Robots for Use in Autism Research

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Abstract

Autism spectrum disorders are a group of lifelong disabilities that affect people's ability to communicate and to understand social cues. Research into applying robots as therapy tools has shown that robots seem to improve engagement and elicit novel social behaviors from people (particularly children and teenagers) with autism. Robot therapy for autism has been explored as one of the first application domains in the field of socially assistive robotics (SAR), which aims to develop robots that assist people with special needs through social interactions. In this review, we discuss the past decade's work in SAR systems designed for autism therapy by analyzing robot design decisions, human-robot interactions, and system evaluations. We conclude by discussing challenges and future trends for this young but rapidly developing research area.

Contents

1. INTRODUCTION

Social interactions are pervasive in the daily lives of most people, but some people struggle with them owing to lifelong developmental disabilities such as autism spectrum disorder (ASD). The family of disorders commonly known as autism manifests largely as social deficits: difficulties recognizing body language, making eye contact, and understanding other people's emotions are among the most common symptoms. This disorder affects as many as 1 in 88 children in the United States and has no cure (1), and the spectrum ranges in severity from very mild to severe. Early intervention and personalized treatment help individuals with autism function in daily life.

One area with potential for aiding the diagnosis and treatment of autism that has gained momentum in the past decade is robotics. Whereas robots have been used in rehabilitation and therapy for physical deficits such as stroke and partial limb paralysis (2), individuals with autism rarely require this type of physical assistance. A more recent trend in robotics focuses on designing and implementing robots that provide assistance to human users through social, rather than physical, interaction. This new research field is termed socially assistive robotics, or SAR (3, 4). Autism therapy is one of the first explored application domains for SAR.

Researchers investigating robots as autism therapy tools often report increased engagement, increased levels of attention, and novel social behaviors such as joint attention and spontaneous imitation when robots are part of the interaction (5–7). Some of these behaviors observed during interactions involving children with autism and robots can be attributed to the fact that robots provide novel sensory stimuli, but some—such as turn-taking with another child, manifestations of empathy, or initiation of physical contact with the experimenter—suggest that robots occupy a special niche between inanimate toys (which do not elicit novel social behaviors) and animate social beings (which can be a source of confusion and distress to children with autism). The goal of researchers investigating SAR for autism treatment is to develop robots that elicit these positive and productive interactions.

Despite productive collaborations between several robotics and clinical groups, many of which are described below, robotics research (which typically falls under computer science or engineering) and clinical psychology are significantly different fields, each with its own research methods and publication standards. For instance, high-quality results in robotics typically appear in shorter-length papers (6 to 12 pages) in proceedings of annual conferences, many of which are peer-reviewed, highly competitive venues, whereas results from clinical psychology studies typically appear in longer manuscripts (10 to 30 pages) in monthly or quarterly journals that are peer reviewed and also highly competitive. These fields also have different experimental standards. User testing in robotics often focuses on careful qualitative and quantitative observations of small numbers of study participants; it is not uncommon to perform a second-by-second analysis of behavior for only three or four participants in a given study. Clinical psychologists tend to focus more on large-scale experiments with strong statistical analysis of large groups of participants, often over several months or years. Such differences often hinder communication between these fields, and, although many attempts have been made to address these differences, no standardized solution has arisen.

This review aims to illuminate the current state of the art in SAR for autism treatment and, in doing so, to make the results accessible to a wide audience. The field contains many studies with different methods and goals, but the projects can generally be divided into three connected but discrete phases: physical robot design, human-robot interaction design, and evaluations of robots in therapy-like settings. Robot design involves creating a physical robot and addresses many questions about its appearance and functionality: How anthropomorphic should the robot appear? What size should it be? Should it be covered in artificial skin, or will robotic components be visible? What range of motion should it have, and which body parts are articulated? Should it be mobile, or fixed to a stand or table? Human-robot interaction design involves the design of the robot's behavior when it interacts with a person: How will the robot encourage prosocial behaviors such as joint attention, turn-taking, and imitation? Will the robot be a tool for the therapist, or is it intended to operate without guidance? Will the robot be tele-operated, or will it operate autonomously? Will the robot adapt its behaviors during the interaction to account for an individual's preferences and mood? Will the robot learn from interactions, or are behaviors prespecified? Finally, evaluations are the test of a robot's physical and interaction designs; they span the spectrum from single-user case studies to multiperson trials and from one-time interactions to multiyear longitudinal studies, using evaluation metrics that range from qualitative behavioral analyses to quantitative measures such as time spent performing prosocial actions.

Clearly, the range of design choices for any SAR system for autism is large, and the studies described below span these issues without reaching a consensus on a single optimal design. This review condenses the field of robotics for autism into a coherent narrative by focusing separately on the three major categories described above (physical robot design, human-robot interaction design, and evaluation). Within each category, we describe the benefits and costs associated with various decisions and highlight state-of-the-art research that exemplifies the options. We conclude by presenting a high-level analysis of trends in this rapidly developing field. Although we are roboticists, we have worked closely for more than a decade with autism researchers, including those at the Yale Child Study Center and at the Children's Hospital Los Angeles Boone Fetter Clinic, premier centers for the treatment and study of autism disorders, and our experiences are influenced by these collaborations.

1.1. Background: Autism

The disorder commonly referred to as autism is a spectrum of developmental disabilities that are classified as autism spectrum disorders (ASDs) (1). Current diagnostic guidelines subdivide ASDs into autistic disorder, Asperger's syndrome, and pervasive developmental disorder–not otherwise specified, although proposed changes for the next revision of diagnostic criteria collapse and remove these divisions (8). ASDs vary substantially in the severity and nature of symptoms but are defined by persistent deficits in social communication and social interaction as well as the presence of restricted, repetitive patterns of behavior. Signs of autism include difficulty talking about personal feelings or understanding the feelings of others, disinclination to share or engage in reciprocal play with others, lack of eye contact and joint attention behavior, difficulty communicating or using language, and sensitivity to physical contact.

There is currently no cure for autism, although behavioral treatments can improve quality of life and independence. Early intervention is critical for a positive long-term outcome, and many individuals need high levels of support throughout their lives (9). Such treatments include applied behavior analysis, in which positive behaviors are encouraged and negative behaviors are discouraged to improve social and communicative skills (10). Other approaches focus on utilizing nonhuman partners to facilitate human-human social interaction, for instance, through pet-assisted therapy (11, 12). Although computer-assisted therapy (e.g., 13–15) and virtual reality approaches (e.g., 16, 17) have shown some success, there has been limited investigation of the parameters of the facilitative interactions and of the conditions necessary to generalize the benefits to interactions with human partners. Notably, there is no best therapeutic approach—what works well for one person might not work well for another.

1.2. Background: Robotics

The term robotics encompasses a variety of research subareas, systems, and applications that span navigation; manipulation; walking, running, and flying; legged, wheeled, and tracked locomotion; autonomous underwater, aerial, and space vehicles; and medical, service, and automation systems. One subarea of robotics, termed social robotics, involves robots that engage in some form of social interaction with humans, through speech, gestures, or other media (18, 19). Another subarea of robotics is assistive robotics, which generally involves robots that aid people with special needs (in contrast to service robotics, which involves any type of helpful robot). Assistive robotics applications have historically involved hands-on treatment or support for physical disabilities; for example, a robot can help a patient perform repetitive therapeutic motions as a physical therapist would (2).

At the intersection of social robotics and assistive robotics lies SAR, which involves robots that are designed to help through social, rather than physical, interaction (3, 4). SAR is a young but rapidly developing field, covering approximately a decade of research so far. SAR systems face challenges different from those faced by other social or assistive robots. Whereas assistive robot design typically focuses on reliability, precision of motion, and repeatability (all important features when a robot engages physically with a person), SAR design emphasizes emotional expressiveness, user engagement, physical appearance, and robustness during interaction. The social features of SAR systems are particularly important because, unlike in typical social robotics applications, SAR systems must aid the user and must coach, motivate, and influence behavior change. Because of the multifaceted expertise required to develop socially assistive systems, the field of SAR is naturally interdisciplinary, drawing from robotics, physiology, psychology, and sociology, among other fields. In this review, we concentrate exclusively on physically present robots, although related work involving virtual robots (20), affective computing (21), and other technological interventions for autism therapy can also provide useful guidance and evaluation methods.

SAR asks important questions regarding how to create effective, adaptable, user-friendly systems: What are the circumstances in which people (especially those with special needs) accept an assistive robot in their environment? How can we model the behavior of and encouragement by the therapist robot as a function of the personality of the user? How can friendly and familiar interaction models be developed? (A detailed discussion of these questions can be found in Reference 4.) These questions are particularly pertinent to autism therapy, in which users are sensitive to novel stimuli and have greater difficulty with attention and engagement than do typically developing individuals. Socially assistive robots for autism therapy must therefore balance goal-oriented treatment with a nonthreatening but engaging and productive interaction.

2. PHYSICAL APPEARANCE OF ROBOTS

A person interacting with a robot is struck first by the robot's physical appearance. There is little consistency in physical appearance of robots for autism therapy; the appearance of these robots has ranged across many levels of anthropomorphism, including humanoid, animal-like, and machine-like (nonbiomimetic) systems, and across the fidelity of the reproduction from stylized features to a realistic, complex appearance. Because few commercially available robot platforms are suitable for autism therapy research, most research groups design their own robots. This results in large variation in form and function of SAR systems for autism (**Figure 1**). Furthermore, certain design decisions about physical appearance have implications on the overall design. For instance, a robot cannot appear both extremely human-like and socially simple.

A central tension in the design of robot appearance concerns how life-like the robot should appear. A robot that more closely resembles a human, with life-like features and motion, might allow a child with ASD to more easily identify the desired social overture that the robot is making or might facilitate the transfer of skills learned in human-robot encounters to human-human interactions. On the one hand, as individuals with ASD often have difficulty generalizing learned social skills outside the context in which they are learned (22), the drive toward life-like anthropomorphic robots can be easily justified. On the other hand, a less life-like appearance might allow for a physical appearance that exaggerates social cues (making them more salient or more easily recognizable) or helps focus attention on particular social cues that are necessary for the skill being trained while limiting distracting or confusing stimuli. For many individuals with ASD, sensory overstimulation is a serious problem (23), and the flood of social cues may be a primary cause for the inability to process social signals. This tension over the degree of realism has resulted in a widely varying set of physical appearances; an assortment of representative systems can be seen in **Figure 1**.

Anthropomorphism in robots takes many forms: It can mean a robot that is built precisely to a child's physical dimensions (24); a robot with highly realistic silicone-based skin and expressive facial features (25, 26); a robot built on a doll's body that has typical, although stylized, human features (27); or a robot that is child-sized and -shaped but with simple stylized features and limited expressive abilities (28, 29). To create evocative but visually simple robots, designers often use a cartoon-like style, with oversized and exaggerated primary features, such as eyes, and an absence of secondary features, such as lower eyelids (30, 31). Robots with machine-like bodies and cartoon faces displayed on a screen are another option for providing socially simplified stimuli (32).

Other robots are nonanthropomorphic by design. Some robots are modeled after animals—for instance, commercial robots Pleo (33) and AIBO (34)—and appear social but nonthreatening. These animal-like robots often allow for the expression of social cues that are simpler than those provided by anthropomorphic robots but that are still appropriate to the physical form and easy to interpret. Finally, some robots are not designed to match any biological form. These nonbiomimetic robots have a range of appearances based on their intended use, but they tend to be simple, easy to operate, and toy-like. Because a nonbiomimetic robot does not possess typical


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social features, it is usually used as a social mediator that aims to engage children in a task or game with adults and other children (35, 36) rather than used to socially engage with children directly.

In addition to physical appearance, realism can be established or limited through varying levels of biological motion. For instance, a robot that moves its arm with multiple degrees of freedom (DOF) in the shoulder seems more human-like than a robot that can move its arms only up and down in a single plane of motion. Once again, the level of realistic biological motion for a particular robot is dictated by the goals of the interaction. Extensive actuation (typically achieved with multiple motors) induces the perception of anthropomorphism and allows for more complex expression. Minimizing actuation, perhaps to as few as one to three motions, reduces the cost of development and limits the range of behaviors expected from the robot, thus simplifying the interaction. Additionally, having fewer motors reduces the chances of hardware failures on the robot, which is particularly important for devices like these that must survive extended periods of interactive play with children.

Highly realistic biological motion is difficult to generate using robotic systems. Facial expression alone demands large numbers of motors to replicate the effect of more than 30 muscles involved in generating human facial expressions. Because actuating a robot with many motors is expensive, delicate, and time consuming, few robots for autism therapy are highly actuated. One example of a highly actuated robot is the facial automaton for conveying emotions, or FACE, which is designed on the basis of biological principles to be a realistic facial display system (26, 37). FACE has servomotors to control facial movement, as well as a biomimetic proprioceptive system composed of an elastic sensing layer within its artificial skin. Motors can be adjusted to achieve realistic expressions on the basis of feedback from the sensing layer. Using this system, FACE can express six basic emotions.

Most robots have less complex actuation systems. For instance, Bandit (29) has two DOF in the mouth and one in each of the eyebrows, allowing limited facial emotion expression without being biologically faithful. It can also turn its head side to side (to indicate "no," for example) and has six DOF in each arm, for deixis (pointing) and gestures. Similarly, a remote-control robot named Kaspar has a realistic face with significantly less actuation (25): It has two DOF in the mouth (open/close and smile/frown) and three DOF in the eyes (up/down, left/right, and open/close the eyelids). According to its designers, Kaspar's minimally expressive face reduces its complexity as a social stimulus. Similarly, Tito (28) and Robota (38) have few DOF in their arms and heads, so they can perform simple actions such as "dancing" and participate in imitation games while maintaining simplicity in design. Keepon was also designed to be simple but expressive (30); it has four motors powering four DOF enabling its body to lean side to side and front to back, bob up and down, and pan or rotate on its base. The researchers determined that these four actions are sufficient to express attention by orienting toward an object or a person (**Figure 2**), as well as happiness (rocking back and forth), excitement (bobbing up and down), and fear (shaking).

Along with actuation of limbs and facial features, robot designers must decide whether to instrument a robot with the ability to locomote within an environment. All robots used in autism therapy research have some movement capability, frequently involving manipulation of body parts

Figure 1

A selection of robots applied to autism therapy: (*a*) Kaspar (courtesy of the Adaptive Systems Research Group, University of Hertfordshire, UK), (*b*) Muu (courtesy of M. Okada, Toyohashi University of Technology, Japan), (*c*) Pleo, (*d*) Tito (courtesy of F. Michaud), (*e*) Robota (courtesy of A. Billard), (*f*) FACE (facial automaton for conveying emotions; from Reference 26), (*g*) bubble blower (courtesy of D. Feil-Seifer), (*h*) Keepon (courtesy of H. Kozima), (*i*) Infanoid (courtesy of H. Kozima), (*j*) Bandit (courtesy of M. Matarić), and (*k*) Roball (courtesy of F. Michaud).

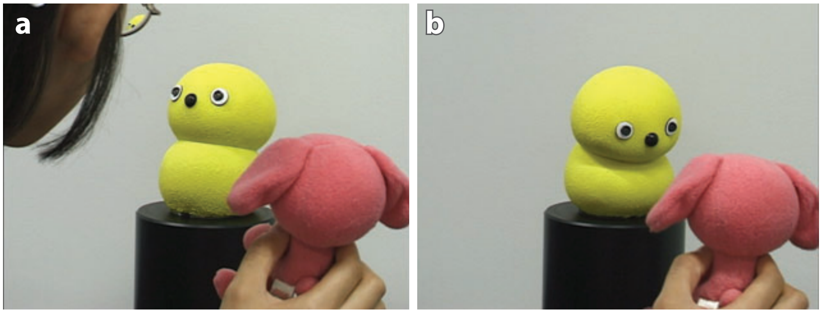

Figure 2

Keepon orients its body (*a*) toward a user's eyes and (*b*) toward an object in an apparent display of joint attention. Photo courtesy of Hideki Kozima.

such as arms and heads, but many are fixed in place on a stand or table (25, 26, 30, 38, 39). More rarely, robots are equipped with the ability to walk or roll around their environment (29, 32, 34, 40). Mobility allows for a greater variety of human-robot interactions by increasing the types of actions that the robot and human can engage in together. However, mobility presents another factor that must be controlled during interactions. For this reason, mobile robots typically have less body actuation than do stationary robots.

3. HUMAN-ROBOT INTERACTIONS

Together with physical appearance, a robot's behavior is critical to how it is perceived and how effective it might be in a therapeutic session. Despite variations in robots' physical appearances, however, all SAR systems for autism aim to generate one or more carefully designed, potentially therapeutic interactions between human users and themselves, involving elicitation, coaching, and reinforcement of social behavior. Human-robot interactions can be described both by the behaviors being elicited from the user and by the robot's role during the engagement. The goal of an interaction might be to elicit joint attention and referencing between the user and an adult, to mediate sharing and turn-taking between the user and others, or to encourage imitative behaviors. At the same time, the robot can act as a teacher in an authoritative role, as a toy intended to mediate behaviors by the user, or as a proxy for the user to allow him or her to express emotions or goals. In this section, we discuss the design of these interactions from the perspective of targeted behavior and the robot's role in the interaction.

3.1. Targeted Behavior

The main intended role of a SAR system in autism therapy is to allow or encourage children to develop and employ social skills. To this end, robots can be designed to take part in numerous different interaction goals, such as capturing and maintaining attention, evoking joint attention, eliciting imitation, and mediating turn-taking. As deficits in these social and communicative skills can have a profound impact on daily activities, SAR systems that can help bring about, elicit, or train these social behaviors could benefit autism therapy significantly.

One common characteristic of ASD is impairment in the use of eye-to-eye gaze, facial expressions, and other social behaviors that regulate engagement (23). Correspondingly, a design goal adopted by many SAR systems is eliciting and maintaining active engagement throughout a therapy session. Many studies report positive effects of robot presence on attention and engagement in therapy-like scenarios, despite using dramatically different robot appearances and capabilities (25, 29, 30, 32–34, 37–39, 41–43). Through appropriately timed movement, social requests, and the display of desirable behaviors (such as blowing bubbles or playing music), many of these robots are able to attract attention and maintain engagement. Some research supports the idea that robot behavior must be correlated with or contingent on users' actions to elicit prolonged engagement (29, 34, 44), whereas other studies fail to demonstrate an effect of contingency on engagement (45). However, in most cases, the effect of the robot's presence on engagement is undisputed. To many, there is no surprise that robots have this effect; the idea that a stimulating toy-like object would generate interest and sustained interaction from a child seems intuitive. However, importantly, the engagement seen in these studies is social in nature, and despite difficulties with social tasks, children with ASD are statistically as engaged as typically developing children during robot interaction (33).

Another difficulty for children with autism is joint attention: demonstrating shared interest toward objects by pointing or using eye contact. This skill is pervasive in typical human communication and is essential for learning and collaborative tasks (23). In many studies, children with ASD interacting with robots show spontaneous joint attention behavior—for example, looking at an adult and back to the robot or pointing to the robot and looking at an adult or another child, with the intention of sharing some feature with that person (25, 30, 32, 35, 37, 38, 42, 43, 46, 47). Children with autism show this behavior despite previously displayed tendencies to avoid eye contact or engagement with unknown adults. Some social robots are even preprogrammed with behaviors that simulate attention from the robot's perspective. For instance, Keepon can orient itself toward a user's eyes and then toward an object in an apparent display of joint attention (**Figure 2**). Such behaviors performed by robots might stimulate similar joint attention behaviors from children with autism.

Imitation is a mechanism for learning appropriate behavior. For instance, children learn social constructs such as waving hello and goodbye by imitating others around them. Children with autism often have difficulty imitating other people's behavior (48). Therefore, therapies that increase the propensity to imitate, or that elicit the urge to imitate, can be leveraged to teach other life skills. Imitation seems to arise naturally in many of the human-robot interactions in SAR research. Sometimes the imitation is structured, in that children are encouraged by adults or by the robot itself to imitate the robot's actions (28, 32, 38, 49). Other imitation occurs spontaneously and develops into a game, with the child imitating the robot's behaviors and vice versa (30, 42, 46). This game even extends to triadic interactions among a child with autism, an adult, and a robot, involving turn-taking and sharing (**Figure 3**).

Difficulties with sharing and turn-taking are a sign of an ASD, presenting challenges for social interactions. Children learn important life skills through social games involving turn-taking, so the ability to engage in these behaviors is important for development. Through their status as an explicit social presence—more animate than typical toys but less socially complex than people—robots can elicit turn-taking with children who tend not to engage in such behavior (25, 30, 32, 38). For instance, **Figure 3** shows a turn-based imitation game with Kaspar. One person controls the robot's movements with a remote, while the other mimics the robot's actions; this game has been successfully used for triadic interaction involving two children with autism and Kaspar (42).

3.2. Roles of the Robot

Robots for autism therapy can inhabit numerous different roles, even within the same therapy session. For instance, the robot can be a leader that demonstrates social behavior and guides the

Figure 3

A child and an adult playing a turn-taking imitation game with Kaspar in which one person controls the robot's movements with a remote, while the other mimics the robot's actions. Photo courtesy of the Adaptive Systems Research Group, University of Hertfordshire, UK.

interaction, or it can be a toy that responds to the child and mediates social behavior between the child and others. More rarely, robots can act as proxies for children, allowing them to express their emotions or desires.

Play is an important element of child development, and robots designed for autism therapy are often present as playthings during therapy-like sessions. These robots are novel, toy-like stimuli that easily attract children's attention, but by being animated and appearing autonomous, SAR systems set themselves apart from traditional toys, thereby further maintaining children's interest. In some cases, robots are presented in a free-form play session individually (35, 41) or grouped with other toys (30). In others, robots are subordinates that need assistance—for instance, in the form of socially appropriate vocal encouragement—from children in therapy (33). Robots can also appear as peers with children in interactions, as in the case of imitative games (28, 49).

SAR systems for autism have had success as social mediators, objects that elicit social interactions between two or more people. Joint attention is a context in which robots act as effective social mediators, and, as noted above, the emergence of joint attention is one of the primary effects noted by researchers developing robots for autism therapy. Extending social mediation further, robots can initiate turn-taking games between two children with autism. Kaspar has been used in this context; because children are able to see the effect of pressing buttons on Kaspar's motion, the remote becomes an object of control. Turn-taking therefore becomes an explicit act of passing the remote control to another person. In fact, researchers report the case of a teenager who, although he previously could not tolerate another child in any play activity, was gradually and successfully introduced to a turn-taking imitation game with his therapist and then with another child (42).

Robots can also take the lead in guiding social interactions. For instance, a robot can verbally ask the child to perform certain behaviors such as spinning (36), guide the child through predetermined play scenarios (28, 32), or simply move autonomously, allowing the child to engage in imitation (38) or free-play interactions (50) at will. More frequently, a therapist or teacher guides the child through interactions with the robot, for instance, by asking the child to touch the robot or to imitate the robot's behavior (34, 38).

Occasionally, robots appear to be proxies or receptacles for children's emotions or intentions. Kozima et al. (46) describe cases in which children express emotional behavior toward the robot in the absence of other people, for instance, by hitting the robot on the head, stroking and comforting the robot, or wrapping the robot in a scarf so it does not catch a cold.

3.3. Robot Autonomy

Children with autism (and, in fact, children in general) do not behave consistently day to day or even hour to hour. Therapy sessions can feature a highly engaged child playing quietly with a toy one day, and a distracted, angry child refusing interaction the next. Therapists are prepared and trained to handle these changes in mood and preferences; SAR systems designed to interact with children must feature the same kind of adaptability if they are to be fully integrated into therapy.

Many SAR systems being evaluated in therapy-like applications are controlled remotely through a technique termed Wizard of Oz (WOZ), after the man behind the curtain in the eponymous film. In these circumstances, an experimenter controls the robot remotely, either from a different room or within the same room using hidden controls. The experimenter can have a whole-world view of the interaction environment (33, 49) or, to provide more realism to the interaction, can take the view through the robot's cameras (46). Through the use of a WOZ technique, the robot's behavior is as adaptable as the human controller and the robot's capabilities allow.

Although WOZ is effective for quickly developing and deploying robots in complex environments, it is not a sustainable technique for long-term, large-scale use. By creating autonomous robots that interact socially with individuals during therapy sessions, researchers have made the goal of having socially assistive robots as part of autism therapies more feasible. This goal is not yet realized, however, in part because robot control has not reached the level of sophistication required to handle complex, dynamic, and unpredictable situations such as those found in typical day-care and therapy environments. Researchers are working toward building robust, flexible robot control architectures that can handle these situations.

Feil-Seifer & Matarić's (29) B^3IA (Behavior-Based Behavior Intervention Architecture) is one such behavior-based control architecture specifically designed for autism intervention robots. Such robot systems must have several capabilities, including sensing and interpreting the child's actions; acting autonomously within established scenarios; processing sensed data over time to understand the history of the interaction; evaluating the interaction with respect to quantity and quality of social behaviors; and altering behavior on the basis of parameters specified by a user, such as a therapist or teacher. **Figure 4** shows a schematic of the B^3IA control architecture and behavior network. Each module corresponds to one of the capabilities required for an autism intervention robot. Feil-Seifer & Matarić (29) successfully implemented this architecture on a wheeled, nonhumanoid bubble-blowing robot and are currently examining which child social behaviors are affected by the robot's autonomous behavior.

Knowing how to behave is dependent on understanding the situation at hand. Therefore, control architectures must be paired with sensing modules that can interpret a child's mood and intentions from observable behavior. These sensors can take the form of physiological detectors monitoring blood pressure, pulse, skin conductance, and brain activity (51) or cameras that detect behavioral trends on the basis of physical locations (50). Sensors that measure physiological data are relatively invasive to people with autism, who are often sensitive to touch, but provide more precise information than distance-based estimations of emotional and mental state.

Of all of the types of interactions described in this section, interactions with autonomous robots that sense and respond to user behavior are the least developed in current research. Significant work is needed before control architectures for autonomous robots can be fully integrated into real-world therapies for autism.

4. EVALUATION STUDIES

Robot appearance and interaction design are important, but they must be tested to ensure that they achieve their intended goals. Currently, each research group tends to perform its own studies

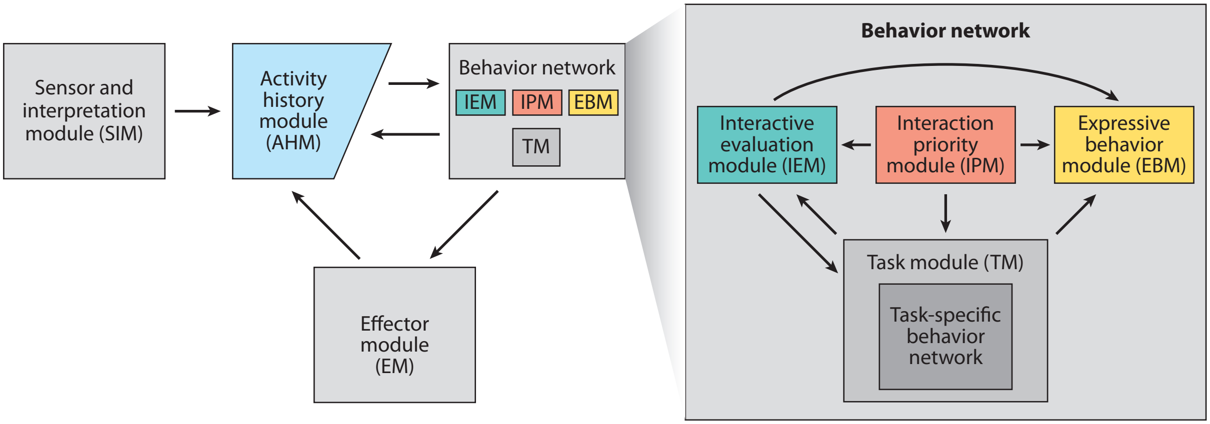

Figure 4

A schematic of the B^3IA (Behavior-Based Behavior Intervention Architecture) control architecture and behavior network, which controls an autonomous robot designed for autism intervention (from Reference 29, courtesy of D. Feil-Seifer).

using its particular robot(s), and there is little collaboration among robotics researchers with respect to participant pools and experimental methods, largely owing to geographic distance between research groups and the lack of affordable commercial autism-relevant robot platforms. As a result, there exist a variety of methodologies for evaluating robots for autism. These studies do not fall into discrete categories but instead tend to vary along particular dimensions that mark the number of interaction sessions, the size of the sample, the degree to which interactions are structured or free form, and the way in which data are analyzed. In this section, we describe some of these dimensions that studies use in evaluating SAR systems.

4.1. Single Versus Repeated Interaction

Studies can vary in the number of interactions that participants have with the robot. Children with autism are particularly sensitive to novel stimuli and changes in routine, so the amount of exposure they have to a robot is significant when evaluating a robot's effect on the child: The child's initial response to the robot as a novel stimulus might differ from that elicited once the robot is familiar. Both single-interaction and repeated-interaction studies have their merits and challenges.

Single-interaction studies (e.g., 26, 33–35, 42) are logistically simpler to perform, and fewer repeated trials often means that more participants can be included in the study, which raises the statistical validity (see Section 4.2). Single trials also reveal how a robot is initially tolerated, useful information for the design of socially assistive robots. When researchers perform within-subject manipulations (i.e., having each participant experience more than one condition and then comparing the results among conditions), children's previous exposure to the robot becomes less important than comparing the conditions (e.g., 29, 34). Novelty can also be mitigated by a familiarization period during which participants and robots interact prior to the experiment (35).

Studies with repeated interactions allow users to adjust to the robot and provide a time course of data regarding human-robot interactions (e.g., 25, 28, 30, 38, 39, 42, 49, 52). Although this time course is sensitive to changes in mood across many days, with sufficient numbers of trials, these studies can show evolving behaviors toward the robot. Most studies to date fall into this category and take place over several weeks, with two to five interactions per child. Some studies take place over the course of several months or years [as does the study by Kozima et al. (30), which takes place over three years]; these studies can report on individual cases in which prosocial behaviors emerge only after multiple interactions with the robot. Care should be taken in interpreting these studies, as it can be challenging to isolate the effects of the robot interactions from the effects of maturation and the effects of other interventions in which the children participate.

4.2. Sample Sizes

Larger sample sizes increase validity and allow researchers to generalize claims about the effectiveness of the robot. However, most studies of robots for autism performed to date involve relatively few participants (typically three to four). Although not ideal, this situation occurs because research groups that perform evaluations of robots for autism tend not to have the same ties and resources as do clinical groups that evaluate other autism treatments. Furthermore, robots used in these evaluations tend to be prototypes, one-of-a-kind constructions built by an individual research group at relatively high cost. With only one robot prototype to work with, it is impossible to accomplish large-scale evaluations, particularly ones that involve long-term use of the robot with individual children, such as in the home. We explore these current limitations in greater depth in Section 5. Some research groups [e.g., Kozima et al. (30)] are able to achieve large sample sizes because their robot can be deployed in a free-form playgroup setting, allowing researchers to examine the behavior of multiple children in a series of unconstrained interactions.

4.3. Structure

Structured interaction trials between children with autism and robots typically have an adult (experimenter or therapist) who guides the child in prespecified exercises with the robot. For instance, the teacher can show a child how to imitate a robot by physically moving the child's body in imitation (38, 49) or by leading the child through imitation games using a remote control (42).

Free-form interactions involve little or no prespecified tasks or behaviors. In evaluations involving free-form interactions, children are allowed to play with the robot as they wish. Sometimes these interactions occur in specific evaluation settings, where children are brought in specifically to interact with the robot (34, 35); at other times, free-form interactions occur in general play settings such as the playroom of a school (30).

Experimental trials can also vary by whether they involve a single child or multiple children interacting with the robot. One-to-one studies, in which a single child interacts with a single robot, have comparatively fewer confounding variables (such as the behavior of other children) in evaluating the robot's influence. It is also easier to control the type of interactions occurring when only one child is present. Consequently, most studies involving robots and children with ASD fall into the one-to-one category. Many-to-one trials can be either structured (42) or free form in a more naturalistic setting, such as a school (30), and they can involve two children with one robot (47) or many children with one robot. These trials allow researchers to measure the effects of the robot on human-human interaction, an essential part of autism therapy.

4.4. Data Collection and Analysis

Data collection generally falls into two categories: qualitative analysis, which is descriptive or observational, and quantitative analysis, which is numerical and statistical. Autism is a behavioral disorder; it is diagnosed and treated on the basis of behavioral observations by trained therapists (see sidebar, Robot Tools for Diagnosing Autism Spectrum Disorders, for more information).

ROBOT TOOLS FOR DIAGNOSING AUTISM SPECTRUM DISORDERS

Autism spectrum disorders (ASDs) are manifested behaviorally. There is no blood test, imaging method, or genetic screening for diagnosis; instead, trained clinicians evaluate individuals by observing their development history and social skills. Because ASD diagnoses are subjective, disagreement can occur among multiple clinicians evaluating an individual or even during a single clinician/patient pairing over time (56). There is a need for quantitative, objective measurements of social functioning for diagnosis, for evaluating intervention methods, and for tracking the progress of individuals over time.

Social robots may aid in diagnosis by providing consistent behavioral evaluations and standardized stimuli in diagnostic settings (45). Because robots can provide consistent, reliable actions, clinicians can ensure that identical stimuli are presented at each diagnostic session. Furthermore, the component systems in socially aware robots may offer noninteractive methods for tracking human-human social behaviors. The perceptual systems of these robots are designed to measure and quantify social behavior—that is, exactly the skills that must be identified during diagnosis. Automated behavior evaluation systems, such as a ceiling-mounted camera-based system capable of distinguishing between positive and negative responses on the basis of body positions (50, 57), are being developed as tools for autism therapy.

Unsurprisingly, most SAR studies to date involve qualitative reports of robot effects. Some evaluations focus on case studies, which highlight particular children and describe their background and intervention histories in addition to their responses to the robots (30). Other evaluations include anecdotes meant to illustrate the effects of robots on particular individuals. Qualitative evaluations are important and useful, particularly when performed by individuals trained for that task [such as conversational analysis used in studies by Robins and colleagues (42, 43)], but it is difficult to generalize the effects of a robot on autism therapy from qualitative reports.

Some studies undertake the difficult task of extracting quantitative data from behavioral observation (28, 33–35, 49, 52). This typically involves a second-by-second analysis of a video-recorded session that notes each prespecified behavioral action, such as time spent looking at the robot, number of joint reference actions, and number of positive vocalizations.

For example, Kim et al. (33) evaluated levels of engagement during human-robot and human-human interactions involving children with autism and typically developing children. In this study, each child was asked to use appropriate vocal prosody to encourage a dinosaur robot to walk across a blue stream pictured on a landscape mat. A therapist elicited social behaviors by engaging the child in conversation before and after the robot interaction. To quantitatively measure engagement, the researchers recorded video of the interactions (**Figure 5**) and analyzed these videos using a coding scheme they had developed. **Table 1** shows a sample of their coding scheme, which used a Likert-type scale from 0 to 5. Two raters independently analyzed video recordings of each interaction, separated into 5-s intervals, by assigning an engagement rating for 1 out of every 4 intervals (i.e., for 5 out of every 20 s of video). Using these ratings, the authors were able to quantitatively evaluate levels of engagement during various interactions.

Such video coding involves significant time and effort, particularly because it requires training on the coding schema as well as validation that the coding was performed reliably, but it can yield more concrete, quantitative information about the effectiveness of robots for autism therapy. Reliable and robust methods for automated video coding could significantly aid the process of behavioral data analysis in general and autism data analysis in particular.

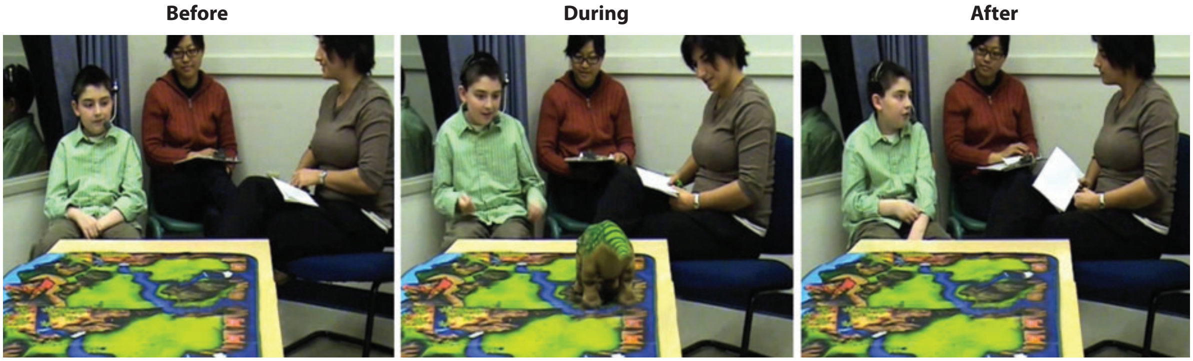

Figure 5

Screenshots of a video-recorded interaction between a child with autism (*left*) and a therapist (*right*). The experimenter (*center*) controlled the robot secretly by using a remote control hidden by her clipboard. Researchers performed second-by-second analysis on these videos to quantitatively evaluate engagement (from Reference 33, courtesy of B. Scassellati).

5. DISCUSSION

In this review, we categorize the development and deployment of SAR systems for autism therapy into three parts: robot design, interaction design, and evaluation. Although robot platforms vary significantly in terms of visual appearance and behavior, they have been shown to evoke prosocial behaviors such as joint attention and imitation from many children with autism. In this section, we look to the future of this research, first highlighting the challenges of SAR for autism and then identifying trends we believe will carry the field forward.

5.1. Challenges in the State of the Art

One major shortcoming in all of the studies described here is that the data are qualitatively but not quantitatively rich: Robot experiments tend to involve descriptive case studies of a small number of individuals over a few days or, rarely, a few weeks or months. At the moment, there are no large-scale longitudinal studies with many participants that provide quantitative measures about how people with autism interact with social robots.

Table 1 A table of ratings of engagement, from 0 (low engagement) to 5 (high engagement), based on descriptions of the coding schema from Reference 33

Rating	Meaning	Example
0	Intense noncompliance	Participant stood and walked away from the table on which the robot interaction took place
1	Noncompliance	Participant hung head and refused to comply with interviewer's request to speak to the robot
2	Neutral	Participant complied with instructions to speak with the robot after several prompts from the confederate
3	Slight interest	Participant required two or three prompts from the confederate before responding to the robot
4	Engagement	Participant complied immediately following the confederate's request to speak with the robot
5	Intense engagement	Participant spontaneously engaged with the robot

In many ways, this is understandable. By the nature of the research, developing and evaluating SAR systems for autism therapy involves researchers who specialize in computational science, mechanical and electrical engineering, robot control, human-robot interaction, social psychology, and clinical research. Few research groups have total coverage of these disparate fields, so groups tend to focus on their strengths, whether they be in robot design, interaction design, or evaluation. Unfortunately, without clinical psychiatrists and psychologists, most research groups lack long-term, continuous access to protected groups such as children with autism, making it difficult to measure the benefit of design decisions. Facilitating collaborations between clinicians and roboticists is probably the only way to enable this kind of in-depth interaction study.

Social robotics has only recently addressed the field of autism therapy and treatment, in part because robotics has only recently progressed to the point at which social robots are a reality outside the research lab. Applications such as robot toys require extremely durable hardware that is relatively inexpensive but sufficiently complex to generate engaging interactions. Robots used in classrooms and therapy sessions must be particularly resilient to knocks, bumps, and drops, which are inevitable, especially when children are involved. However, current robot hardware can be extremely sensitive and easily broken. Building sufficiently sturdy, mobile, flexible robots to interact in naturalistic settings is a challenge in its own right. Having robots engage children with autism while remaining simple and nonthreatening is an even greater challenge.

As an example of this engineering challenge, imagine a robot that engages in imitative games. To generate imitation behavior from a child, the robot must be either controlled remotely or programmed to autonomously imitate observed physical behavior. To achieve imitation, the robot must know when to begin, must sense the child's body motion with sufficient accuracy to recognize individual body parts, must calculate how the body is moving through space, and must be able to map those motions to its own, potentially limited, effectors in order to replicate the movement as closely as possible, in a recognizable fashion. In fact, imitation is itself a research problem in robotics, even under simple, controlled conditions (53–55). Packaging these systems so that the sensing, actuation, and computation can be contained within a robot suitable for use by children with ASD represents a substantial engineering challenge and investment.

There is a problem innate to behavioral psychology research regarding how to compare and understand the behavior of individual children. For instance, contexts such as mood, time of day, and previous events can affect the way a child interacts during a treatment session. Isolating the effects of a robot during these sessions is an additional challenge that must leverage the knowledge of the psychology community. Several surveys exist for professional psychologists to evaluate a child's condition, but significant training is required to be able to perform this task. Again, roboticists must be paired with psychologists to obtain and present their results in a way that is meaningful to the autism treatment community—that is, therapists and psychologists—who are the intended users of some of the SAR technologies being developed. The absence of quantitative data about robots' influence on children with autism is not necessarily a shortcoming of the field, but there are challenges that must be met before SAR can make a significant, widespread impact in autism treatment.

5.2. Trends in Socially Assistive Robotics for Autism

In analyzing the state of the art in robotics for autism therapy, we have identified several trends that we predict will become central as this field develops. Many current robot systems being evaluated for autism therapy typically employ a WOZ setup to provide appropriate responses, but this technique is not viable for widespread robot use because a human must control the robot during every human-robot interaction. Instead, a promising development in the field of

SAR is architectures for robot controllers that sense users' actions and respond appropriately. By building a robot control architecture specific to autism therapy applications, researchers can also make guarantees about robot behavior—for instance, that it will always provide a certain stimulus when a certain scenario is detected—which is an important assertion for socially assistive applications. Obviating the need for a human controller and providing a rigorous definition of robotic behavior are useful effects of building control architectures for robot-based autism therapy applications. Another avenue of research is SAR systems that respond to high-level commands from the therapist, allowing the therapist to drive the general direction of the interaction within the therapy session without having to devote attention to detailed step-by-step tele-operation of the robot.

Along with robots that can detect and respond to users' actions, a newly emerging trend in robotics for autism involves robots that can detect users' moods and preferences and can adapt their behavior in real time to those factors. For instance, a child who is sensitive to bright lights will not respond well to therapies that involve brightly colored video images; therapists and teachers of children with autism are trained to recognize and adapt to such variations among and within children. Robots for autism therapy must also become capable of such flexibility before they can be autonomous entities in therapeutic interactions. Some systems that identify mental and emotional states from physiological (51) and behavioral (50) data have already been proposed, but more work in this area is needed before robots can reliably respond to users' moods and preferences.

Most robots being developed for autism therapy are prototypes built by individual research groups. Owing to economies of scale, constructing a single robot is often more expensive (per robot) than building multiple copies of the same robot, so deploying and testing robots in multiple therapeutic environments can be prohibitively costly. Some research groups choose to adapt commercially available, programmable robot platforms to perform interaction design and evaluation (33, 34). Although they lose the ability to customize aspects of the robotic hardware, these groups gain widely available platforms for interaction design and evaluation. Because such robots are sold as consumer commodities, usually as toys, they are generally robust and less prone to failure than are research robots. Despite being toys, some consumer robots contain a wealth of sensors and actuators that allow great flexibility in robot behavior. Furthermore, because these consumer robots are widely available, clinicians, parents, and teachers can also acquire them. When robots for autism have become sufficiently developed to be deployed in homes or in multiple long-term settings, commercially available robot platforms will simplify the problem of evaluation and adoption. Before this can happen, affordable and robust platforms to develop the robots for autism are necessary.

As noted in Section 3, despite the variety of robot forms being explored for autism therapy, most of the platforms manage to evoke attention and prosocial behavior from many children with autism. As more groups begin to evaluate robots in therapy-like settings, robots with visually simple appearances—fewer moving parts, less human-like skin and features, and simpler motions—are likely to perform well in a cost-benefit analysis, and perhaps better than robots on which researchers expend significant resources to attain anthropomorphism. Highly realistic human-like robots have an important role to fill, but the wide range of robots for autism therapy seems to be trending toward visually and kinetically simple designs, especially given the sensitivity of individuals with autism to highly realistic human features.

Finally, although the effects demonstrated by SAR systems are consistently reported across studies that vary in geography, the degree of disability present in participants, the robot appearance and capabilities, and the nature of the interaction, there are no clear conclusions on why these robots succeed in establishing and, in some cases, maintaining social engagement (45). There are many viable hypotheses about why robots generate prosocial behaviors in many children:

Perhaps the simplified social cues that robots present result in less overstimulation of the children; perhaps robots offer more predictable and reliable responses than those from a human partner with ever-changing social needs; perhaps robots trigger social responses without the learned negative associations that some children have with human-human interactions; and perhaps the exaggerated social prompts that robots provide are better triggers for social behavior than the nuanced and subtle social prompts from a human partner. Although SAR research studies have documented numerous interesting effects, few of these efforts offer real insight into why many children with ASD tend to respond to robots with positive social behaviors. Understanding the basic causes of these effects represents perhaps the most critical future direction for SAR research.

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