these children. Their feedback helped refine the scale to ensure it was appropriate and comprehensive. The scale's development emphasized convergent validity by aligning with existing validated measures and divergent validity by ensuring low correlation with unrelated these targeted behaviors. The SRSS scale was used to assess the five target behaviors during the baseline, intervention, and maintenance phases, with each child undergoing a 30–40 minute assessment per phase. All researchers observed the video-recorded children's performance to systematically monitor and code the five targeted behaviors as well as each participant's responses.

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Table 2. The SRSS Item and given Scores.

The skills of social reciprocity	Joint engagement (JE)	0: Was not open to others' presence.
		1: Rejected others from joining tasks, displaying an unhappy facial expression.
		3: Welcomed others to join tasks (e.g., by clicking the red button on the robot) but showed a neutral facial expression.
		5: Warmly welcomed others with a happy facial expression, was able to click the red button on the robot, and engaged by holding hands with the person joining the tasks.
	Turn-taking (TT)	0: Did not want to listen and walked away.
		1: Listened but made noises during the tasks.
		3: Was able to stay quiet and listen but could not maintain eye contact with the researcher or robot while they were speaking.
		5: Was able to stay quiet and maintain eye contact with the researcher or robot for more than 5 seconds while they were speaking.
	Making eye contact/gaze (EC)	0: Gave no response.
		1: The participant glanced at the researcher, then resumed their own activity.
		3: Looked at the robot or researcher for more than 3 seconds or glanced at the researcher without responding.
		5: Looked at the researcher or robot for more than 3 seconds and was able to respond to the researcher or robot.
	Experience sharing (ES)	0: Gave no response.
		1: When the participant finished the task, they might have tried to find the researcher or robot.
		3: The participant could have shown something to the researcher or robot, or they could have brought a reward to the researcher or robot.
		5: Upon finishing the task, the participant looked at the researcher or robot and said, "Look at this, I have done it.
	Cooperative partner/ tasks (CP)	0: Gave no response.
		1: Simply handed something (like a sticker or reward) to the researcher or robot.
		3: The participant managed to give something to the researcher or robot and engaged in conversation with them.
		5: The participant made eye contact with the researcher, gave something to the researcher or robot, and engaged in conversation with them.

Settings

The three children with ASD participating in the study engaged in two sessions per week, each lasting 30–40 minutes. In each session, each participant selected two tasks, and the researchers followed the rules of the teaching content for each task to ensure the implementation of the teaching principles. The baseline and maintenance sessions involved researchers acting out social scenarios and posing social questions to the participants.

The intervention sessions utilized the assistive robot, which played the role of a partner for the participants in completing the assigned tasks. These sessions were conducted in the university's research lab, which featured a playroom with a soft floor to allow the robot to "walk" and provide a comfortable environment for the children. To provide real-time responses during interactions with the robot, some of the robot's functions depended on the Wizard of Oz (WoZ) approach, where a researcher controlled the robot's movement, speech, body gestures, and behaviors from another room, out of sight of the participants. The robot was connected to a laptop (ASUS PU301L, Windows 7 Professional Edition) operated by Researcher A, which may have enhanced the effectiveness of the robot's interactions and technological execution (Riek et al., 2012).

The performance of target behaviors was assessed at the end of each phase using the SRSS scale to collect scores for each participant. Participants could withdraw from the study at any time if needed. The three graduate students serving as researchers/observers were from the university's Special Education and Psychology departments, had experience with children with ASD, and received specific training for this study. All sessions were recorded using a camcorder.

Experimental Procedure

The study employed a multiple-probe research design, which included three phases: baseline, intervention, and maintenance. Researcher B led each participant to the laboratory and greeted Researcher C and the robot, *Rudolf*, ensuring that the participant was situated in a quiet environment without disturbances. The SRSS scale was used to measure changes in targeted behaviors across three sessions.

During the intervention and maintenance phases, if a participant could not complete a given task, Researcher B and Researcher C assisted the participant or demonstrated how to perform the targeted behaviors. Researchers also encouraged participants to ask for help from either the researchers or *Rudolf* if they were unable to complete the task or were unsure how to proceed (Chung, 2019). Prompts included both verbal instructions and actions.

Baseline phase

This phase was conducted twice a week, and involved 4–5 sessions with researchers and participants (Figure 4). Two tasks were randomly selected to evaluate the targeted behaviors (JE, TT, EC, ES, and CP/T). Researcher B led each participant to the other researchers, at which point he/she could say "hi" to the others. The participants could select two tasks and start to tackle the selected tasks in each session. The three participants started the first session the same time; the first participant continued and finished the sessions. After completing the tasks, each participant used the SRSS scale for measurement; all three observers scored and recorded each child's responses. Given that the targeted behavior tasks were appropriately performed and stabilized during this phase, the first participant was required to complete three sessions in the baseline phase, demonstrating stable performance before the next participant could begin their baseline phase. Once this criterion was met, the intervention could proceed as planned.

Intervention phase

After the first participant demonstrated stable performance in the baseline phase, they moved to the intervention phase. This procedure was repeated for each subsequent participant. The intervention involving the robot positioned it as an assistive partner, capable of providing hints, task instructions, guidance, and encouragements. The robot, *Rudolf*, was programmed to call the participant by name using vocalizations and perform welcoming gestures. Researcher A, located in another room, controlled *Rudolf* (using a Wizard-of-Oz approach) and provided appropriate responses to the participant in real-time. Two tasks were randomly selected to evaluate the targeted behaviors. At the start of each "greeting" session, Researcher B introduced *Rudolf* to the child. *Rudolf* would say "Hello," prompting the child to respond, thus eliciting a reaction or engagement. Following this, Researcher B patted *Rudolf* on the shoulder and invited the other researchers to sing and dance together. *Rudolf* then offered encouragement by saying, "You all are so great! Everyone can get one sticker." This interaction involved *Rudolf* acting as an assistive partner, providing encouragement and feedback through both voice and behavioral expressions. Instructions for the tasks were also delivered through *Rudolf*'s voice.

Example Task 1: 'Basket Game'. *Rudolf* invited the child to play a 'basket game' with Researcher B and Researcher C. *Rudolf* explained the rules, and everyone selected a colored ball and rolled a die to determine who would throw first. When a child made a basket, they were expected to inform *Rudolf* by waving their hand. After the task was completed, *Rudolf* congratulated the child, saying, "You are so great! Everyone can get another sticker." The child then distributed the stickers to others.

Example Task 2: 'Playing Puzzles'. Three types of puzzles were provided, and *Rudolf* explained the rules to the participant. Once the puzzles were completed, *Rudolf* announced, "You can all get a big reward. It's in my box. Go and find it." When the participant found the box, they were required to report and show it to *Rudolf*. The session ended with *Rudolf* saying "goodbye," and the child was expected to reciprocate the farewell (see Figure 3).

Figure 3. The participant interacted with the robot.

Maintenance phase

Once the intervention phase was completed, participants moved to the maintenance phase to assess whether they could maintain the skills learned during the intervention. The performance was measured using the SRSS, with the maintenance phase following the same structure as the baseline to ensure consistency.

Data Collection and Analysis

Observations for all sessions were recorded using a camcorder. The performance of each targeted behavior was observed and scored by three researchers. To ensure interrater reliability, the consistency of the scores was verified. Performance levels for the targeted skills were assessed on a 5-point scale, ranging from zero to 5, with a total possible score of 50. Each targeted behavior was measured and coded by three independent researcher-observers, who used the SRSS scale to score the behaviors based on the videotapes. Interrater reliability was assessed by calculating inter-observer agreement (IOA). This was done by dividing the number of agreements by the number of disagreements and multiplying by 100 (Tekin-Iftar et al., 2001). Agreement was achieved when all observers recorded the same score for the same behavior, while disagreement occurred when different scores were recorded for the same behavior. The IOA for the participants was as follows: Daniel had an average reliability of 94.2%, Joseph had 95.8%, and Matthew had 90.8% (see Table 3).

Based on the visual analysis results, scores were measured, followed by analysis and comparison to assess the effectiveness of the robot approach in teaching the five targeted skills (as shown in Table 4). The data from all sessions were carefully examined and visually inspected by three independent observers to identify evidence of the targeted skills. These observers had familiarized themselves with the Social Robot Skill Set (SRSS) Scale, participated in practice sessions, and were supervised with regular feedback to ensure the accuracy and consistency of their observations. This rigorous training process ensured that the data collected were reliable and valid for analyzing the effectiveness of the intervention. Figure 4 shows that each child exhibited substantial improvement in their targeted skills.

Table 3. The Score of each Phase in the Three participants.

Participants	Phase	Range	Change	Mean
Alex	A	12.7–16	+1	14.5
	B	28–48	+18	36.8
	C	46.7–48	+1.4	45.9
Andy	A	12–5.7	−4	9.5
	B	32–47	+12	38.4
	C	46–45	−2	44.6
Tommy	A	13–10	−0.3	11.5
	B	40.7–46	+3.5	40.8
	C	45.7–44	−1.3	44.6

Daniel

Daniel's mean score on the SRSS scale was 14.5 (range = 12.7–16) during the baseline phase. As shown in Table 4, Daniel demonstrated continuous progress during the intervention phase, with his mean score rising to 36.8 (range = 28–48). He also maintained a stable performance during the maintenance phase, achieving a mean score of 45.9. This improvement indicates that using *Rudolf* effectively enhanced his targeted skills. During the baseline phase, Daniel's behavior scores ranged between 2 and 3.4, with his lowest mean score being for the skill of joining a group. In the intervention phase, all targeted behaviors showed notable improvement, with mean scores ranging from 5.3 to 8.4. His score for "CP/T" was 7.2, the highest among the three participants. In the maintenance phase, Daniel's scores for "TT" were 10, and "ES" was 8.7. Overall, Daniel's performance across the five targeted behaviors showed significant improvement.

Table 4. Scores of Targeted Behaviors Across Phases for Daniel, Joseph, and Matthew.

The targeted behaviors	Participant	Phase A	Phase B	Phase C
JE	Daniel	2	8	9.5
	Joseph	0.2	7.1	9.2
	Matthew	1.7	8.6	8.2
TT	Daniel	3.3	8.4	10
	Joseph	4	7.2	6.7
	Matthew	3.7	8	9.6
EC	Daniel	3.4	5.3	8.9
	Joseph	1.2	7.6	10
	Matthew	1.5	8	8.4
ES	Daniel	2.5	7.9	8.7
	Joseph	0.3	7.6	8.7
	Matthew	1	7.4	8.4
CP/T	Daniel	3.3	7.2	8.8
	Joseph	3.8	8.9	10
	Matthew	3.6	8.8	10

Joseph

Joseph's mean score on the SRSS scale was 9.5 (range = 5.7–12) during the baseline phase (see Table 4). He showed significant improvement in targeted skills during the intervention phase, with his mean score rising to 38.4 (range = 32–47). This increase compared to the baseline score suggests that the robot substantially enhanced his performance. In the maintenance phase, Joseph's mean score remained high at 44.6, indicating that he retained his targeted skills after interacting with *Rudolf*. During the baseline phase, Joseph's mean scores ranged between 0.2 and 0.3, with "JE" and "ES" scoring below 1, highlighting particular challenges in these areas. Conversely, his scores for "EC" and "TT" were higher. In the intervention phase, each behavior showed distinct improvement, with mean scores ranging from 7.1 to 8.9. His "CP/T" score of 8.9 was the highest among the three participants. The data from the intervention phase indicate that interactions with *Rudolf* improved all of Joseph's targeted skills. In the maintenance phase, his mean scores ranged from 6.7 to 10, which were the highest among the targeted behaviors of all three participants (see Table 5).

Matthew

Matthew's mean score on the SRSS scale was 11.5 (range = 10–13) during the baseline phase (see Table 4). During the intervention phase, his mean score increased to 40.8 (range = 44–45.7), indicating a dramatic improvement in his targeted skills. In the maintenance phase, Matthew's mean score was 44.6 (range = 44–45.7), demonstrating that he retained his targeted skills after interacting with *Rudolf*. During the baseline phase, Matthew's targeted behavior scores ranged from 1 to 3.7, with better performance in "TT" compared to "EC" and "ES." Following the intervention, his scores for the targeted skills improved to between 8 and 8.8. In the maintenance phase, his scores remained between 8.2 and 10, indicating that the intervention effectively enhanced his targeted skills (see Table 5).

Discussion

This study sought to explore how a child-height assistive robot, *Rudolf*, could improve social reciprocity skills in children with ASD. The findings indicated that this population demonstrated collaborative reciprocity by willingly engaging in group activities, taking turns to interact actively with others, sharing experiences, and displaying an ability to recognize facial emotions. More specifically, these participants expressed intentions of companionship, intimacy, trust, and affection toward the *Rudolf* robot—essential aspects for their social reciprocity (similar to Church et al., 2000). Robots could also provoke initial behaviors and contribute to the development of academic skills (Diehl et al., 2012; Midway et al., 2020). The research yielded intriguing results. The participants demonstrated enhanced social reciprocity skills, promoted collaboration, shared experiences with the researcher, and showed predictability and trust in the robot's interactions. This *Rudolf*-robot environment proved beneficial in enhancing predictability, motivating and encouraging social reciprocity practices, and facilitating eye contact. The customizable functionality in the robot's design allowed for tailored interactions based on individual skill levels. These practices are grounded in research and are considered great practices for promoting social reciprocity and other social skills in individuals with ASD.

Firstly, the children who participated in the study responded very positively to the intervention involving the *Rudolf* robot. They not only engaged with the tasks but also displayed marked improvements in their social reciprocity skills, such as turn-taking, making eye contact, and sharing experiences. These skills were critical in enhancing their social interactions, which are typically challenging for children with ASD, the similar study also demonstrated in Cabibihan et al. (2013). More specifically, these participants with ASD actively engaged their minds and displayed longer attention spans on eye-gaze with the researchers compared to the beginning of the experiment. However, they still exhibited more interest in the robot than in the researchers. This suggested that interaction with the robot helped participants learn vital social skills despite their usual difficulties with eye contact and empathy, although they still had difficulty showing social reciprocity and trust (Volkmar & Klin, 2000). Nonetheless, these participants displayed an affinity towards the researchers, even assisting when they saw the researcher was falling. One of the participants mentioned that they learned these skills because "I had interacted with the robot. Individuals with ASD often struggle with maintaining eye contact and expressing empathy during social interactions (Gengoux et al., 2019). These challenges are common among

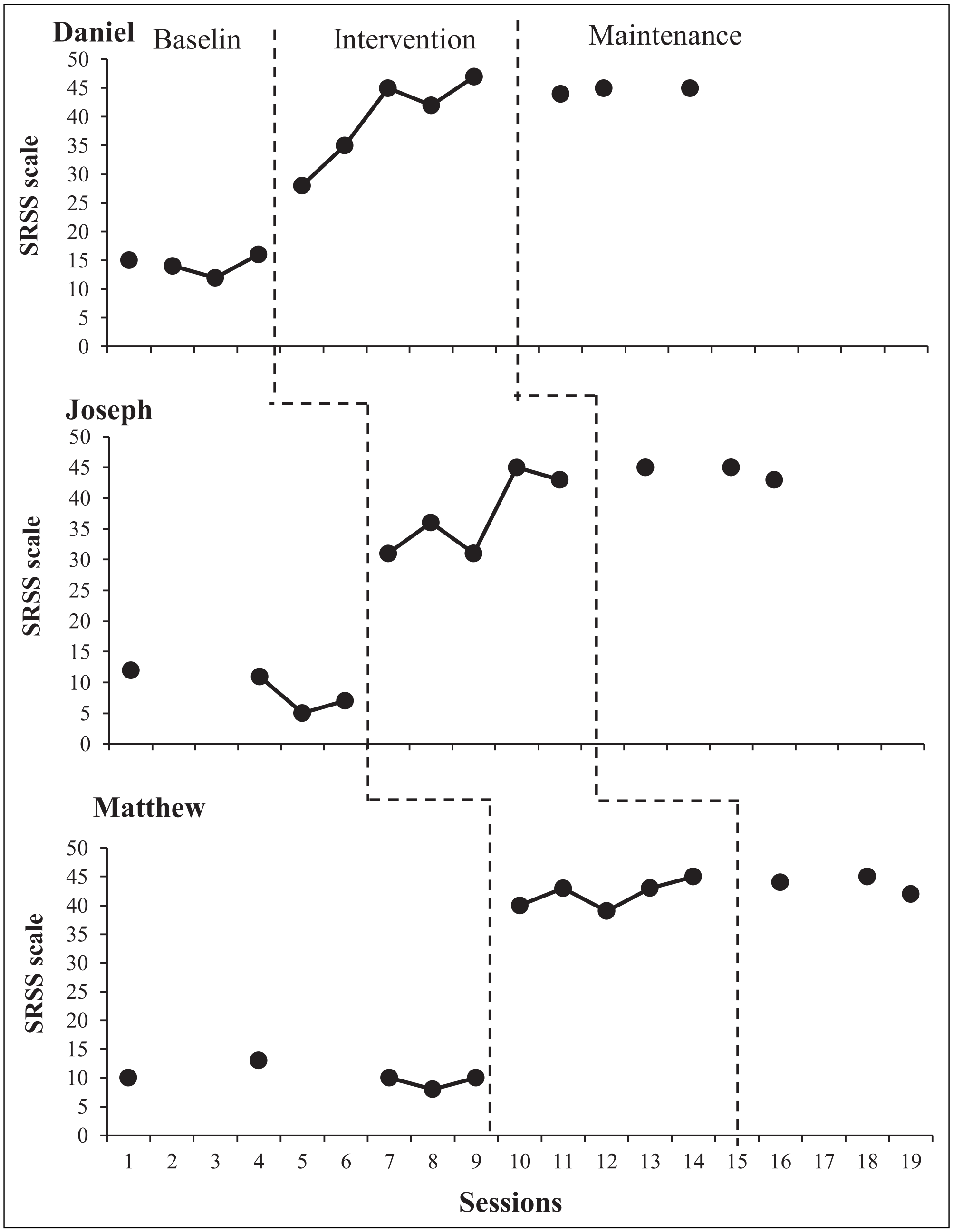

Figure 4. The scores of three participants in SRSS scale during baseline, intervention, and maintenance.

this population and are significant barriers to effective social reciprocity. Furthermore, the assisted robot played a helpful role in enhancing partnership, predictability, social collaboration, and practical implications. In terms of collaborative task, these participants were encouraged to engage in social collaboration with the *Rudolf* robot, directed towards the researchers. Despite the participants' inherent obsessive tendencies, they demonstrated a willingness to adopt the role of "a trusted playmate" when interacting with *Rudolf*, viewing it as a reliable and predictable partner in tasks. Their actions, such as actively engaging in tasks, following instructions, taking turns, responding predictably to prompts, completing tasks, and participating in reciprocal behaviors like sharing and helping, indicated their readiness to engage in the social scenarios provided. This willingness extended to the researchers, even though forming relationships might not be inherently easy for them, as noted by van Ommeren et al. (2012). Similar joint attention skills involve the ability to focus on an object or event with another person, which is crucial for social interaction and communication development in children with ASD (Cheng & Huang, 2012). The robot, perceived as a cooperative partner, notably increased the children's interest compared to human interactions, offering new social opportunities for this group. This aligns with the findings of a study indicating that the human-like robot garnered more interest from these participants than actual humans did, and the potential of robots offered social opportunities for this population (Laurie et al., 2022). For example, Joseph regarded *Rudolf* as a cooperative partner and shared experiences with it, such as asking, "Could you please help me take off the tear-off slip?" or running up to *Rudolf* to display an award like a sticker in front of its eyes and asking, "Do you know what this is?" He also attempted to share his experiences with the researcher towards the end of the maintenance session when he received his award. In this context, the predictable nature of the robot's interactions fostered a sense of security and a trustworthy, reliable social environment for the participants. These findings suggest that children with ASD attributed anthropomorphic thoughts and greater trust to the robot (Zhang et al., 2019). However, a key finding of the study was that the improvements in the children's social reciprocity skills were sustained beyond the intervention phase. During the maintenance phase, participants continued to exhibit enhanced social behaviors, such as better turn-taking, improved eye contact, and increased cooperation. This suggests that the behavioral changes were not merely temporary effects of the robot-assisted sessions but were integrated into their regular social interactions.

Secondly, the strength of the customizable functionality of the *Rudolf* robot lies in its practical implications for children with ASD. It provides a tangible presentation and human-like feedback that captivates participants through visual or tactile experiences. In designing the child-height robot to encourage eye contact practices within the *Rudolf*-robot environment, participants effortlessly directed their gaze toward its 'face,' which displayed facial expressions. The participants' eye levels were horizontally aligned with those of the robot throughout the intervention period. They did not need to lower their heads to search for the robot's eyes, which made maintaining eye contact easier and enhanced their ability to connect with others and maintain more stable emotional states. Although some studies have indicated that smaller robot shapes could improve eye contact for children with ASD (Chung, 2019; Fujimoto et al., 2011), they potentially require children to lower their heads to locate the smaller robot's eye positions.

To facilitate physical interactions (e.g., hugging, chatting, and touching or calling through tactile sensors), the robot was designed to be at a height similar to that of the participants, making the interactions more realistic. These participants exhibited a tendency to touch hands with the researchers upon completing the task, potentially indicating efforts toward rehabilitating social reciprocity. On the other hand, Matthew displayed more appropriate physical contact behavior with the robot. He approached the robot closely, maintaining eye contact, which was noteworthy given that children with ASD typically respond to touch in an unconventional manner (Szymona et al., 2021). Conversely, physical contact or affective closeness was rarely displayed with humans due to this population's lack of theory of mind (Laurie et al., 2022). Notably, participants did not focus their attention on the robot's outfit. They exhibited a positive response to *Rudolf*'s cartoon-style appearance at child-height. This *Rudolf* robot was not a commercially designed robot with a visually striking appearance; instead, its design prioritized enhanced functionality and immediate interactions tailored for this specific population. This positive response was attributed to *Rudolf*'s non-threatening, cartoon-style appearance, which differed from more commercially designed robots.

Finally, the customizable modularity of each designed function in the operating system of this assistive robot could be adapted and combined to suit appropriate actions based on the varying levels of participants with ASD. The behaviors associated with autonomy, including feedback from tactile sensors on the shoulder buttons or the infrared sensor in the palm, sparked interest and provided immediate feedback that motivated participants with ASD to engage with the robot. The semi-autonomous functions included facial expressions, speech capability, the ability to raise arms and both hands (welcoming, hugging), and simulated "walking" movements. These features were displayed in replicable and practicable ways for this specific population. They encouraged the participants to collaborate with *Rudolf* to attain more responses or rewards, thereby enhancing tangible interactions. This implied that the child-height robot with *Rudolf*'s social reciprocity-supportive features aligned with the criteria set for robot design (Diehl et al., 2012). Thus, the robot's human-like behaviors and child-friendly design made it easier for participants to connect with *Rudolf*, fostering companionship, trust, and affection. This positive engagement indicates that the robot-assisted intervention was both effective and enjoyable, making it a successful tool for promoting social behavior. Finally, given that the study showed significant improvements of social reciprocity in these participants, it can be inferred that parents would have viewed the intervention favorably, recognizing its potential to positively impact their children's social development. In summary, the role of *Rudolf* provided a tangible presence, eliciting motivation and interest among the participants. It also enhanced the potential to create opportunities for improving social reciprocity and providing companionship to children with ASD.

This improvement can lead to better integration into community and school settings, increased opportunities for forming and maintaining relationships, and a reduction in feelings of isolation. As social reciprocity skills improve, individuals with ASD may experience greater social participation, more positive social relationships, and enhanced emotional well-being, all of which contribute to a higher quality of life.

Limitations and Future Research Directions

This study represents an initial step toward the goal of providing a child-height robot companion for children with ASD. However, several limitations were noted. Firstly, the study focused on children with cognitive capabilities, recognizing that their ability to comprehend basic communication was essential for their participation and engagement. As a result, the findings may not be applicable to all children with ASD, particularly those with lower cognitive functioning. Future studies should include a more diverse range of participants with varying levels of cognitive abilities and communication skills. Secondly, this study utilized a small sample size to explore how participants with ASD interacted with the *Rudolf* robot and to examine the impact of the robot's design features on this population. While the findings indicated that the robot's design facilitated individual performance improvements among the participants, the small number of participants increases the likelihood that the results are influenced by individual differences rather than representing the broader ASD population. This highlights the need for larger-scale studies to validate the results. Thirdly, all participants were drawn from a single region, which may limit the applicability of the findings to children with ASD in other geographical areas. Regional factors such as cultural, educational, and healthcare differences could influence the effectiveness and reception of the intervention. Expanding the research to include participants from different regions and cultural backgrounds would help assess the intervention's effectiveness across various contexts. Lastly, *Rudolf* was specifically designed with features tailored for the study. While this customization enhanced the study's focus, it also limits the applicability of the findings to other robot designs. The non-commercial, child-height, and cartoon-style appearance of *Rudolf* might have contributed to the positive responses from the participants, which may not be replicated with different robot designs. To better facilitate practical interactions for children with ASD, further research should explore the use of different robot designs, including commercially available models.

Conclusions

This study demonstrates the potential benefits of child-height assistive robots, like *Rudolf*, in enhancing social reciprocity and skill development in children with ASD. The robot-assisted environment was simplified, predictable, and reliable, making it particularly suited to the needs of individuals with ASD. *Rudolf*'s functionalities included tactile and infrared sensors that provided immediate feedback, speech capabilities, horizontal eye contact, pronounced body language gestures, and simulated "walking" motions, all specifically designed for children with ASD. The robot's ability to execute behaviors that mimic human actions played a key role in engaging children with ASD. The research suggested that the tangible presence of an assistive robot could enhance intrinsic sociability and support the development of social skills in children with ASD. These findings pave the way for further research and the design of child-friendly robots tailored to the unique needs of this population, ultimately contributing to their social development.

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