Published in final edited form as:
Res Autism Spectr Disord. 2012 ; 6(1): 249–262. doi:10.1016/j.rasd.2011.05.006.

The Clinical Use of Robots for Individuals with Autism Spectrum Disorders: A Critical Review

Joshua J. Diehl[1], **Lauren M. Schmitt**[1,2], **Michael Villano**[1], and **Charles R. Crowell**[1]

Joshua J. Diehl: joshua.diehl@nd.edu; Lauren M. Schmitt: lschmitt@psych.uic.edu; Michael Villano: Micheal.A.Villano.4@nd.edu; Charles R. Crowell: ccrowell@nd.edu

[1]Department of Psychology, 118 Haggar Hall, University of Notre Dame, IN, USA.

[2]Center for Cognitive Medicine, 912 South Wood Street, Suite 235, University of Illinois at Chicago, Chicago, IL, USA.

Abstract

We examined peer-reviewed studies in order to understand the current status of empirically-based evidence on the clinical applications of robots in the diagnosis and treatment of Autism Spectrum Disorders (ASD). Studies are organized into four broad categories: (a) the response of individuals with ASD to robots or robot-like behavior in comparison to human behavior, (b) the use of robots to elicit behaviors, (c) the use of robots to model, teach, and/or practice a skill, and (d) the use of robots to provide feedback on performance. A critical review of the literature revealed that most of the findings are exploratory and have methodological limitations that make it difficult to draw firm conclusions about the clinical utility of robots. Finally, we outline the research needed to determine the incremental validity of this technique.

Keywords

Autism; Asperger; therapy; intervention; social skills; robot

1. Introduction

Rapid progress in technology, especially in the area of robotics, offers tremendous possibilities for innovation in treatment for individuals with Autism Spectrum Disorders (ASD). Advances in recent years have enabled robots to fulfill a variety of human-like functions, as well as to aid with the goal of improving social skills in individuals with ASD. The clinical use of interactive robots with individuals with ASD has received considerable media attention over the past decade, even though efficacy and effectiveness research on this topic is in its infancy. Moreover, much of the published research is in journals that focus on robotics (e.g., *Autonomous Robots, Robotica*) rather than in prominent ASD journals or clinically-focused journals. Therefore, it is important to scrutinize existing research on the clinical applications of the technology, rather than the development of the technology itself.

Corresponding Author: Joshua John Diehl, Ph.D., Department of Psychology, 118 Haggar Hall, University of Notre Dame, Notre Dame, IN 46556. Phone: (574) 631-1371. joshua.diehl@nd.edu. Fax: (574) 631-8883.

For this purpose, it is crucial to outline a rationale for the clinical use of robots and then to review current research within the framework of this rationale.

The clinical use of interactive robots is a promising development in light of research showing that individuals with ASD: (a) exhibit strengths in understanding the physical (object-related) world and relative weaknesses in understanding the social world (Klin, Lang, Cicchetti, & Volkmar, 2000; Klin, Lin, Gorrindo, Ramsay, & Jones, 2009), (b) are more responsive to feedback, even social feedback, when administered via technology rather than a human (Ozonoff, 1995), and (c) are more intrinsically interested in treatment when it involves electronic or robotic components (Robins, Dautenhahn, & Dubowski, 2006). Yet, most of the support to date for its use in therapy is based on anecdotal evidence, and lacks support for generalizability of skills (Ricks & Colton, 2010). Considerable attention has been given to what type of robot (humanoid vs. non-humanoid; Ricks & Colton, 2010) might be effective, but not as much emphasis has been placed on the best ways to integrate the robot into therapy sessions. There are several open questions such as *what* the best roles for robots are in therapy, *how* to best integrate robots into interventions, and *who* amongst individuals with ASD are best suited for this approach. In this review, we focus on our current knowledge for the *what* and *how* questions, with an acknowledgment that the *who* question is a much needed future research direction.

1.1 Framework for therapeutic application of robots

In the context of the current diagnostic and therapeutic approaches that are being used to address ASD symptomatology, there are several potential applications of a robot. In this review, we identify three broad categories of clinical application that either: (a) have already received research attention, (b) have been proposed as potential clinical applications in theoretical papers (e.g., Dautenhahn, 2003; Feil-Seifer & Matarić, 2009; Picard, 2010; Scassellati, 2007), and/or (c) have particular appeal given the context of an existing and commonly used diagnostic technique or established treatment technique (see Table 1 for a summary). In addition, a fourth category was added to specifically emphasize the potential clinical impact of using a robot over a human (see Table 1). Although studies in this category do not directly test a clinical intervention as the other categories do, these studies directly compare how individuals with ASD respond to robots or robot-like characteristics versus human characteristics/behaviors. Importantly, we are focusing on the broad approach of using robots, rather than any one particular target behavior (e.g., imitation, joint attention; Ricks & Colton, 2010).

1.2 Purpose of the study

The purpose of this study was to critically review the existing literature on the clinical uses of robots for individuals with ASD in the context of the application framework described above. We focused our review on articles that were published in either peer-reviewed journals or peer-reviewed, published conference proceedings that offered sufficient diagnostic information and clinical outcome data to evaluate the technique. We highlighted important methodological characteristics of therapeutic studies involving participants with ASD, such as how the individuals were identified and how the diagnoses were confirmed, the appropriateness of control conditions/groups, and sample sizes. The goals were to understand the current status of empirically-based evidence for this experimental therapeutic technique, to identify gaps in the literature, and to provide the foundation for future research in this area.

2. Methods

A literature search was conducted using the ISI Web of Knowledge (http://isiknowledge.com), PsychINFO (http://www.apa.org/pubs/databases/psycinfo/index.aspx), and IEEE Xplore (http://ieeexplore.ieee.org/Xplore/guesthome.jsp). In order to be included in our review, the article had to be in a peer-reviewed journal or a peer-reviewed published conference proceeding and had to involve data that was collected on at least one individual with an ASD. Additionally, the data had to: (a) be the direct result of a therapeutic intervention, (b) have implications for group identification or diagnosis, or (c) be an empirical study that compares type, speed, and/or frequency of interactive responses to a robot or robot-like characteristics in comparison to a human or other non-robotic object. Book chapters, theoretical articles, review articles, and conference presentations that were not published or only published abstracts were excluded from this review. All papers were published in March, 2011 or earlier. The reference sections were examined for additional peer-reviewed research articles. Finally, an additional ISI Web of Knowledge search was conducted for all articles that met our criteria in order to identify other papers that had cited these studies.

The search identified 15 peer-reviewed journal articles that matched our criteria (Table 2). Only three studies (Lund, Pederson, & Beck, 2009; Pierno, Mari, Lusher, & Castiello, 2008; Wainer, Ferrari, Dautenhahn, & Robins, 2010) contained more than six participants. There was a group of five papers (Dautenhahn & Werry, 2004; Robins, Dickerson, Stribling, & Dautenhahn, 2004; Robins, Dautenhahn, te Boekhorst, & Billard, 2005; Robins et al., 2006; Stribling, Rae, & Dickerson, 2009) that used subsets of the same study samples. Therefore, the 15 original papers were essentially based on eleven unique samples. Only two of the 15 studies were published in clinical journals (Pierno et al., 2008; Stribling et al., 2009), and none of the studies were published in an ASD journal. Neither of the two studies from clinical journals tested the robot's use in an intervention. Of the 15 studies, only four used a standardized diagnostic measure for diagnostic confirmation (Duquette et al., 2008; Pierno et al., 2008; Pioggia et al., 2005; Pioggia et al., 2008); whereas seven relied on community diagnosis or medical records, and four did not report a diagnostic confirmation.

We recognize that much of the research in the robotics field is published through conference proceedings; therefore, we included a representative sample of papers from the major IEEE and ACM outlets in our review. But, in order to be included, papers in these outlets needed to meet all of the criteria above, had to be published by a peer-reviewed conference, and had to be accessible in a published paper form. It should be noted, however, that it can be hard to ascertain the clinical significance of any empirical data included in these papers if they focus heavily on technical and developmental details of the project rather than on more clinically relevant aspects of their methodology such as participant diagnosis/characteristics, group matching, and reliable/valid outcome measures. We selected five published conference papers (Costa, Santos, Soares, Ferreira, & Moreira, 2010; De Silva, Tadano, Saito, Lambacher, & Higashi, 2009; Bird, Leighton, Press, & Heyes, 2008, Feil-Seifer & Matarić, 2011; Stanton, Kahn, Severson, Ruckert, & Gill, 2008) that met all of our criteria and that we believe are representative of this literature. Please note that some of these conference proceedings are one of a number of publications on similar data; therefore, we selected what we determined to be the most comprehensive, most recent, and/or most relevant publications in these instances.

3. Results

Studies reviewed here are grouped with regard to the framework established above: (a) the response of individuals with ASD to robots or robot-like behavior in comparison to human behavior, (b) the use of robots to elicit behaviors, (c) the use of robots to model, teach, and/or practice a skill, and (d) the use of robots to provide feedback on performance. Note that in one study (Duquette, Michaud, & Mercier, 2008), the robot had two roles in the intervention (practice and reinforcement); therefore, relevant parts of this work are included in both sections.

3.1 Response to Robots or Robot-like Characteristics

One very basic question is whether individuals with ASD prefer robots or robot-like characteristics to human characteristics or non-robotic toys/objects, and if so, what is particularly appealing about these characteristics? Answering this question will provide necessary additional support for the theoretical framework or rationale for using robots in its other roles. In the robotics literature, considerable attention has been given to the question of whether humanoid vs. non-humanoid (e.g., animal-like) robots have more appeal to individuals with ASD. Some have argued that although non-humanoid robots might have more general (or “initial”) appeal to individuals with ASD, human-like robots would have greater potential for generalizing skills (Ricks & Colton, 2010). It is important to consider these questions in the context of existing data, while considering the possibility that due to the heterogeneity of the ASD population, some individuals on the autism spectrum might not prefer robots or robot-like characteristics to humans.

Previously, it has been reported that individuals with ASD show both positive and negative responses to robots. A small single session study (Pioggia et al., 2006) compared one child with ASD to one typically developing control on their behavioral and physiological response to a robotic face. The child with ASD did not show increases in cardiac rate in response to the robotic face, suggesting that the child was not alarmed, although it was noted that the child did not look at the robot at first. In contrast, the typically developing child was reported to feel "uncomfortable" and showed an increased heart rate. A follow-up study, however, found that participants with ASD showed varying responses to the robotic face in comparison to a human interaction, with some showing an increase in social-communication, some showing no change, and one showing a decrease when interacting with the robotic face (Pioggia et al., 2008). Feil-Seifer and Matarić (2011) showed that within a group of eight children with ASD (ages 5–10), there was tremendous variability in the valence of affective response toward a mobile robot, depending on whether or not the robot’s behavior was contingent on the participant or random. They argued that these responses were consistent with previous data from their lab showing highly individualized affective responses to their humanoid robot (Feil-Seifer & Matarić, 2009)

There is evidence that *some* individuals with ASD prefer robots to non-robotic toys or humans. Dautenhahn and colleagues completed a series of studies that investigated the preferences of four 5–10 year olds with ASD with limited verbal abilities (Dautenhahn & Werry, 2004; Robins et al., 2006). Dautenhahn and Werry (2004) found individual differences in whether or not children with ASD preferred robots over non-robotic toys. Two of the four participants had more eye gazes toward and physical contact with the robot than with the comparison toy. The other two participants, however, showed the opposite pattern of behavior, with more social behaviors directed at the toy than at the robot. Using three of the four participants from this sample, Robins et al. (2006) found that these children with ASD more frequently directed behaviors indicative of interest toward a person or robot with a more robotlike appearance when a less robot-like alternative also was present. Additionally, participants showed increased social behaviors directed toward a human examiner in the room when the mime or robot looked more like a robot than a human. Although participants showed an initial preference for robot-like characteristics, differences between conditions disappeared over a 6 month period of time, suggesting limits to these preferences.

If individuals with ASD show preferences for robots, then one prediction that would follow would be that performance on tasks could improve if the same actions were modeled by a robot in comparison to a human. Two larger studies found increased imitation speed to robot models in comparison to human models (Bird et al., 2007; Pierno et al., 2008). Bird and colleagues (2007) reported a speed advantage in adults with ASD imitating robotic hand movements over human hand movements. Pierno and colleagues (2008) found that children with ASD had significantly faster movements to grasp a ball when they saw a robotic arm perform the movement first than when they viewed a human arm, whereas typically developing children showed the opposite effect. These studies suggest that individuals with ASD might benefit from tasks that involve imitating robots in comparison to imitating humans. It should be noted, however, that participants in this study were told to respond to the auditory signal and were not directly instructed to imitate. Thus, it is possible that the advantage involved implicit rather than explicit imitation, and it is unclear whether the findings are the result of cognitive factors related to imitation or an affective preference for the robot over the human.

3.1.1 Summary—

Taken together, these seven studies suggest that some (but not all) individuals with ASD prefer interactive robots compared to passive toys (Dautenhahn & Werry, 2004), initially prefer robot-like characteristics over human-like characteristics in social interactions (Robins et al., 2006), and respond faster when cued by robotic movement than human movement (Bird et al., 2007; Pierno et al., 2008). Individual affective responses to the robots were highly variable (Feil-Seifer & Matarić 2011; Pioggia et al., 2005). Although these findings are promising, there are several important factors to consider about these studies. Five of the seven studies were exploratory, and the data are inconsistent even within these small samples, which limits their interpretability. Additionally, not all individuals with ASD showed an increase in social-communication when interacting with a robotic interlocutor in comparison to a human interlocutor, and some showed a decrease (Pioggia et al., 2008). It is also important to note that these studies varied considerably in the amount of information that they provided on the characteristics of the group (diagnosis, verbal/cognitive abilities), which limits the ability to investigate patterns of ability/disability that might explain individual differences. To understand the responses (both behavioral and psychophysical) of individuals with ASD under these type of manipulations, future studies will need to include larger matched comparison groups and counterbalanced comparison conditions (similar to Pierno et al., 2008) in order to test hypotheses about these variables. Furthermore, the inconsistent responses highlight the heterogeneity of the disorder, and thus greater consideration needs to be given to predictors that might account for individual patterns of response to robot-like vs. human behavior.

3.2 Robots Used to Elicit Behavior

One potential clinical use of a robot is to elicit target behaviors from a child with ASD (Ricks & Colton, 2010; Scassellati, 2007). A working hypothesis is that because individuals with ASD seem to have an intrinsic interest in technology, robots might be particularly useful for eliciting behaviors. Target behaviors could be characteristics of ASD (e.g., repetitive behaviors) or even prosocial behaviors (e.g., joint attention). The former example could be useful for diagnostic purposes, while the latter could be useful for increasing prosocial behaviors.

3.2.1 Robots used to elicit target behaviors for diagnosis—

Theoretical works by Scassellati and colleagues (Scassellati, 2007; Tapus, Matarić, & Scassellati, 2007) outlined several potential uses of a robot for diagnosis. First, a robot could give a set of social presses designed to elicit social responses for which the presence, absence, or quality of response is diagnostic. This approach is similar to the social presses used in the Autism Diagnostic

Observation Schedule (ADOS; Lord, Rutter, DiLavore, & Risi, 1999), but would have the added advantage of being identical across all administrations, possibly increasing the instrument's reliability. For example, the robot could be programmed to take on the role of the bubble gun in the ADOS, producing bubbles in order to elicit an interaction between the child and the examiner (Feil-Seifer & Matarić, 2009). Second, the robot could provide quantitative measurements of behaviors that are diagnostic characteristics of the disorder. Through passive observation, robots could record behaviors and either directly or indirectly transduce social behaviors (e.g., tone of voice, eye gaze) into quantitative measurements (Scassellati, 2007; Tapus et al., 2007).

Data-driven research on the diagnostic utility of robots, however, is very limited. The studies to date have focused on the ability of the robot to elicit target behaviors for intervention or the ability to elicit, measure, and/or possibly classify behavior for diagnostic purposes. Stribling et al. (2009) used interactions between a robot and a child with ASD to elicit and analyze perseverative speech in one individual with ASD who was labeled as "high-functioning." Interaction samples were collected using data from a participant in previous studies (e.g., Dautenhahn & Werry, 2004; Robins, Dautenhahn, & Dubowski, 2006; others) in which the child was encouraged to interact with a robot that imitated the child's behavior. Although it was not the major focus of the study, the authors were able use the robot-child interaction to collect a sufficient number of samples of perseverative speech to conduct Conversational Analysis on the interchanges. These preliminary data suggested that robot-child interactions might be useful for eliciting characteristic behaviors such as perseverative speech, but more data from a large sample is needed before meaningful conclusions can be drawn about the clinical utility of this practice. In another study, Lund and colleagues (2009) used games involving "modular robotic tiles" to identify individual behavior response patterns in 7 children (6 with ASD). The program was accurate (88%) at identifying the individual behavioral patterns of the seven children. The study analyzed the program's ability to identify individual differences, rather than group differences, and no control groups were included, so data on sensitivity and specificity were missing.

There are programs underway to develop this line of research (see Scassellati, 2005), but the data for this purpose is limited. Whether the robot is being used to elicit a diagnostic behavior or a program within the robot is being used to measure or transduce a characteristic behavior, there are several important methodological considerations for this type of research. It will be crucial to collect appropriate diagnostic, cognitive, and language data on these individuals in order to assure that diagnostic classifications made by a program are valid. Additionally, it will be necessary to have appropriate comparison groups without ASD in order to ensure that approaches are both sensitive and specific to ASD. Finally, it will be necessary to examine the incremental benefit of using a robot over a human interaction for diagnostic purposes.

3.2.2 Robot used to elicit prosocial behaviors—Robots that are programmed to provide interesting visual displays, or respond to a child's behavior in the context of a therapeutic interaction, could encourage a desirable or prosocial behavior (Dautenhahn, 2003; Feil-Seifer & Matarić, 2009). For example, if there were another individual in the room with the child and the robot, behaviors of the robot could be used to elicit joint attention behaviors or shared enjoyment in an experience, both of which are infrequent and difficult for many individuals with ASD to exhibit. In this case, the robot either could be the object of shared attention (Dautenhahn, 2003) that could serve as a "catalyst" for social interactions with another individual (Feil-Seifer & Matarić, 2009), or it could provoke joint attention to be direct elsewhere (e.g., the robot could say, "Look, what is that?"). Through these prosocial opportunities, the child might then generalize these behaviors outside of the context involving the robot. To date, this area of research on clinical applications for robots with individuals with ASD has received the most attention. Here, we review studies that examine prosocial responses to the robot, to another person in the room, and amongst a group of peers.

Three studies examined the utility of using a robot to elicit prosocial behaviors in response to the robot. Robins et al. (2005) found some preliminary support for the use of a humanoid robot to elicit social behaviors. Investigators tracked eye gaze, touch, imitation, and proximity to the robot. Each child's behavior was analyzed individually and no group analyses were performed. No more than two of the four children showed an increase in the measured behaviors (e.g., eye gaze, imitation of robot), but each child showed an individual pattern of increased interaction with the robot in some but not all measured behaviors. François et al. (2009) integrated a mobile robotic dog into an existing non-directive intervention program for 4–11 year old children with ASD. Similar to other studies, the authors found individual differences among individuals with ASD in their engagement with the robot, the extent to which they enjoyed interacting with the robot, and their engagement with the therapist regarding the robot. There was no comparison condition without the robot and no statistics were reported, so it is difficult to determine whether there is any incremental benefit to adding the robot to the intervention. De Silva and colleagues (De Silva et al., 2009) found that five individuals with ASD were able to follow social referencing behaviors made by a robot, and the robot was able to detect with 75% accuracy the object of the child's gaze. This finding suggests that there is potential for joint attention to objects of shared interest, and the robot might be able to detect whether or not the child with ASD is displaying shared attention. However, in all three of these experiments only individual (and not group) data were provided and no comparison groups were used, so it is difficult to determine whether there were any informative group patterns of change in behavior.

Other studies have directly examined whether a robot can be used to elicit social behaviors between a child with ASD and a third interlocutor, such as an experimenter, therapist, or peer. Costa and colleagues (2010) provided qualitative observations that two participants with ASD continued to play a ball game with each other after learning it from a robot. Robins et al. (2004) also used a qualitative technique (Conversational Analysis on selected segments) to identify instances in which a performing robot could elicit joint attention and social referencing between a participant and a third interlocutor. The study used three of the four children (5–10 years old, “low-functioning”) from previously reviewed studies (Dautenhahn & Werry, 2004; Robins et al., 2006). No group analyses were performed and there were no control conditions, so it is difficult to determine whether or not there was something uniquely beneficial about using the robot to elicit those behaviors. A second study found that two of three children with ASD between the ages of 3–5 included a third interlocutor in an interaction about a remotely controlled “creature-like” robot. Data also were presented about a large number of typically developing peers, but no group comparisons were made. The authors noted, however, that the 3-year-old peers acknowledged that the robot's movements were a form of communication, while the children with ASD did not.

Feil-Seifer and Matarić (2009) suggested that the rules governing the robot’s behavior is important for promoting prosocial behaviors. Participants were two children with ASD (no diagnostic/cognitive data provided) and one typically developing peer between the ages of 1 and 12-years-old. Participants engaged in a scenario similar to Bubble Play from the ADOS, where the production of bubbles by the robot was used to elicit social interaction between an adult and a child. In one condition, the robot produced the bubbles contingent on the child pushing buttons on the robot, while in the other condition the robot produced bubbles randomly. Qualitative and quantitative observations of the participants showed that social behaviors toward the robot and the adult increased when the robot acted contingently, rather than randomly, across all children. Stanton et al. (2008) had similar findings with a larger group of 11 children with ASD; although their findings did not have a large enough sample size to reach statistical significance on all measures. Similar to other studies, these papers suggested that robots can increase prosocial behavior in individuals with ASD, but the rules governing the robot's behavior (e.g. contingency) were an important factor influencing outcomes as well.

Using a slightly different approach, Wainer et al. (2010) found that just the presence of robot-based activities can elicit social interactions, even in older high-functioning children with ASD. The study examined seven children with high-functioning ASD (no diagnostic/cognitive data provided) in an afterschool class. Participants were given Lego robot kits and worked with peers on programming the robots. Enjoyment in class and the amount of interactions inside and outside of class were measured using video analysis of behavior, semi-structured interviews with children, and child/parent questionnaires. Results suggested that children with ASD enjoyed the class, found it easy to collaborate with others in class and easy to continue interactions after class. Also, given the school-aged sample, the study shows that the benefits of robots may not be limited to younger children with ASD. However, the study had no comparison conditions to determine whether this robotics class had any additional effect over other afterschool classes. Moreover, only participants who came to 60% of the classes were examined, and it is possible that a selection bias affected the results (i.e., participants who did not enjoy the class did not come regularly).

3.2.3 Summary—These very preliminary results seem to indicate that a robot-child interaction has some potential to elicit different types of behaviors in individuals of different ages and levels of ability. Most of the literature on this topic is theoretical, however, and the amount of published data on actual robot effectiveness is limited to date. Two studies utilized the robot to elicit stereotyped/repetitive behaviors that are characteristic of ASD (Lund et al., 2009; Stribling et al., 2009), but neither provided any sort of independent diagnostic confirmation using a gold standard diagnostic tool (e.g., ADOS). Six studies examined whether or not a robot can elicit prosocial behaviors between the child and the robot or with a third (examiner/therapist/peer) interlocutor (Costa et al., 2010; De Silva et al., 2009; François et al., 2009; Kozima et al., 2007; Robins et al., 2004; Robins et al., 2005; Wainer et al., 2010), but all seven were limited by their small sample sizes and several showed significant individual variation in response to the robot. An additional pilot study highlighted the advantages of the robot's behavior being interactive and contingent on the behaviors of the child (Feil-Seifer & Matarić, 2009; Stanton et al., 2008). This is a very promising area of research, but there is a major need for studies that examine the incremental benefit of using a robot to elicit behaviors using large, carefully diagnosed participant groups. Moreover, it would be clinically useful to understand the predictors of which individuals with ASD are more likely to respond positively to an interaction with the robot.

3.3 Robots Used to Model, Teach, or Practice a Skill

A third potential application of robots is to create an environment where the robot could model specific behaviors for the child (Dautenhahn's "model social agent"; Dautenhahn, 2003) or the child could practice specific skills with the robot (where the robot is a "social crutch"; Scassellati, 2007; Tapus et al., 2007). The goal would be to teach a skill that could the child could imitate or learn and eventually transfer to interactions with humans. Unlike in the previous category, the robot in this instance would be directly active in teaching/modeling a skill with the child or directly interacting with the child to practice the skill.

Theoretically, a robot would be ideal for simplifying social behaviors to facilitate learning (Dautenhahn, 2003). Social-communication is a complex task that involves speech, gestures, facial expressions, and context (among other factors), all of which are integrated automatically into a communication act. Robots can give individuals with ASD a predictable and consistent environment with the ability to isolate social input. Dautenhahn (2003) envisioned a role of the robot as a therapeutic teaching device or “persuasive machine” in a setting that involves one child, one robot, and a therapist mediator. This approach could provide a medium in which the child could repeatedly practice a behavior (e.g., imitation) or social interchange (e.g. initiating a conversation) without the social pressures of a peer interaction. Similarly, Scassellati and colleagues discussed using robot as a “social crutch” (Scassellati, 2007; Tapus et al., 2007). In this approach, the goal would be to limit the social complexities typically experienced in therapy, so that individuals with ASD could attend to the lowest level of information and subsequently build social skills into complex behaviors from their more basic components.

We only found one preliminary study that examined ways in which a robot can be integrated into a treatment protocol. Duquette et al. (2008) examined the use of a humanoid robot to help a well-diagnosed group of four children with ASD (ages 4–5 years) practice imitation behaviors in a series of intervention sessions. In both conditions, the interaction partner performed a behavior, asked the child to imitate the behavior, and if the child was successful, provided positive reinforcement by raising arms and saying "Happy!" The authors found that participants with the robot showed significantly more interest in the interlocutor (e.g., were closer, looked at it more) than did those with the human interaction partner. Also, those with the robot engaged in fewer repetitive behaviors with their favorite toy with a robot present. However, children with the robot showed significantly fewer imitations of verbal behaviors than did those with the human partner, and fewer (although not significantly) imitations of body movements or actions than those exhibited by children with the human interaction partner.

3.3.1 Summary—We found only one study that used a robot to model, teach, or practice a skill. Duquette and colleagues (2008) observed greater interest in individuals with ASD toward a robot therapeutic partner than a human, but in most cases participants showed better verbal and nonverbal imitation performance in response to a human partner. Although this finding might seem in contrast to Pierno and colleagues (2008), who found faster motor imitation of robotic movement over human movement, it is likely that these studies were tapping into different mechanisms. Whereas Pierno and colleagues likely were looking at differences in performance when a participant was primed by robotic movement (i.e., observed a movement before being asked to complete the same task) rather than being asked to imitate the movement, Duquette and colleagues measured explicit imitation, so it is difficult to make direct comparisons between the two studies. Studies in this area would benefit from integrating robots into established, empirically-supported treatments such as Applied Behavior Analysis (ABA) in order to examine whether there are specific benefits beyond general therapeutic change to including such an agent in therapy. A recent case study (Tang et al., 2011; Villano et al., 2011) suggests that this approach might have clinical utility, but this area of research is clearly in its infancy.

3.4 Robots Provide Feedback or Encouragement

A robot also could provide feedback (reinforcement, redirection, etc.) during a skill learning intervention such as ABA. For example, a child may be receiving food as a reward contingent upon learning a skill or performing a desirable behavior. A goal could be for the child to transition from food related rewards to social reinforcement provided by the therapist. The provision of performance feedback from a robot might facilitate the transition from food-related rewards to therapist social feedback. The use of a robot rather than a human to teach skills here fits with object-oriented preferences of individuals with ASD (Klin, Jones, Schultz, Volkmar, & Cohen, 2002). Unlike traditional computers, robots are physical devices with human-like characteristics, and they can be made to mimic human sounds and behaviors interactively. First, by capturing attention as a physical object and then transferring that attention to their own human-like qualities, interactive robots could hasten the child's progression from receiving object-related feedback (food, toys) to the more desirable human social feedback by bridging the gap between the physical and social world for individuals who tend to prefer the former.

Through feedback or encouragement, the robot could also take on the role of a social mediator/facilitator in social exchanges between a child with ASD and a partner (e.g., Dautenhahn's "social mediator," Dautenhahn, 2003). In this approach, the robot would encourage a child with ASD to interact with an interlocutor who is present in the therapeutic setting. Although Dautenhahn originally conceived this approach as involving two children (with the robot encouraging one or both children), such a scenario could just as easily involve one child and one therapist, where the therapist takes the role of an interlocutor and the robot provides instruction/support for the child during the interaction. The robot would assume the role of a therapist and/or cheerleader, encouraging the child to proceed with the interaction, or providing prompts for the appropriate behavior in the situation that could be withdrawn over time.

One important component of Duquette et al. (2008), described in detail in the previous section, was that if the child was successful at imitating a behavior, the robot or human interaction partner provided positive reinforcement by raising arms and saying “Happy!” in addition to practicing the skill with the child. Thus, while it is possible that group differences (more interest in robot than human, better imitation of human than robot) in this study were the result of general factors related to the robot, it is also plausible that these differences emerged from the use of the robot to practice the skill and/or specifically from the fact that the robot was providing positive reinforcement. This preliminary study did not separate the individual effects on outcomes of either of these robot roles. It is also plausible that the robot could respond to internal stimuli from the child, such as when biofeedback is used as an indicator of the affective state or level of arousal of the child, to increase the individualized nature of treatment (Picard, 2010). This type of “affect aware” response capability could be useful for providing the child with feedback regarding his/her own emotional state, or to trigger an automatic redirection response when the child becomes disinterested (Liu, Conn, Sarkar, & Stone, 2008b). The robot also could regulate its behavior to make the interaction optimally challenging for the child.

Liu et al. (2008a) studied whether an affect recognition system could provide feedback to a robotic game in order to tailor the responses of the robot to the preferences of six high-functioning children with ASD (ages 13–16) based on the child’s affective responses. Preliminary results indicated that simple affective states can be measured with affect recognition programs and can be used influence robot behavior. The children participated in a robotic basketball game with two conditions: 1) the robot adjusted the difficulty of the game based on the child’s preference as indicated by psychophysiological measures and affective models for that child, or 2) the difficulty of the game was randomly adjusted without reference to the affective models. The study found that the robotic game was correctly adjusted 80–85% of the time based on the participants’ affective preferences. Thus, it is possible that robotic therapists could be integrated with affect recognition programs to provide redirection for the child if they become disinterested, or to provide encouragement for discouraged children.

3.4.1 Summary—We only found one study (Duquette et al., 2008) in which the robot provided positive feedback on participants' performance. Moreover, despite the predominance of reinforcement-based therapies in the treatment of ASD along with the extent of empirical support this approach has received, we did not find any studies exploring the integration of a robot into this type of therapy using the robot to provide reinforcement,. There are two case studies using this approach (Tang et al., 2011; Villano et al., 2011), but it is clear that much more work is needed using this approach given the positive effects of technological feedback on the performance of other tasks (Ozonoff, 1995). We identified one study (Liu, Conn, Sarkar, & Stone, 2008a) that examined the use of affect recognition based on psychophysiological responses to modify the behaviors of a robotic game. It should be noted that the robot behavior in Feil-Seifer and Matarić (2009; 2011) was contingent upon the actions of the child with ASD, but the robot behaviors were antecedents to the target social behaviors, rather than providing reinforcement/feedback for the social behaviors. Thus, currently, there is little information on the utility of robot feedback (automatic or not) in interventions for individuals with ASD.

4. Discussion

The use of interactive robots in therapy for individuals with ASD is a unique approach that has received considerable media attention recently. This paper reviewed the current state of literature related to the clinical applications of robots with this population. This area of research is in its infancy, with virtually all of the peer-reviewed studies on the topic being preliminary or exploratory. Much of this work is pioneering, with innovative ideas for how a robot can be integrated into clinical use. Yet, at this early stage, there is very little empirical testing on the clinical efficacy of robots for individuals with ASD beyond the possibility that these individuals may have a preference in some circumstances for this type of technology over humans. There are multiple potential uses for robots in clinical settings, especially for robots that have a level of interactive capability. We have integrated and expanded the approaches described in theoretical papers (Dautenhahn, 2003; Feil-Seifer & Matarić, 2009; Picard, 2010; Ricks & Colton, 2010; Scassellati, 2007) in order to provide a broader framework for understanding the current research literature. Because this is a relatively new area of exploration, it was important to classify different approaches in order to encourage systematic follow-ups to these preliminary studies.

We identified 15 peer-reviewed research articles for which a clinical application of a robot with individuals with ASD was examined. Of those, several shared samples, and a closer analysis revealed that there were eleven unique samples in those 15 papers. We found that most of the studies examined individual responses only (much like case studies) rather than examining both individual and group effects. Only six studies provided statistical analysis, five of which gave statistically significant results. The majority of the studies were published in robotics journals, while only two of the peer-reviewed articles were published in clinical journals and none had been published in ASD-related journals. There was a slightly larger body of non-journal published work on robots and ASD, but the focus of much of this work is on robot development and robot methodology rather than clinical effectiveness/efficacy and did not provide sufficient details for analysis. Still, we identified several reports published in peer-reviewed conference proceedings that were useful in constructing this review.

Most of the studies reviewed here had similar methodological limitations. Due to their preliminary nature, sample sizes ranged from 1–32 participants with only six studies (including conference proceedings) having more than six participants with ASD. Many of the studies relied on community diagnoses and lacked an independent diagnostic confirmation using gold-standard techniques such as the ADOS, the Autism Diagnostic

Interview-Revised (ADI-R; Rutter, Le Couteur, & Lord, 1993), or a screening questionnaire. Only two of the studies (Feil-Seifer & Matarić, 2009; François et al., 2009) attempted to integrate the robot into an established treatment paradigm, although Duquette and colleagues (2008) used a technique that was quite similar to some of the available behavioral techniques. Few studies made statistical comparisons between groups or between conditions, and none tested the independent contribution of the robot to the clinical application. Also, even with the longitudinal design of some of the studies, the experiments did not necessarily show ability to generalize skills over time, place, or context.

We organized the present studies into three broad categories based on the clinical application of the robot to: (a) elicit behaviors, (b) model, teach, and/or practice a skill, (c) or provide feedback. Over the course of our review, we encountered several studies that examined the responses of individuals with ASD to robots in comparison to other human or toy characteristics. Preliminary findings showed that many (but not all) individuals with ASD showed a preference for robot-like characteristics over non-robotic toys and humans (Dautenhahn & Werry, 2004; Robins et al., 2006), and even responded faster when cued by robotic movement than human movement (Bird et al., 2007; Pierno et al., 2008). The majority of the literature regarding the use of a robot to elicit behavior was theoretical or preliminary, and the amount of published data on its effectiveness was limited mostly to small pilot studies. Still, some studies showed promising preliminary data that a robot could elicit stereotyped/repetitive behaviors (Lund et al., 2009; Stribling et al., 2009) or even prosocial behaviors such as joint attention, triadic interactions, or cooperation with peers (Feil-Seifer & Matarić, 2009; François et al., 2009; Robins et al., 2004; Robins et al., 2005; Wainer et al., 2010). Two studies examined the integration of a robot into a therapeutic protocol, and these studies highlighted individual differences both in participant reactions (Feil-Seifer & Matarić, 2011) and in therapeutic outcomes (François et al., 2009). In another study, improvement on a skill was greater when positive reinforcement was from a human partner than from a robot, despite a greater interest among participants in the robot (Duquette et al., 2008). Finally, we found research testing the powerful potential of integrating robots and affect recognition technology to develop truly "affect-aware" interactive robots that might adjust their behavior based on psychophysiological feedback from the child (Liu, Conn, Sarkar, & Stone, 2008b).

4.1 Future Directions

There are several important future directions that we have highlighted within each category in our results section. More generally, however, we think that there are several broader methodological considerations for future studies that will help with the interpretability of findings and the applicability of these studies to clinical settings. An important future direction for all studies in this area, but particularly for those experiments attempting to use robots for diagnostic purposes, is the detailed characterization of participants. Studies need to conduct independent diagnostic confirmation using established diagnostic techniques to account for natural variation in community diagnoses. Given the heterogeneous nature of the ASD diagnoses, groups should receive cognitive and language evaluations to determine areas of strengths and weaknesses and to appropriately match across groups and conditions. Studies that specifically target the use of robots to classify and diagnose individuals must correctly identify as many individuals with ASD as possible (sensitivity), but must also distinguish behaviors in this population from those in other populations (specificity).

The preliminary nature of these pioneering studies on the use of robots in a clinical context highlights the important need for rigorous empirical studies that examine the incremental validity of this approach over other available techniques, as well as the generalizability of skills learned with a robot in relation to those learned from human interaction. Many of the published studies highlighted the ability of a robot to participate in clinical settings but few specifically showed that the addition of the robot to a therapeutic program had better outcomes than the exact same program without the robot or with other visually stimulating options such as animated video robots or non-robotic characters. Moreover, if individuals successfully learn social skills while interacting with robots, a crucial next step is to examine the extent to which the use of these skills increases during subsequent interactions with humans as well. One way to systematically examine these issues is to integrate the robot into an empirically-supported treatment for ASD (Liu, Conn, Sarkar, & Stone, 2008a), such as ABA, so that progress and outcomes can be viewed in the context of a larger literature.

Future research should focus not only on the *what* (what kind of robot) and the *how* (best clinical uses), but also the *who* question noted earlier. More specifically, researchers need to determine who among these individuals respond best to this approach, and which characteristics of this subset of individuals make the treatment more appropriate for them. Currently, we do not know whether or not variables such as the level of cognitive and linguistic functioning, degree of social impairment, prominence of stereotyped and repetitive behaviors, sensory issues, or other important factors contribute to therapeutic outcomes. Several studies (e.g., Dautenhahn & Werry, 2004; Feil-Seifer & Matarić, 2009; Francois et al., 2009) underscore considerable individual differences in how individuals with ASD respond to robots. With the heterogeneity of the sample and outcomes, it is important to analyze group change and predictors of individual differences in order to understand the broader utility of the approach as well as how it can be tailored to individuals in therapy.

Although the design of the robot has received considerable attention, the therapeutic protocol has received very little scrutiny. In some instances, there are as many as two to four individuals in the room with the participant and the robot, with one of these individuals controlling the response of the robot. This setup is neither feasible nor economical for clinical application. Ideally, technology and software should be adapted so that the robot is controlled by the therapist, whether the therapist is inside or outside the room. Future studies will need to examine the relative importance of having a robot that is an active and interactive participant in the therapy, versus purely reactive to the responses of the child. The presence of an interactive robot along with a therapist also should be examined in light of what is known about other therapeutic arrangements in which two therapists (e.g., a therapist and a peer or parent) are co-present during treatment (see Rao, Beidel, & Murray, 2008, for a review).

Additionally, studies must not focus purely on behaviors, but also on cognitive processes as well. Very little research has been done on what specific cognitive mechanisms might be targeted or affected by robot vs. human interactions. A growing body of literature suggests that different mechanisms are used by individuals with ASD in response to objects versus biological motion (e.g., Klin et al., 2002; Klin & Jones, 2006; Klin et al., 2009), and emerging literature (e.g., Duffy, 2003; Powers & Kiesler, 2006; Powers, Kiesler, Fussell, & Torrey, 2007) examines how humans think about and classify different types of artificial entities, like robots or avatars. It will be especially important in clinical applications of robots to fully understand what specific aspects of technology-augmented therapies are critical to whatever effectiveness they promote. Moreover, it will be important from a more basic research standpoint to determine if the various ways in which individuals with ASD differ from typically developing peers in terms of human social interactions (e.g., face processing, Schultz, 2005; South & Diehl, 2010; emotional reactivity, Schoen, Miller, Brett-Green, & Hepburn, 2008; prosody, Diehl & Paul, in press) also are present in their interactions with non-human (robot-like or avatar) entities. Furthermore, if individuals with ASD fundamentally think about, interact with, and respond to robots differently than humans, it will be necessary to determine how this may effect the generalization of skills. We believe that this work, in combination with work on clinical effectiveness and efficacy, will be mutually informative. Undoubtedly, the integration of these two lines of research will be crucial for advancing the field.

4.2 Conclusions

There are many potential advantages to using interactive robots in clinical settings with individuals with ASD. These advantages include the intrinsic appeal of technology to individuals on the spectrum, robots' ability to produce simple and isolated social behaviors repetitively, and the fact that they can be readily be programmed and adapted so that each child gets individualized treatment. Despite these promising possibilities, research in this area is in its infancy, and further research is needed to determine the incremental validity of this approach. It will be important to publish some of this research in ASD journals in order to have the work evaluated with experts who have clinical expertise in this field.

Research Highlights

- Reviewed current literature on clinical application of robots with individuals with ASD
- Most studies focus on technology development, rather than clinical application
- The majority of studies are exploratory and have methodological limitations
- Research is needed to determine incremental validity of the approach

Acknowledgments

This paper was supported in part by NIH Indiana Clinical Translational Sciences Institutes (NIH RR025761) Notre Dame Project Development Team grant, and the Rodney F. Ganey, Ph.D., Collaborative Community-Based Research Grant (Co-PIs: J. Diehl, C. Crowell, M. Villano, K. Wier), and the Boler Family Foundation. These funding sources had no role in the study design, data collection/analysis, or in the writing of this report. We would like to thank Kristin Weir and Piper Nuñez for their feedback on this manuscript, and the children with ASD and their families who make this work possible.

References

Bird G, Leighton J, Press C, Heyes C. Intact automatic imitation of human and robot actions in autism spectrum disorders. Proceedings: Biological Sciences. 2007; 274:3027–3031.

Costa, S.; Santos, C.; Soares, F.; Ferreira, M.; Moreira, F. Promoting interaction amongst autistic adolescents using robots; 32nd Annual International Conference of the IEEE/EMBS; Buenos Aires, Argentina. 2010. p. 3856-3859.

Dautenhahn K. Roles and functions of robots in human society: Implications from research in autism therapy. Robotica. 2003; 21:443–452.

Dautenhahn K, Werry I. Towards interactive robots in autism therapy: Background motivation, and challenges. Pragmatics & Cognition. 2004; 12:1–35.

De Silva, PRS.; Tadano, K.; Saito, A.; Lambacher, SG.; Higashi, M. Therapeutic-assisted robot for children with autism; IEEE/RSJ International Conference on Intelligent Robots and Systems; New York, NY: ACM Press; 2009. p. 3561-3567.

Diehl JJ, Paul R. Acoustic differences in the imitation of prosodic patterns in children with autism spectrum disorders. Research in Autism Spectrum Disorders. (in press).

Duffy BR. Anthropomorphism and the social robot. Robotics and Autonomous Systems. 2003; 42:177–190.

Duquette A, Michaud F, Mercier H. Exploring the use of a mobile robot as an imitation agent with children with low-functioning autism. Autonomous Robots. 2008; 24:147–157.

Feil-Seifer D, Matarić MJ. Toward socially assistive robotics for augmenting interventions for children with autism spectrum disorders. Experimental Robotics. 2009; 54:201–210.

Feil-Seifer, D.; Matarić, MJ. Automated detection and classification of positive vs. negative robot interactions with children with autism using distance-based features; Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction; New York, NY: ACM Press; 2011. p. 323-330.

François D, Powell S, Dautenhahn K. A long-term study of children with autism playing with a robotic pet: Taking inspirations from non-directive play therapy to encourage children's proactivity and initiative-taking. Interaction Studies. 2009; 10:324–373.

Klin A, Jones W. Attributing social and physical meaning to ambiguous visual displays in individuals with higher-functioning autism spectrum disorders. Brain and Cognition. 2006; 61:40–53. [PubMed: 16497422]

Klin A, Jones W, Schultz R, Volkmar F, Cohen D. Visual fixation patterns during viewing of naturalistic social situations as predictors of social competence in individuals with autism. Archives of General Psychiatry. 2002; 59:809–816. [PubMed: 12215080]

Klin A, Lang J, Cicchetti DV, Volkmar FR. Brief report: Interrater reliability of clinical diagnosis and DSM-IV criteria for autistic disorder: Results of DSM-IV autism field trial. Journal of Autism and Developmental Disorders. 2000; 30:163–167. [PubMed: 10832781]

Klin A, Lin DJ, Gorrindo P, Ramsay G, Jones W. Two-year-olds with autism orient to non-social contingencies rather than biological motion. Nature. 2009; 459:257–261. [PubMed: 19329996]

Kozima H, Nakagawa C, Yasuda Y. Children-robot interaction: A pilot study in autism therapy. Progress in Brain Research. 2007; 164:385–400. [PubMed: 17920443]

Liu C, Conn K, Sarkar N, Stone W. Online affect detection and robot behavior adaptation for intervention of children with autism. IEEE Transactions on Robotics. 2008a; 24:883–896.

Liu C, Conn K, Sarkar N, Stone W. Physiology-based affect recognition for computer-assisted intervention of children with autism spectrum disorder. International Journal of Human-Computer Studies. 2008b; 66:662–677.

Lord, C.; Rutter, M.; DiLavore, PC.; Risi, S. Autism diagnostic observation schedule. Los Angeles: Western Psychological Services; 1999.

Lund HH, Pederson MD, Beck R. Modular robotic tiles: Experiments for children with autism. Artificial Life and Robotics. 2009; 13:393–400.

Ozonoff S. Reliability and validity of the Wisconsin Card Sorting Test in studies of autism. Neuropsychology. 1995; 9:491–500.

Picard RW. Emotion research by the people, for the people. Emotion Review. 2010; 2:250–254.

Pierno AC, Mari M, Lusher D, Castiello U. Robotic movement elicits visuomotor priming in children with autism. Neuropsychologia. 2008; 46:448–454. [PubMed: 17920641]

Pioggia G, Igliozzi R, Sica ML, Ferro M, Muratori F, Ahluwalia A, De Rossi D. Exploring emotional and imitational android-based interactions in autistic spectrum disorders. Journal of CyberTherapy and Rehabilitation. 2008; 1:49–62.

Pioggia G, Izliossi R, Ferro M, Hluwalia A, Muratori F, De Rossi D. An android for enhancing social skills and emotion recognition in people with autism. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2005; 13:507–515. [PubMed: 16425833]

Powers, A.; Kiesler, S. The advisor robot: Tracing people's mental model from a robot's physical attributes; Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction; New York, NY: ACM Press; 2006. p. 218-225.

Powers, A.; Kiesler, S.; Fussell, S.; Torrey, C. Comparing a computer agent with a humanoid robot; Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction; New York, NY: ACM Press; 2007. p. 145-152.

Rao PA, Beidel DC, Murray MJ. Social skills interventions for children with Asperger's syndrome or high-functioning autism: A review and recommendations. Journal of Autism and Developmental Disorders. 2008; 38:353–361. [PubMed: 17641962]

Ricks, DJ.; Colton, MB. Trends and considerations in robot-assisted autism therapy; 2010 IEEE International Conference on Robotics and Automation (IRCA); 2010. p. 4354-4359.

Robins B, Dautenhahn K, Dubowski J. Does appearance matter in the interaction of children with autism with a humanoid robot? Interaction Studies. 2006; 7:509–512.

Robins B, Dautenhahn K, te Boekhorst R, Billard A. Robotic assistants in therapy and education of children with autism: Can a small humanoid robot encourage social interaction skills? Universal Access in the Information Society. 2005; 4:115–120.

Robins B, Dickerson P, Stribling P, Dautenhahn K. Robot-mediated joint attention in children with autism: A case study in robot-human interaction. Interaction Studies. 2004; 5:161–198.

Rutter, M.; Le Couteur, A.; Lord, C. Autism diagnostic interview-revised. Los Angeles: Western Psychological Services; 2003.

Scassellati, B. IEEE International Workshop on Robots and Human Interactive Communication (ROMAN). Nashville, TN: ACM; 2005. Quantitative metrics of social response for autism diagnosis; p. 585-590.

Scassellati B. How social robots will help us diagnose, treat, and understand autism. Robotics Research. 2007; 28:552–563.

Schoen SA, Miller LJ, Brett-Green B, Hepburn SL. Psychophysiology of children with autism spectrum disorder. Research in Autism Spectrum Disorders. 2008; 2:417–429.

Schopler E, Reichler RJ, De Vellis RF, Daly K. Toward objective classification of childhood autism: Childhood Autism Rating Scale (CARS). Journal of Autism and Developmental Disorders. 1980; 10:91–103. [PubMed: 6927682]

Schultz RT. Developmental deficits in social perception in autism: The role of the amygdala and fusiform face area. International Journal of Developmental Neuroscience. 2005; 23:125–141. [PubMed: 15749240]

South, M.; Diehl, JJ. Neurobiology: FMRI. In: Hollander, E.; Kolevzon, A.; Coyle, J., editors. Textbook of autism spectrum disorders. Arlington, VA: American Psychiatric Publishing; 2010. p. 485-496.

Stanton, CM.; Kahn, PH., Jr; Severson, RL.; Ruckert, JH.; Gill, BT. Robotic animals might aid in the social development of children with autism; Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction; New York, NY: ACM Press; 2008. p. 271-278.

Stribling P, Rae J, Dickerson P. Using conversation analysis to explore the recurrence of a topic in the talk of a boy with autism spectrum disorder. Clinical Linguistics and Phonetics. 2009; 23:555–582. [PubMed: 19669991]

Tang, K.; Diehl, JJ.; Villano, M.; Wier, K.; Thomas, B.; Shea, N.; DuBois, Z.; Millea, M.; Uhland, K.; Crowell, CR. Enhancing empirically-supported treatments for autism spectrum disorders: A case study using an interactive robot; Presented at the International Meeting For Autism Research; San Diego, CA: 2011.

Tapus A, Matarić M, Scassellati B. The grand challenges in socially assistive robotics. IEEE Robotics and Automation Magazine. 2007; 4:35–42.

Villano, M.; Crowell, CR.; Wier, K.; Tang, K.; Thomas, B.; Shea, N.; Schmitt, LM.; Diehl, JJ. DOMER: A wizard of oz interface for using interactive robots to scaffold social skills for children with autism spectrum disorders; Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction; New York, NY: ACM Press; 2011. p. 279-280.

Wainer J, Ferrari E, Dautenhahn K, Robins B. The effectiveness of using a robotics class to foster collaboration among groups of children with autism in an exploratory study. Personal Ubiquitous Computing. 2010; 14:445–455.

Table 1

Categories for clinical applications of interactive robots.

Category	**Description**	**Examples of Potential Applications**
Responses to robots or robot-like characteristics	Compares type, speed, and/or frequency of interactive responses to a robot or an interlocutor with robot-like characteristics in comparison to a human or non-robotic toy.	Studies do not have direct clinical applications, but provide insight on how children with ASD might respond differently to robots or robot-like characteristics
Eliciting behavior	Robot performs an action or interacts with the child for the purpose of inducing a target behavior	To obtain characteristic behaviors as part of a diagnostic evaluation; To promote prosocial behaviors (e.g., joint attention) with an interactive human partner
Modeling, teaching, or practicing skills	Robot serves as a tool for learning an practicing a target behavior or skill	Robot models a behavior for the child to imitate; Robot engages in scripted interaction with the child to practice a skill (e.g., initiating a conversation)
Providing feedback or encouragement	Robot is the purveyor of behavioral contingencies or social support during an activity	Robot gives positive reinforcement when child correctly executes a target skill; Robot provides encouragement and necessary prompts to encourage communication with another interactive partner

Table 2

Methodological characteristics and findings from articles.

Authors, Date	Participants			Matching	Method	Results
	No.	Diagnosis	Age			
Studies that test preference for robot-like characteristics						
Bird, Leighton, Press, & Heyes, 2008	32	16 with Autism Spectrum Disorder, confirmed by ADOS	Adults, mean age in 30's	16 typical peers matched on age, gender, and IQ	Compared speed of imitative response to robotic and human hand movements	Group with ASD responded faster to robotic hands, comparison group showed opposite pattern
Dautenhahn & Werry, 2004	4	Description suggests children with ASD had limited verbal abilities	5–10	No control group, did not match across conditions.	Compared participants' responses to a purely reactive mobile and a non-robotic passive toy	Two of the four participants directed a greater number of behaviors that indicated interest at the robot
Feil-Seifer & Matarić, 2011	8	Previously diagnosed using ADOS/ADI, minimum level of verbal abilities	5–10	No control group	Measured positive and negative responses to robot that reacted contingent upon behavior, or randomly	High level of individual differences in response to the robot, regardless of the condition
Pierno, Mari, Lusher, & Castiello, 2008	24	12 with high- functioning ASD, 12 typically developing controls	10–13	Gender and chronologic al age	Participants viewed either a human or a robot arm grab a ball, then heard an auditory cue for them to grab another ball	ASD group faster reach for ball after robot model than human model, controls had opposite effect.
Pioggia, Igliozzi, Ferro, Ahluwalia, Muratori, & Rossi, 2005	2	1 child with high-functioning ASD, 1 typically developing child	7–8	Chronologi cal age	Participants view robotic facial display, attempt to identify an one expressed emotion, cardiac frequencies measured	Child with ASD did not initially acknowledge robot, but guessed emotion correctly, showed no elevation in cardiac response to robot
Pioggia, Igliozzi, Sica, Ferro, Ahluwalia, Muratori, & Rossi, 2008	4	Individuals with autism, wide range of functioning (IQ - 52 - 105)	8–20	None	All participants were scored on Childhood Autism Rating Scale (Schopler, Reichler, De Vellis, & Daly, 1980) while interacting with the robotic facial display, and when interacting with a human	Individual differences in CARS scores in response to the robot when compared to human interactions
Robins, Dautenhahn, & Dubowski, 2006	4	Description suggests children with ASD had limited	5–10	No control group; each child participated in all four conditions	Compared responses to mime dressed as a robot vs. traditional human clothing, and prototypical robot with or without human dress	All participants directed a greater number of behaviors that indicated interest at the object that had more robot-like characteristics
Studies that use robot to elicit behaviors						
Costa, Santos, Soares, Ferreira, & Moreira, 2010	2	2 adolescent s with autism, no additional informatio n given	N/ A	None	The two participants engaged individually with robot in a simple ball passing game, with each other, and also together with the robot	Data only on one participant, who showed increase in interaction with robot over time. Qualitative description of an increase in interaction between two participants when together.
De Silva, Tadano, Saito, Lambacher, & Higashi, 2009	5	Described only as children with ASD	10–11	none	Robot referenced object in the room, and attempted to detect participant's gaze	Children spent majority of time interacting with robot, followed robot's social referencing, robot correctly

Authors, Date	Participants			Matching	Method	Results
	No.	Diagnosis	Age			
						identified object of child's gaze 75% of the time
Feil-Seifer & Matarić, 2009	3	Children with ASD, no additional information	1–12	One typically developing peer	Engaged with robot whose responses were either contingent on their behavior, or random	Robot with contingent responses elicited increased interactions with robot, and with others
François, Powell, & Dautenhahn, 2009	6	Previous diagnosis of ASD, wide range of abilities per author description	4–11	No control group, did not match across conditions.	Engaged in non- directive intervention with therapist, room included a robotic dog that responded to touch	Each case examined individually, authors argue that each child showed individual patterns of conceptual and play development, no statistics provided
Kozima, Nakagawa, & Yasuda	3	Described as children with ASD with mild to moderate intellectual disability	2–5	25 typical infants and toddlers, 27 3-year-old typical peers, but made few comparisons	Free play daycare setting where robot could move gaze toward interlocutor, and made simple movements and sounds to express excitement	Observational data on three case studies suggest children with ASD showed interest in robot, and two of the three children engaged a third interlocutor in the interaction
Lund, Pederson, & Beck, 2009	7	6 children with a previous ASD diagnosis, 1 child with developmen tal disability	Not given	No control group, did not match across conditions.	Used participants' responses in a game using modular robotic tiles to identify each individual child using a neural network model	Neural network model correctly identified individual behavioral patterns of the children with 88% accuracy
Robins, Dautenhahn, te Boekhorst, & Billard, 2005	4	Description suggests children with ASD had limited verbal abilities	5–10	No control group, did not match across conditions.	Same methodology as Robins et al. (2004), except additional trials during which robot imitated behavior of participants	No group analyses, but authors argue that each participant showed an individual pattern of increased interaction with the robot and a human.
Robins, Dickerson, Stribling, & Dautenhahn, 2004	3	Author description suggests children with ASD had limited verbal abilities	5–10	No control group, did not match across conditions.	Longitudinal study examining participants' responses to dancing robot that performed nursery rhymes; Examined behaviors directed at robot and another human	No significant results indicated. Possible trend of increased imitation in final two weeks of study. Considerable individual differences observed in all behaviors.
Stanton, Kahn Jr., Severson, Ruckert, & Gill, 2008	1 1	Diagnosed with autism with "some" verbal ability	5–8	No control group, did not match across conditions	Measure participants responses to robotic dog versus mechanical toy dog	Children with ASD preferred robotic dog, spoke more with dog, and engaged more with a third (peer) interlocutor
Stribling, Rae, & Dickerson, 2009	1	Described as high- functioning ASD	Not given	Only one participant	Used conversational analysis to examine stereotyped/repetitiv e speech elicited by robot	Authors were able to use robot to elicit stereotyped/repetitive speech (not the primary goal of study)
Wainer, Ferrari, Dautenhahn, & Robins, 2010	7	High- functioning ASD per author description	8–14	No control group or condition	Participants engaged in a robotics class, programmed robots, worked with peers who also had an ASD	Children showed enjoyment in class, collaborations with peers in the class, and continued interactions after class ended
Studies that use robot to model, teach, or practice a skill						
Duquette, Michaud, & Mercier, 2008	4	2 nonverbal participants with ASD 2 preverbal participants with ASD	4–5	Pairwise matching across conditions based on verbal abilities	Practiced imitation with a robot or human therapist across several domains, including facial expressions, and gestures	Participants showed a greater interest in robot, but showed more imitation improvement on several variables with human therapist

Authors, Date	Participants			Matching	Method	Results
	No.	Diagnosis	Age			
Studies that use robot provide feedback or encouragement						
Duquette, Michaud, & Mercier, 2008	4	2 nonverbal participants with ASD, 2 preverbal participants with ASD	4–5	Pairwise matching across conditions based on verbal abilities	Same study as above, but it is noted in this category that robot or human gave positive reinforcement for correct responses.	Participants showed a greater interest in robot, but showed more imitation improvement on several variables with human therapist
Liu, Conn, Sarkar, & Stone, 2008a	6	High- functioning ASD determined by review of medical records	13– 16	No control group, participants engaged in all conditions.	Played robotic game, difficulty varied based on child's affect as determined by psychophysical measurements	Affective model had 80– 85% accuracy at predicting participants' affective state