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A Feasibility Study Evaluating the Emotionally Expressive Robot SAM

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Abstract This two-part feasibility study evaluated the functionality and acceptability of Socially Animated Machine (SAM), a humanoid robotic monkey developed to elicit social interaction in children with Autism Spectrum Disorder (ASD). Socially Animated Machine was designed with an approachable, animal-like appearance, while preserving the essential features of a human face. The intent was to design a robot that would be interesting and engaging to children with ASD, yet maintain the capability to model facial expressions that convey emotional subtlety. Study 1 evaluated the accuracy of SAM's emotional facial expressions. Typically developing children ($N = 35$) labeled and matched SAM's expressions to photos of human expressions with moderate-to-substantial levels of agreement. Study 2 compared children's level of social engagement across an interaction with SAM and an interaction with an adult experimenter. Children with ASD ($N = 13$) spent significantly more time attending to the partner's face while interacting with SAM. When asked to rate their interaction with SAM, children with ASD reported high levels of happiness and comfort and requested additional interactions. These results suggest that SAM may serve as a useful tool in interventions to improve social skills, including emotion recognition, in children with ASD.

Keywords Autism spectrum disorder (ASD) · Social robot · Human–robot interaction · Emotion recognition · Engagement

1 Introduction

Autism Spectrum Disorder (ASD) is a neurodevelopmental disability that affects approximately 1 out of 68 children in the United States [1]. ASD is characterized by significant impairments in social communication and interaction [2]. Individuals with ASD have trouble understanding the pragmatics of social interaction, such as turn-taking, perspective-taking, and the appropriate use of context during conversation [3,4]. Their conversations often lack a sense of social reciprocity and involve reduced sharing of interests and emotions [5–7]. Individuals with ASD also have marked difficulties in producing and perceiving nonverbal behaviors during social interactions. This often includes unusual eye contact, decreased use of facial expressions and gestures, and failure to read and accurately interpret these nonverbal behaviors when used by others [3,8,9]. The long-term implications of social skills deficits can be serious, as impairments are often exacerbated during development as the social world becomes more complex and demanding [10]. When integrated with typically developing peers, adolescents with ASD are at an increased risk for peer rejection and social isolation [11]. Furthermore, social skills deficits may contribute to academic and occupational underachievement, as well as mood and anxiety problems later in development [10,12].

1.1 Technology-Based Social Skills Interventions

The increasing prevalence of ASD, coupled with the devastating long-term implications, necessitates an immediate

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effort to improve social skills among children with this disorder. Traditional behavior-based, human-delivered intervention approaches have been found to teach positive social behaviors and improve functional communication skills in children with ASD [13]. Notably, these interventions typically involve the presence of a therapist who works directly with the child to develop particular skills. It is important to consider that even in a therapeutic setting, social interaction can be confusing and stressful for a child with ASD. Children with ASD have difficulty paying attention to multiple cues during social interactions, making these interactions complex and difficult to understand [14]. As such, the child may have difficulty attending and learning presented skills [15,16].

As an alternative to traditional therapist-administered interventions, researchers have explored the use of technology-based interventions to teach social skills to individuals with ASD. Technology-based tools follow a predictable format, which can reduce the stress and pressure that children with ASD often experience during direct human contact, thereby creating a more enjoyable and effective learning environment [15–17]. Unlike other therapist-administered interventions that occur in one-on-one or small group sessions, technology-based interventions can also be more easily replicated and distributed to meet the needs of a widespread number of individuals. Recent research exploring technology-based strategies for use in individuals with ASD has utilized social robotics. As robots exist and interact in three-dimensional space, they seem to "occupy a special niche between inanimate toys and animate social beings" [18, p. 276]. Social robots may therefore have the ability to elicit certain desirable social behaviors in children with ASD that are not typically seen in other interaction settings [16].

1.2 Previous Robotic Designs

Numerous robotic approaches and applications have been developed to improve social communication skills in individuals with ASD. Social robots utilized in past research vary significantly in their design, size, and level of anthropomorphism depending on specific aims for intervention. Social robots are also widely diverse in their modes of intervention. While some research teams aim to evaluate whether the presence of a robot can elicit social behaviors during an interaction session with a human, others aim to design robots to teach particular skills that can be learned and eventually transferred to interactions with humans outside of the therapeutic setting. Overall, researchers investigating robots as tools for social interaction in ASD have reported increased engagement, attention, and positive social behaviors during these interactions [16,19,20]. Robots have also been shown to help children with ASD develop important social skills, such as initiating communication, turn-taking, imitation, emotion recognition, eye gaze, and joint attention [15,21–24].

1.2.1 Non-humanoid Robots

Non-humanoid robots have been created due to their simplicity and ability to interest and engage children with ASD [16]. Notable examples include Keepon, a small creature-like robot, that was designed to maintain simple nonverbal interactions with children with ASD. This robot resembles a snowman-like creature with an upper sphere containing two stationary eyes and a nose. Keepon directs attention by turning and nodding its head and expresses emotions, such as pleasure and excitement, by bobbing and rocking from side-to-side [25]. Pleo, a socially expressive robotic dinosaur, was designed to serve as an embedded reinforcer that can elicit and reward positive social behaviors in children with ASD during interaction sessions. Pleo demonstrates emotional states and social intent through vocalizations and body movements, including interest, disinterest, happiness, disappointment, agreement, and disagreement, similar to a pet animal [26].

The elephant-like, huggable robot, Probo, was developed to serve as an interactive interface between an operator and a child. Probo contains a fully actuated head and trunk, including eyes, eyelids, eyebrows, ears, and mouth, and can demonstrate emotions through facial expressions and affective nonsense speech. The robot can also be operated by a facilitator to interact with children with ASD by telling specific, individualized social narratives [27,28]. CHild-centered Adaptive Robot for Learning in an Interactive Environment (CHARLIE) is a simple interactive robot that plays turn-taking and imitation games to engage children with ASD during therapist-led interventions. CHARLIE was designed with a plush body, including movable arms and head with stationary eyes, ears, nose, and mouth. The robot can autonomously participate in user-driven games and uses hand and face tracking to monitor the progress of a child with ASD [29].

Interactive Robotic Social Mediators as Companions (IROMEC) is a mobile robotic platform designed to engage children with ASD in play routines and interactions. IROMEC contains a head with a digital display screen featuring a cartoon-like face that can exhibit basic facial expressions such as happiness and fear. Play scenarios include turn taking, imitation games, cause-and-effect games, and pretend play [30]. Bubble Play, a computer-controlled bubble-blower mounted to a mobile robot, encourages human–robot contact by turning and producing bubbles at the push of a button. The robot maintains a simple design, consisting of two buttons controlling the bubble-blower, with the intent of providing a catalyst for social interaction. It operates autonomously by interpreting the child's actions and responding appropriately within established scenarios [31].

1.2.2 Humanoid Robots

Researchers have also developed humanoid robots to better approximate true human interactions [16]. For example, Kinesics And Synchronisation in Personal Assistant Robotics (KASPAR), is a minimally expressive child-sized robot that uses facial expressions, body movements, and gestures to interact with humans. KASPAR maintains specific human-like features and contains a movable head, arms, and face along with stationary legs. Given eyelids and a mouth that can open and shut, the robot is able to display minimally expressive emotional states including neutral, happiness, sadness, and surprise [30,32,33]. Facial Automaton for Conveying Emotions (FACE) is a life-like android designed as a mechanical clone of a human head. With FACE's artificial silicon skin and complex facial movements, the robot can produce semi-naturalistic emotional expressions. FACE was designed to engage children with ASD in an interaction scheme based on imitation and empathy to increase understanding and use of emotional information in social contexts [22,23].

NAO, a humanoid robot with a sleek design and simple face containing two eyes, was developed by Aldebaran Robotics [34] and has been used by a variety of research teams exploring human–robot interaction in children with ASD. NAO is equipped with 25 degrees of freedom across movable arms, legs, head, and torso, allowing for the display of emotion postures using gross motor movements, such as anger, happiness, fear, and sadness. NAO can be programmed to autonomously engage children with ASD in various imitative and interactive games [35–38]. The Robota robots, a series of small humanoid robotic dolls, were designed to engage children with ASD in socially-oriented imitative interaction games. The robots respond by verbalizing, gesturing, and mimicking head and arm movements, with the goal of helping children to develop stronger social interaction skills [39,40].

1.3 Design Considerations

In designing a robot to promote development of social skills in individuals with ASD, it is important to consider specific targets for intervention that have the greatest potential for functional skills improvement in the natural environment. A contending theory of social skills deficits in ASD is that difficulties in recognizing and responding to emotions may underlie core social difficulties associated with the disorder [41]. Emotion recognition skills are thought to be essential to the development of more complex social perception skills, such as identifying one's own mental states (e.g., thoughts, desires, and intentions) and attributing these mental states to others, a concept coined "theory of mind" [42,43]. The goal of addressing such social-emotional difficulties presents specific challenges when considering robotic design, specifically regarding the appearance of the robot and level of anthropomorphism, or "human likeness."

To target skills such as emotion recognition and understanding others' perspectives, a robot must have the ability to demonstrate different emotional states. Though affective states can be displayed through multiple modalities (e.g., vocalizations, body posture, gestures), the face plays a particularly important role in the expression of emotion. Past research suggests that 55% of affective information is displayed via facial expression, whereas spoken language and paralanguage account for only 7 and 38% of this information, respectively [44]. To accurately convey emotional facial expressions, the robot must maintain a certain level of facial detail and adherence to features observed in the human face. Humanoid robots can offer a better approximation of human–human interactions and may provide the greatest potential for skill generalization [16].

Additionally, a robot developed for use with children should appear friendly, playful, and approachable and should be interesting and engaging during human–robot interactions. As opposed to humanoid robots that more closely imitate the human form, non-humanoid robots can take on many fun and attractive shapes and appearances (e.g., animals, cars, toys) and can be built to efficiently complete specific tasks. This allows for increased flexibility in accentuating key features or social cues necessary for developing specific social skills [18]. These robots also avoid evoking an "uncanny valley" experience. Mori [45] describes a curve along which artificial agents become increasingly familiar as they become more anthropomorphic. However, a sharp decrease in familiarity and acceptance occurs when an artificial agent becomes too human-like [46]. By evading the reaction of withdrawal and avoidance that can accompany interactions with human-like beings, non-humanoid robots can be particularly engaging to children with ASD [16].

Exploration of previous designs highlights areas for further innovation when addressing the specific task of teaching emotion recognition skills to individuals with ASD. Non-humanoid robots typically offer a limited range of facial expressions and fail to accurately imitate true human–human interactions. For example, robots such as Keepon [21,25] and CHARLIE [29] are designed with humanoid-like lateral symmetry and predictable behavior to allow individuals with ASD to feel comfortable. However, these robots lack the facial structure to provide the subtle cues that movements of the eyes and mouth give toward the emotional state of the interaction partner. Similarly, many humanoid robots take the general form and appearance of a human but were specifically designed with minimally expressive capabilities so as not to overwhelm individuals with ASD. While robots such as KASPAR [32], NAO [34], and Robota [39] perform gross motor movements and display basic emotional states, they lack the ability to make detailed facial movements that are needed to express more complex emotions.

2 The Robot SAM

The current study attempted to bridge this gap in robotic design by creating a robot with an approachable, animal-like appearance, while preserving the essential features of a human face. The intent was to design a robot that would be interesting and engaging to children with ASD, yet maintain a humanoid form with the capability to model facial expressions that convey emotional subtlety. Given the previously discussed "uncanny valley" experience [45], the research team aimed for a robotic appearance along the upward swing of the curve, prior to the valley. Results of research efforts led to the creation of the humanoid robotic monkey, Socially Animated Machine (SAM; Fig. 1). SAM was developed by a team of researchers at the University of Alabama at Birmingham (UAB) and was constructed and programmed by a graduate student within the Department of Psychology.

Fig. 1 Socially Animated Machine (SAM)

2.1 The Appearance of SAM

The first prototype of the robot SAM is designed for tabletop use and sits at 50 cm tall. It has a hand-cut plate aluminum head, a prefabricated torso, and two prefabricated arms, all of which maintain space for servos, as well as two stationary legs. The torso is mounted on a PVC post, which is in turn mounted vertically on a 12×18 in wooden board. SAM possesses a total of 10 degrees of freedom, all of which are controlled through servo motors. Six servos move SAM's neck and arms, offering a good range of mobility throughout the upper torso. Two of these control the pan and tilt of the head, allowing SAM to "look" in any direction achievable by a typical human. The other four servos are in the shoulders, with 2 servos in each shoulder. SAM's range of motion in the shoulders allows for raising and lowering of the arms, as well as their crossing and spreading. Both arms can move in any direction in the forward hemisphere, provided the required space is not otherwise occupied by the other arm or torso. These motors allow SAM to carry out many basic conventional and instrumental gestures, such as clapping, shrugging, pointing, head nodding, and head turning and shaking.

The head of SAM, measured at 16×16 cm, contains eyes, eyebrows, ears, a nose, and two lips forming a mouth. SAM is equipped with four small servos that control the eyebrows and mouth: one servo for each eyebrow and one for each lip. Eyebrow servos rotate to achieve the angle required for each emotion, and lip servos act to push up or pull down on the center of each lip. The lips themselves are made from a single elastic band, anchored to a single stationary screw at each corner of the mouth. By changing the angle of the eyebrows, as well as the curvature of the lips and the gap between them, SAM can produce a variety of facial expressions (Fig. 2). The lips also move in synchronization with verbal output. This was accomplished by first recording the scripted questions

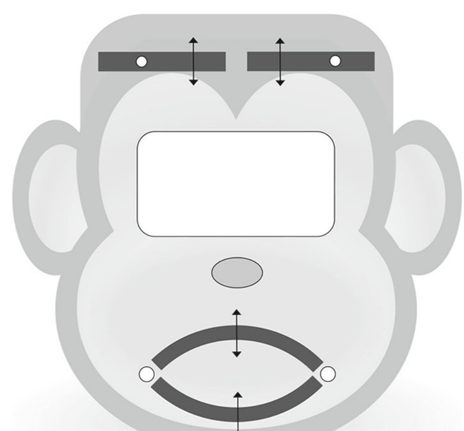

Fig. 2 SAM's facial degrees of freedom

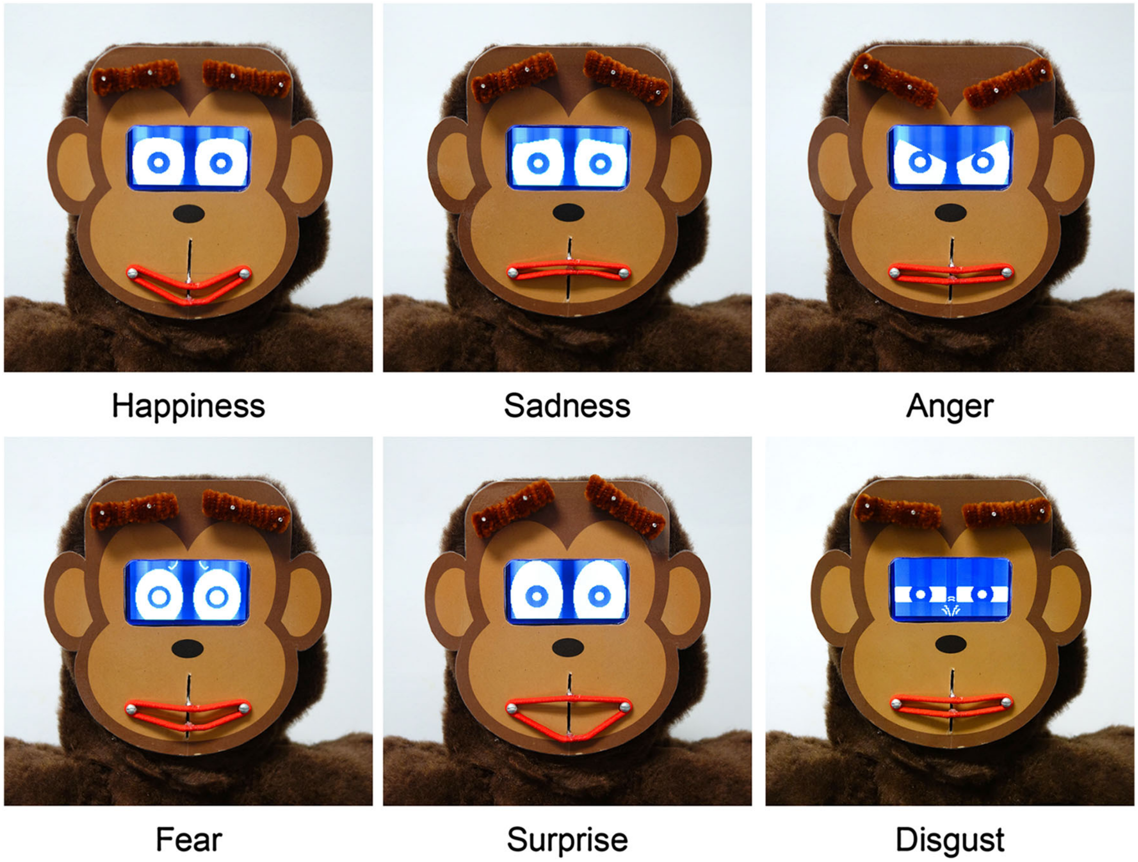

Fig. 3 SAM's emotional expressions

and responses as WMA files, then writing the necessary code to move the servos in synchrony with the audio. Audio files are located on a Surface Pro 2 tablet [47] and played through its speakers.

SAM's eyes are displayed on a 7 × 4 cm graphic LCD screen, with resolution of 128 × 64 pixels. The screen is based on the common and well-supported KS-0108 GLCD, allowing for modification and use of much pre-existing control language. Using a low-cost screen with a great deal of readily accessible code in the online electronics community was in line with the overarching principle of creating an easily reproducible robot for the ASD community. The digital display also provides a way to capture the detailed, subtle changes to the eyes and surrounding area (e.g., eye lids, skin folds) that accompany different facial expressions, without investing the time and expense of creating skin that would respond realistically to the movements of SAM's motor-driven facial features. While the presentation of SAM's eyes on a two-dimensional screen allows for additional detail, the remaining aspects of SAM's face operate in three dimensions to promote realistic and natural facial movement and expression. SAM's eyes are rounded and exaggerated, similar to those seen in a cartoon character. The eyes, including any appropriate creases around them, were created manually as bitmaps in Photoshop© [48], uploaded, and displayed in sequence, as in animation or a flipbook, to convey gradual change. With this setup, SAM was programmed to model the six basic emotional expressions [49]: happiness, sadness, anger, fear, surprise, and disgust (Fig. 3).

2.2 The Operation of SAM

SAM is operated in automatic mode. The interaction session is programmed through Presentation® software, Version 17.2 [50], a system that provides stimulus delivery and communication with external devices. SAM interacts with human users by displaying different social behaviors following responses made on the touchscreen tablet. Using Presentation's own programming language, coded signals specifying certain actions are sent from the tablet to SAM via USB, while audio files are played simultaneously on the tablet. Based on the nature of the signal, SAM displays a response, which has been programmed in the Arduino® integrative development environment and uploaded to the embedded Arduino Mega 2560 microcontroller [51]. The microcontroller is mounted with screws to the back of SAM's torso, along with a small breadboard containing some additional circuitry. Contrast and brightness of the GLCD are controlled with potentiometers that are also found in the back. Responses consist of preprogrammed motor movements and sequential GLCD (facial) displays, both of which are synchronized with vocal recordings. For example, when the correct answer is chosen on the tablet, SAM responds by exclaiming, "That's right!" while clapping and displaying a happy expression. By asking questions and responding with various preprogrammed social behaviors, SAM is able to maintain the human–robot social interaction without requiring outside control by experimenters. This design allows for a high level of consistency across interactions with different users.

3 Aims of Current Research

The overarching goal of this study was to design a novel social robot, SAM, with a unique mix of humanoid and animal-like features allowing for the expression of complex emotional states. It was hoped that this distinct design would provide the ideal platform to address the development of emotion recognition skills in individuals with ASD. A feasibility study was conducted to examine both the accuracy of SAM's emotional facial expressions as well as the functionality and acceptability of SAM among children with ASD. There were three specific aims, which were implemented and explored over the course of two studies:

(1) To analyze the accuracy with which SAM can produce facial expressions depicting various emotional states.
(2) To assess the level and quality of engagement of children with ASD during a human–robot interaction in comparison to a human–human interaction.
(3) To explore whether children with ASD find the human–robot interaction to be both enjoyable and comfortable.

4 Accuracy of SAM's Emotional Facial Expressions

Study 1 provided a preliminary analysis of whether SAM is capable of forming complex facial expressions to display an array of emotions similar to those observed in the human face. To assess the accuracy with which SAM displays different emotions, a sample of typically developing children was asked to examine photos of SAM's face and identify the expressed emotion. To assess the generalizability of SAM's facial expressions to human expressions, participants were also asked to match photos of SAM's face to photos of a human face displaying these emotions. It was predicted that SAM's facial expressions would be labeled and matched with high accuracy. Strength of agreement, based on Fleiss' [52] generalized kappa (κ), was expected to fall at or above the moderate range.

4.1 Methods

4.1.1 Participants

Thirty-five typically developing children between the ages of 6 and 12 were enrolled in this study ($M = 8.5$, $SD = 2.3$). Of the 35 enrolled participants, 18 were female. Thirty-two participants were Caucasian and three were African American. Participants were recruited from various clubs and organizations in a large, urban setting in the Southeastern United States. To be included in the study, participants could have no previous diagnoses of developmental disabilities or other psychiatric or learning disorders.

4.1.2 Materials

The Identifying Emotion Questionnaire was developed to assess the accuracy with which SAM can successfully model six target emotions: happiness, sadness, anger, fear, surprise, and disgust. To assess the identifiability of these facial expressions, the first section of the questionnaire involved labeling photos of SAM's face from a word bank of emotions. To assess the generalizability of SAM's facial expressions to true human expressions, the second section involved matching photos of SAM's face to photos of a human face displaying various emotions. Face photos consisted of black-and-while pictures of a female model and were acquired through Ekman and Friesen's [49] work on emotion recognition.

4.1.3 Procedure

All procedures were approved by the Institutional Review Board. Study procedures took place at the child's club or organizational meeting site. Parents gave written informed consent after full explanation of study procedures, and written child assent was obtained from children ages 7 and older. After consent was obtained, participants completed the Identifying Emotion Questionnaire. Questionnaires took approximately 20 min to complete and were finished on an individual basis under the supervision of study personnel.

4.2 Results

Descriptive statistics were generated to examine the accuracy with which participants were able to label SAM's facial expressions. Overall, SAM's expressions were identified with 83.3% accuracy, $SD = 21.8$. On average, partici-

Table 1 Accuracy for labeling SAM's emotions

SAM's face	Emotion labels											
	Happiness		Sadness		Anger		Fear		Surprise		Disgust	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Happiness	**35**	**100.0**	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Sadness	0	0.0	**32**	**91.4**	0	0.0	3	8.6	0	0.0	0	0.0
Anger	0	0.0	1	2.9	**32**	**91.4**	0	0.0	1	2.9	1	2.9
Fear	0	0.0	1	2.9	0	0.0	**21**	**60.0**	10	28.6	3	8.6
Surprise	0	0.0	0	0.0	0	0.0	9	25.7	**25**	**71.4**	1	2.9
Disgust	0	0.0	1	2.9	3	8.6	1	2.9	0	0.0	**30**	**85.7**

Bold values indicate correctly identified emotions

Table 2 Accuracy for matching SAM's emotions

SAM's face	Human face											
	Happiness		Sadness		Anger		Fear		Surprise		Disgust	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Happiness	**32**	**91.4**	0	0.0	0	0.0	2	5.7	0	0.0	1	2.9
Sadness	1	2.9	**27**	**77.1**	3	8.6	1	2.9	1	2.9	2	5.7
Anger	0	0.0	0	0.0	**25**	**71.4**	0	0.0	0	0.0	10	28.6
Fear	1	2.9	2	5.7	0	0.0	**21**	**60.0**	10	28.6	1	2.9
Surprise	1	2.9	0	0.0	1	2.9	10	28.6	**20**	**57.1**	3	8.6
Disgust	0	0.0	6	17.1	8	22.9	1	2.9	2	5.7	**18**	**51.4**

Bold values indicate correctly identified emotions

pants correctly labeled five of SAM's six expressions ($M = 5.0$, $SD = 1.3$). To further analyze agreement across participants while accounting for agreement due to chance, Fleiss' [52] generalized kappa (κ) was calculated. Based on guidelines suggested by Landis and Koch [53], overall strength of agreement was substantial, $\kappa = 0.681$, 95% CI [0.670, 0.692], $p < .001$.

Follow-up descriptive statistics explored accuracy for labeling SAM's expressions of individual emotions. Table 1 displays the number and percentage of participants who correctly identified each emotion. Happiness was accurately identified by 100% of participants, followed by sadness (91.4%), anger (91.4%), disgust (85.7%), surprise (71.4%) and fear (60.0%). Participants had the most difficulty labeling expressions displaying fear and surprise. The most common error was fear mistaken for surprise (28.6%), followed by its inverse, surprise mistaken for fear (25.7%). All other error levels were less than 10.0%.

Descriptive statistics were also generated to examine the accuracy with which participants were able to match SAM's facial expressions to photos of human expressions. Overall, SAM's expressions were matched with 68.1% accuracy, $SD = 28.1$. Participants on average correctly matched four of SAM's six expressions ($M = 4.1$, $SD = 1.7$). To further analyze agreement across participants while accounting for agreement due to chance, Fleiss' [52] generalized kappa (κ) was calculated. Overall strength of agreement was moderate, $\kappa = 0.434$, 95% CI [0.424, 0.445], $p < .001$.

Follow-up descriptive statistics explored accuracy for matching SAM's expressions of individual emotions to human expressions of emotions. Table 2 displays the number and percentage of participants who correctly matched each emotion. Happiness was accurately matched by 91.4% of participants, followed by sadness (77.1%), anger (71.4%), fear (60.0%), surprise (57.1%), and disgust (51.4%). Participants had the most difficulty matching expressions displaying disgust, surprise, and fear. The most common errors were fear matched with surprise (28.6%), surprise matched with fear (28.6%), and anger matched with disgust (28.6%). Errors also occurred when disgust was matched with anger (22.9%) or sadness (17.1%). All other error levels were less than 10.0%.

5 Engagement and Enjoyment with SAM

Study 2 examined the functionality and acceptability of SAM within a group of children with ASD. The objective was to investigate how children with ASD engage with and respond to SAM during a social interaction session. Engagement, defined as "sustained attention to an activity or person," is often characterized by maintenance of eye gaze on relevant stimuli [54]. For this study, engagement was measured in terms of time spent viewing regions of interest (ROIs) within the environment. Engagement was compared across a human–robot interaction and a similar human–human interaction. It was hypothesized that children with ASD would be more engaged and therefore spend more time viewing ROIs during the human–robot interaction. It was further hypothesized that children with ASD would spend more time attending to the face of the interaction partner during the human–robot interaction.

In examining the acceptability of SAM, Study 2 also explored whether children with ASD would find the human–robot social interaction enjoyable. To assess level of enjoyment, participants completed a brief questionnaire after interacting with SAM. The questionnaire contained rating scales to assess how happy and comfortable these children felt throughout the interaction, as well as how much they would like to interact with SAM again. It was hypothesized that children with ASD would rate their interaction with SAM highly across all domains.

5.1 Methods

5.1.1 Participants

Of the 14 children who were initially enrolled, one withdrew before completing study procedures. Thirteen children between the ages of 5 and 11 completed the study ($M = 8.4$, $SD = 2.0$). Of the 13 participants, five were female. Nine participants were Caucasian, two were African American, one was Hispanic, and one was of mixed descent. Participants were recruited from a local private school that offers specialized services for children with ASD. Inclusion criteria included a previous diagnosis of ASD according to the Diagnostic and Statistical Manual of Mental Disorders (DSM-V) by a licensed community professional [2]. Diagnostic eligibility was confirmed by the Autism Diagnostic Observation Schedule—Second Edition (ADOS-2) [55]. Based on the developmental and language levels of children in the sample, Module 3 was completed for all participants. All participants received ADOS-2 total scores at or above criteria for ASD ($M = 12.3$, $SD = 3.6$, Min = 7, Max = 18).

To ensure that cognitive skills were adequate to participate in the study protocol, additional inclusion criteria included mild-to-no cognitive impairment (SS $\geq$ 80). Cognitive eligibility was confirmed by the Kaufman Brief Intelligence Test—Second Edition (KBIT-2) [56]. All participants achieved an overall IQ composite score within the range of mild-to-no cognitive impairment ($M = 97.8$, $SD = 13.4$, Min = 80, Max = 130). Lastly, participants were not permitted to have uncorrected vision problems, given that it may interfere with their ability to engage within the interaction sessions.

5.1.2 Materials

To assess overall response to SAM and the human–robot social interaction, participants were asked to complete a brief enjoyment questionnaire. The enjoyment questionnaire contained rating scales to assess three domains: how happy the children felt during the interaction with SAM, how comfortable they felt talking with SAM, and how much they would like to interact with SAM on another occasion. Self-reported levels of enjoyment were measured using ten-point Likert-type scale items, where higher ratings were indicative of high enjoyment, comfort, and desire for future interactions. To promote understanding of the task, a thermometer was used to illustrate the 10-point rating scale for each question.

5.1.3 Procedure

Institutional review as well as consent and assent processes were completed in the same manner as with Study 1 (Sect. 4.1.3). Study procedures took place on UAB's campus. On the scheduled appointment day, participants were accompanied to the session by at least one caregiver. Caregivers completed a demographic information form. Children completed the ADOS-2, KBIT-2, an emotion recognition task with SAM, and the enjoyment questionnaire. FaceLAB^{TM} [57] eye tracking technology was utilized during the KBIT-2 (human–human social interaction) and the emotion recognition task (human–robot social interaction). Appointments lasted approximately 2 h.

5.1.4 Interaction Conditions

Human–robot interactions were structured around an emotion recognition task. As SAM will ultimately be used in a social skills intervention promoting the development of emotion recognition abilities, the task used in this study was modeled after a session from the proposed intervention program. The emotion recognition task involved a series of mini-games that include SAM modeling various emotional expressions and asking participants to identify expressions pictured in photos of human faces [49] and schematic drawings [58]. During the task, SAM spoke directly to participants by asking questions, showing pictures on the touchscreen tablet, and giving helpful feedback on performance. As such, the human–robot social interaction was structured in a way that participants were required to listen to verbal prompts from SAM, use a tablet to evaluate potential answers from an array of choices, and make responses. Interactions with SAM lasted approximately 10 min ($M = 614.6$ s, $SD = 33.0$).

Human–human interactions with the experimenter involved administration of the KBIT-2 cognitive assessment [56]. Participants completed cognitive tasks designed to measure receptive language skills, general knowledge, and the ability to solve visual analogies and puzzles. To more closely resemble the structure of the human–robot inter-

Table 3 Contrast of human–robot and human–human interaction conditions

Variable	Robot		Human		$t(12)$	p	95% CI		d
	M	*SD*	M	*SD*			*LL*	*UL*	
Overall % engagement	59.80	15.94	63.22	21.29	−.45	.659	−19.87	13.04	0.13
% Engagement time on face	28.52	15.08	7.69	12.02	4.27	.001	10.19	31.48	1.18

N = 13
CI confidence interval, *LL* lower limit, *UL* upper limit

action, only subtests involving the use of a stimulus book (e.g., Verbal Knowledge and Matrices) were considered as part of the interaction session. Exclusion of the third subtest (e.g., Riddles) also kept the interaction conditions to a comparable duration. Similar to the human–robot condition, the human–human social interaction required participants to listen to verbal prompts from the experimenter, use a stimulus book to evaluate potential answers from an array of choices, and make responses. Interactions with the experimenter lasted approximately 15 min ($M = 892.3$ s, $SD = 306.8$).

5.1.5 Eye Tracking

During the two interaction conditions, participants' eye gaze patterns were monitored and recorded by the faceLAB™ eye tracking system, Version 5 [57]. Eye tracking cameras sat non-intrusively on a table between the child and the interaction partner. Cameras tracked the children's eye movements by measuring their infrared pupillary and corneal reflections, and recorded the viewed stimuli at a rate of 60 frames per second. For each of the interaction conditions, coordinates of relevant stimuli in the environment, deemed regions of interest (ROIs), were defined within the faceLAB™ system. For the human–robot interaction, ROIs included SAM's face, body, and the workspace (e.g., touchscreen tablet). For the human–human interaction, ROIs included the experimenter's face and the workspace (e.g., stimulus book). All undefined stimuli within the viewing environment were recorded as "Other."

Viewing patterns were analyzed as an objective measure of engagement during the interaction sessions. Eye gaze is often described as an important nonverbal component of social engagement, and many studies assessing engagement in robotic research utilize recordings of participant eye gaze [59–61]. Past research has found consistency between eye gaze patterns and subjective ratings of engagement made by observers [62]. For this study, we developed an algorithm to calculate the proportion of interaction time spent viewing each ROI, as well as the proportion of time spent viewing ROIs collectively. Estimates of engagement, based on time spent viewing ROIs, were generated for each interaction condition. Time spent viewing other non-relevant stimuli was categorized as distraction.

5.2 Results

To assess overall engagement, a paired samples t-test was conducted to compare the proportion of time spent viewing ROIs across the human–robot and human–human interactions (Table 3). Analyses confirmed that participants did not spend significantly more time viewing ROIs during either interaction condition, $t(12) = -0.45$, $p = 0.659$. Participants displayed similar levels of overall engagement while interacting with SAM ($M = 59.8\%$, $SD = 15.9$) and with the experimenter ($M = 63.2\%$, $SD = 21.3$).

To further analyze how engagement time was utilized across the interaction conditions, a paired samples t-test was conducted to compare the proportion of engagement time spent viewing the face across the human–robot and human–human interactions (Table 3). Analyses confirmed that participants spent significantly more engagement time viewing the face during the human–robot interaction than during the human–human interaction, $t(12) = 4.27$, $p = .001$. The effect size for this analysis ($d = 1.18$) exceeded Cohen's [63] convention for a large effect ($d = .80$). While engaged with SAM, participants spent 28.5% of time ($SD = 15.1$) looking at the face. In contrast, they only spent 7.7% of time ($SD = 12.0$) looking at the face while engaged with the experimenter.

To explore whether participants enjoyed interacting with SAM, descriptive statistics were generated to determine level of happiness, comfort, and desire for future interactions. Participants reported feeling very happy ($M = 9.5$, $SD = 1.1$) and comfortable ($M = 9.2$, $SD = 1.9$) while talking with SAM. Participants in this study were also very eager to have an additional interaction with SAM ($M = 9.0$, $SD = 2.8$).

6 Discussion

The purpose of this two-part feasibility study was to design and evaluate the functionality and acceptability of a novel social robot. SAM was created with a unique mix of humanoid and animal-like features, allowing for the expression of complex emotional states while maintaining social interactions that are engaging and enjoyable for children with ASD. This study examined the accuracy of SAM's emotional facial expressions within a sample of typically developing

Table 4 Emotion identification rate for different social robots. Adapted from Saldien et al. [64], Probo [64], Kismet [65], Eddie [66], Feelix [67]

	SAM	Probo	Kismet	Eddie	Feelix
Happiness	100	100	82	58	60
Sadness	91	87	82	58	70
Anger	91	96	76	54	40
Fear	60	65	47	42	16
Surprise	71	70	82	75	37
Disgust	86	87	71	58	–
Overall %	83	84	73	57	45

children as well as the functionality and acceptability of SAM among children with ASD.

The results of Study 1 suggest that SAM's robotic design allows for the formation and display of complex facial expressions similar to those observed in the human face. Analyses exploring the identifiability of SAM's expressions were promising. Overall, participants were able to label SAM's expressions at a rate of 83.3% accuracy with substantial agreement ($\kappa = 0.681$). When compared to the emotion identification levels that have been achieved using other social robots, SAM's expressions were generally labeled at or above accuracy levels for those designs (Table 4) [64–67]. This finding is particularly notable considering the current study assessed emotional expressions for the original prototype of SAM, which has yet to undergo revision. Analyses examining the generalizability of SAM's expressions to true human expressions were also encouraging. Participants were able to match SAM's expressions to human expressions at a rate of 68.1% accuracy with moderate agreement ($\kappa = 0.434$). Given the increased difficulty of the generalizability task and the multiple steps involved in identifying robotic and human expressions and matching them together, it is not surprising that performance was slightly lower within this domain.

Notably, participants displayed more difficulty identifying and generalizing certain emotional expressions. Overall, happiness, sadness, and anger were correctly labeled and matched most consistently. Although disgust was frequently labeled correctly, participants often confused this expression with anger and sadness when matching robot expressions to human expressions. Additionally, fear and surprise were often mistaken for one another across both tasks. These findings are consistent with past research exploring the facial expressions of social robots, where complex emotions are more difficult to identify and discriminate. Concerning SAM's emotions, only subtle differences exist between expressions of fear (e.g., pupil dilation, furrowed brow) and surprise (e.g., widening of mouth). This may be overlooked by children, especially when viewing small photos of the face. However, these subtle facial details make SAM's expressions unique, and can be used to highlight the differences between emotions when teaching emotion recognition skills to children with ASD. Future versions of SAM will aim to improve upon the display of these complex emotions by modifying and emphasizing salient facial features. For example, the research team has discussed adding an additional axis to each eyebrow and possibly one more to each lip to allow for more flexibility of expression.

Results of Study 2 revealed that children with ASD were equally engaged across interactions with SAM and the experimenter. Participants spent a similar amount of time attending to ROIs within the environment during human–robot and human–human interactions. However, the quality of engagement varied significantly across interaction conditions, in that children were engaged in a much more social manner when interacting with the robot. Children with ASD spent a significantly greater amount of engagement time looking at the partner's face while interacting with the robot ($M = 28.5\%$) than while interacting with the experimenter ($M = 7.7\%$), meaning that children spent over three-and-a-half times longer viewing the robot's face than the human's face. Not only did participants engage with and attend to the face while interacting with SAM, they also rated their interactions quite highly. On 10-point Likert-type rating scales, children with ASD reported high enjoyment ($M = 9.5$), comfort ($M = 9.2$), and desire for additional interactions with SAM ($M = 9.0$).

6.1 Limitations

Results of these studies are promising; however, certain limitations should be noted. In Study 1, participants viewed photos of SAM's emotional expressions rather than observing the expressions in a face-to-face interaction with SAM. During a live interaction, participants can view the transition of SAM's face from a neutral expression to the emotional expression, which provides additional information about the emotion that was not present in the photos. As such, subtle facial details may have gone unnoticed that would have been more recognizable when viewing SAM's face directly. Additionally, Study 1 enrolled only typically developing children. Similar research [64] has also examined accuracy ratings from healthy adults, who display a higher cognitive capacity and increased ability to understand and identify emotional content, particularly for complex emotions. Considering these limitations, we expect future research examining revised versions of SAM will utilize face-to-face interactions and include both healthy children and adults, with the goal of demonstrating increased accuracy ratings for labeling and matching SAM's emotional expressions.

Study 2 also had limitations. Though the human–robot and human–human interaction conditions were structured in a similar manner, the content of the interactions was different. The human–robot interaction, given its focus on emotion recognition, may have inherently prompted more opportunities to look at the face of the interaction partner. All instructions were given verbally, and while it was hoped that participants would look to SAM's face to gain valuable emotion information—just as they might look to the face of the human interaction partner to read nonverbal cues—it was not necessary to make accurate responses. However, the nature of the task may explain some of the increase in socially directed engagement. Additionally, the same experimenter served as the partner during all human–human interactions, thereby confounding individual characteristics with human–human interactions in general. These issues are thought to be minor in the current research but should be clarified in future studies by comparing engagement across interactions involving the same task and with different experimenters. Additionally, although the current research contains an adequate number of typically developing children and a much larger sample of children with ASD than many other robotic studies that rely on case examples, larger sample sizes in both studies would likely strengthen the results.

6.2 Future Research

Overall, this study indicates that SAM's prototypal design provides a successful first step toward filling the void in robotic technology geared toward individuals with ASD. SAM operates as intended, and shows potential for use in social skills interventions, particularly those focused on improving skills such as emotion recognition. This is largely due to the fact that children with ASD, who have difficulty looking at others' faces during human–human interactions, are able to remain engaged and attentive to SAM's face during a human–robot interaction. As over half of emotional intent is displayed through facial expressions [44], this makes a robot like SAM the ideal tool for modeling and teaching emotions. Given higher levels of attentiveness to the robot's face, SAM may also prove to be a useful platform for improving nonverbal social behaviors such as appropriate eye contact and joint attention.

Based on overwhelmingly positive ratings of enjoyment collected via the post-interaction questionnaire, it seems likely that SAM will be accepted by the majority of elementary school age children with ASD. Ratings on happiness, comfort, and desire for additional interactions offer promising evidence toward the inclusion of SAM in an intervention protocol. As social skills are developed and built upon over the course of several intervention sessions, disinterest and attrition can often pose a problem. It is therefore important that children enjoy the intervention and feel motivated to succeed. Taken together, the results of this study have significant implications for future work with SAM on developing social skills in children with ASD. Addressing questions about the practicality, efficacy, and ultimate benefit of this tool will be a primary focus of future research, including whether skills developed with SAM can be carried over into human–human interactions.

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Compliance with ethical standards

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