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Robot-Mediated Interventions for Teaching Children with ASD a New Intraverbal Skill

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Abstract

Socially assistive robots (SAR) have the potential to impact therapies for Autism Spectrum Disorder (ASD) by supporting clinicians in increasing learning opportunities presented to individuals. Recent research on robot-mediated intervention (RMI) delivery has predominantly addressed social deficits in ASD with positive outcomes. Current literature has minimal focus on teaching children with ASD a skill not known apriori by the individual. Furthermore, it is unclear how to integrate robots in clinical settings because current RMIs do not adhere to Applied Behavior Analysis (ABA) protocols. In this work, we investigated whether a RMI could be utilized to teach children with ASD a completely new language and communication skill they could not exhibit at baseline. We utilized a standard ABA assessment tool to first identify appropriate skills to teach children with ASD. We then developed, implemented, and evaluated a RMI intervention that followed standard clinical operating procedures in ABA and targets participants' unique skill deficits. We examined the effects of the RMI training on teaching wh-question answering. All sessions were conducted with the SAR as the primary therapist using evidenced-based ABA human teaching protocols. All participants acquired the wh-questions answering skill within seven sessions which is in line with their typical acquisitions rates.

Keywords: Autism Spectrum Disorder, Applied Behavior Analysis, Socially Assistive Robots, Child-Robot Interactions, Intraverbals

Robot-Mediated Interventions for Teaching Children with ASD a New Intraverbal Skill

Autism Spectrum Disorder (ASD) is defined by the Centers for Disease Control and Prevention (CDC) as a developmental disability that can cause significant social, communication, and behavioral challenges and was identified to affect nearly 1 in 54 children (CDC, 2020). Some common indications of ASD include repetitive behaviors, poor eye contact, limited or non-functional play skills, difficulty adapting to routine changes, trouble expressing and understanding emotions, and restricted social skills. The severity of these challenges and symptoms vary from person to person. Although ASD is a lifelong disorder, early intervention has been proven to be significantly more effective when compared to those who receive intervention at a later age. Teaching strategies for a child with ASD often include the reinforcement of desired skills and behaviors through individualized instruction, intensive training, repeated instruction, and generalization across environments (Ruble, Dalrymple, & McGrew, 2012).

Computer-assisted instruction has become an increasingly popular teaching strategy for individuals with ASD (Root et al., 2017). Computer-based interventions have been used to teach academic skills (Root et al., 2017), social skills (Valencia et al., 2019), and communication skills (Ramdoss et al., 2011). Although these interventions have shown successful outcomes, some remaining limitations include the inability to provide naturally occurring reinforcers, lack of generalization to real-life contexts, and only interactions via a digital screen (Ramdoss et al., 2011). Namely, reinforcements generated by computers typically include digitized auditory and visual stimuli presented on a screen which does not exist in real-life scenarios. Naturally occurring reinforcers in real-life scenarios include embodied social praise/approval and access to preferred items. Similarly, the antecedent stimuli for evoking behaviors in real-life social interactions typically include embodied social attributes such as eye gaze, physical proximity, posture, facial expressions, social touch, and gestures (Szafir, 2012). This is important because interventions should use mediating stimuli that are naturally occurring in real-life to facilitate generalization of learned skills to real-life scenarios (Stokes & Baer, 1977).

Robot-mediated therapies have the potential to address these limitations because robots are physically embodied and do not require individuals with ASD to interact with a digital screen. Namely, humanoid robots mimic the appearance of a human body which enables it to make eye contact, communicate verbally and through gestures, inhabit the same physical space, and deliver personalized human-like strategies. These robot features can act as mediating stimuli to help generalize skills learned from the robot to human interactions by utilizing naturally occurring antecedents (e.g., eye contact followed by speech) and reinforcers (e.g., social praise and celebratory body language) during therapy delivery. Robot-mediated therapies may also help reduce anxiety associated with the learning process and increase motivation for learning. Namely, Intensive World Theory of Autism suggests that avoidance of stimulus loaded situations (e.g., complex social interactions) and defaulting to behavioral routines (e.g., stereotypic and repetitive behaviors) is a barrier to learning for individuals with ASD (Markram & Markram, 2010). These behaviors are often a consequence of anxiety with social interactions or over simulation (i.e., information overload). Robots are consistent and non-judgmental which could add predictability and reduce social anxiety during interventions with individuals with ASD (Scassellati, 2007). Thus, these robot attributes could help individuals with ASD learn faster and transfer those skills into real-life scenarios more easily (Smith, 2001). Social Motivation Theory further emphasizes that individuals with ASD do not seek or maintain relations with human partners but prefer nonhuman and mechanical stimuli (Chevallier et al., 2012). For individuals who lack social motivation with humans, robots could be used as an intermediary agent for supporting teaching these individuals' new skills. Numerous researchers have already demonstrated that robots can elicit prosocial behaviors from an individual with ASD (Costa et al., 2010; De Silva et al., 2009; François et al., 2009; Kozima et al., 2007; Robins et al., 2004) and more importantly with other peers and adults (Robins et al., 2005; Wainer et al., 2014).

A review by Cabibihan et al. (2013) identified that a major research area for Socially Assistive Robots (SARs) is on the delivery of language and communication interventions to individuals with ASD. Current literature in language and communication consists of studies with robot's eliciting social interaction, vocalizations, and self-initiated interactions (Kim et al., 2013; Kozima et al., 2007; Michaud & Larouche, 2007; Robins et al., 2009; Vanderborght et al., 2012; Wainer et al., 2014). Namely, robots were utilized to elicit or encourage social interactions from children with ASD (Michaud & Larouche, 2007; Robins et al., 2009; Vanderborght et al., 2012). Robots have also been utilized to target vocalizations in children with ASD by using the robot to evoke questions/comments (Kim et al., 2013; Kozima et al., 2007) and increase vocalization to peers (Wainer et al., 2014). Hence, current research in language and communications interventions for individuals with ASD has primarily focused on spontaneous and social communication interventions delivered by socially assistive robots. These studies are important in that they demonstrate children with ASD will show increases in a variety of social communication when interacting with robots. However, these increases in communication may only be due to the introduction of a novel stimulus and focus only on increasing the utilization of existing skills (Begum et al., 2015). Contingent reinforcers were also not utilized in the aforementioned literature (Kozima et al., 2007; Michaud & Larouche, 2007; Robins et al., 2009; Wainer et al., 2014). Namely, contingent reinforcement refers to the delivery of a reinforcer (e.g., preferred activity or social praise) only immediately after a correct response. In order for a new communication skill, previously not known apriori by an individual, to be learned it is necessary for a targeted behavior to be followed by contingent reinforcement (Cooper et al., 2019). Furthermore, it has been shown that when a robot provides contingent reinforcement to a child with ASD there will be an increase in targeted behaviors in comparison to when a robot randomly provides the preferred reinforcer (Feil-Seifer & Matarić, 2009). The use of contingent reinforcers to increase behavior change is a fundamental principle of Applied Behavior Analysis (ABA) which is the most commonly utilized therapy to help alleviate the symptoms of ASD.

More recently, a handful of research has focused on using ABA-based therapies with contingent reinforcement during language and communication interventions (Barakova et al., 2015; Begum et al., 2015; Huskens et al., 2013, 2015; Yun et al., 2017). In Begum et al. (2015), a social praise-based contingent reinforcement was delivered when adolescents with ASD responded to greetings from the robot. Results of the intervention showed that one out of three adolescents demonstrated an increase in greetings from baseline. Similarly, in Huskens et al. (2013) six adolescents with ASD were provided a contingent reinforcer when they asked the robot a question. The contingent reinforcement consisted of the robot exhibiting the action the adolescent requested of the robot. The adolescents demonstrated an increase in self-initiated question asking from baseline after participating in the intervention. In Yun et al. (2017), fifteen children with ASD were provided social praise or celebratory-based contingent reinforcements when the robot displayed an emotion and they verbally responded with the correct emotion. After the intervention, the children's ability to correctly identify facial emotions increased from baseline. Lastly, in Barakova et al. (2015) and Huskens et al. (2015) a robot provided prompts and reinforcements during a triadic LEGO game between two children with ASD and the robot.

Prompting and reinforcement were provided by the robot for asking questions related to the game or making verbal statements to the robot or other child. There were increases in social communication from baseline for three child participants. To date, current research has demonstrated that robot-mediated interventions utilizing contingent reinforcements increase targeted behaviors from baseline. In these studies, the individuals were demonstrating the targeted behavior at baseline. To the authors' knowledge, there is presently no studies that have a robot teaching an individual with ASD a new communication or language skill where the individual has not previously demonstrated the skill (i.e., zero skill demonstration at baseline). Teaching a new skill that presently does not exist in a child's repertoire requires a different teaching process than increasing a behavior that is already occurring (Cooper et al., 2019). For behavior that does not exist in a child's repertoire, the addition of prompts is necessary to first evoke the targeted behavior and contingent reinforcement is utilized to increase the future frequency of the evoked behaviors.

While there have been significant developments in SARs delivering ABA-based interventions to individuals with ASD, there has also been a lack of research towards utilizing assessments to ensure robot-mediated interventions target the unique skill deficits of an individual. Current robot-mediated interventions primarily focus on simple tasks and game performance with some recent interventions targeting the core deficits of ASD (DiPietro et al., 2019). Namely, existing studies include participants in an intervention based on only an individual's ASD diagnosis (e.g., Diagnostic and Statistical Manual of Mental Disorders [DSM-5]) but do not aim to target unique skill deficits of the individual (Simut et al., 2016; Barakova et al., 2015; Huskens et al., 2015). In Vanderborght et al. (2012) and Yun et al. (2017) participants were included in the studies based on their skill deficits, but the assessment tools utilized to identify skill deficits and levels of an individual were not described. To target unique deficits, standard clinical operating procedures require curriculum-based assessments (e.g., Verbal Behavior-Milestones Assessment and Placement Program [VB-MAPP]) to identify existing skill deficits in an individual's repertoire (Barnes et al., 2014). This leads to appropriate target skill selection according to both missing skills and existing developmental skill level. Assessment is important because if not applied can lead to targeting skills already mastered by an individual or skills that are too challenging (Gould, et al., 2011). Hence, this can lead to motivational challenges and ineffective as well as inefficient use of therapy time.

In this study, we investigated whether a SAR could deliver an ABA-based intervention with contingent reinforcement to teach an individual with ASD a completely new language and communication skill not known by the individual apriori. The language and communication skill targeted in this study was the intraverbal skill of answering wh-questions. The robot was developed to mimic standard operating procedures (e.g., time delayed prompting protocol) and actions (i.e., body language and paralanguage) used by behavior technicians at a University-based Autism Clinic to deliver an ABA-based intraverbal intervention. The efficacy of the robot-mediated intervention was evaluated by incorporating it as a component of the daily curriculum for three pre-school children diagnosed with ASD at the clinic. In order to ensure that the intervention meets the unique needs of the participants and to ensure they did not have the skill, the following standard procedure was used prior to the interventions: 1) assessment of deficits in an individual to confirm zero skill demonstration at baseline, 2) developing an intervention plan to address an individual's unique needs, and 3) implementing the intervention with ongoing frequent reassessment (The Council of Autism Service Providers, 2020).

Method

This study used a multiple baseline design to investigate the acquisition of the intraverbal skill of answering wh-questions using an ABA-based robot-mediated intervention. An intraverbal is defined as a verbal stimulus (e.g., who drives a tractor) which evokes a verbal response (e.g., farmer). We have chosen the intraverbal skill of answering wh-questions because they make up the majority of an individual's speaking behavior and form the basis for social interaction (Cooper et al., 2019). Furthermore, according to research reviewed by Eigsti et al. (2011), language milestones such as intraverbals are strongly related to long-term prognosis in ASD.

Standard Operating Procedures: Assessment and Objective Selection

Due to the strengths and deficits being unique to all individuals with ASD, the first step in ABA clinical practice is to perform assessments to determine the appropriate goals for each individual. In this work, we used the Verbal Behavior – Milestones Assessment and Placement Program (VB-MAPP) as an assessment tool. The VB-MAPP consists of 170 verbal behavior milestones, 16 different verbal operants (i.e., language objectives) and related skills, and is broken up into 3 developmental levels (0-18, 18-30, and 30-48 months). The assessment results in a score ranging between 0-170 with higher scores correlating to more advanced skill acquisition. Overall scores lead to the development of an individualized intervention plan which includes goals, objectives, procedures for instruction, error correction, prompt fading, reinforcement and performance data collection. All participants underwent a VB-MAPP assessment after we received parental consent to participate in this study.

Participants

Participants were selected for this study based on the following inclusion criteria: 1) 3-8 years old, 2) DSM-5 diagnosis for ASD, and 3) have not mastered wh-questions. In total three children were recruited for this study. All participants had previous exposure to answering wh-questions but did not demonstrate during baseline the wh-questions used in the study. Two of the three participants had previous exposure to the robot through a reading program mediated by the robot.

Marvin was a 5-year-old boy who had a Verbal Behavior Milestones Assessment and Placement Program (VB-MAPP) Milestone score of 144, a listener repertoire of 1200 words, and a tacting (i.e., labeling) repertoire of 1000 words. Brandon was a 5-year-old boy who had a VB-MAPP Milestone score of 136.5, a listener repertoire of 250 words, and a tacting repertoire of 750 words. Walter was a 5-year-old boy who had a VB-MAPP Milestone score of 149.5, a listener repertoire of 600 words, and a tacting repertoire of 500 words. These VB-MAPP scores identified that the participants would benefit from wh-question answering interventions and the interventions were at the appropriate developmental skill level.

Setting

The study took place in a university-based ABA autism clinic located in a midwestern state within a private therapy room approximately 11' x 22' in size with carpeted floor, Figure 1. The room had two tables and four chairs. One GoPro video camera was placed in the room to record the intervention for post-interaction analysis. A researcher was present in the room to keep the participant from physically interacting with the robot and seated in a chair. The researcher was also responsible for collecting data. A second researcher was in the room to control the actions of the robot via a laptop computer. A layout of the room is presented in Figure 2.

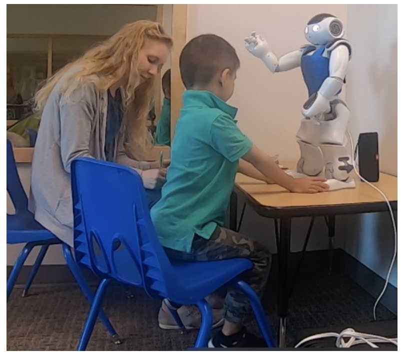


Figure 1. Participant interacting with the Socially Assistive Robot

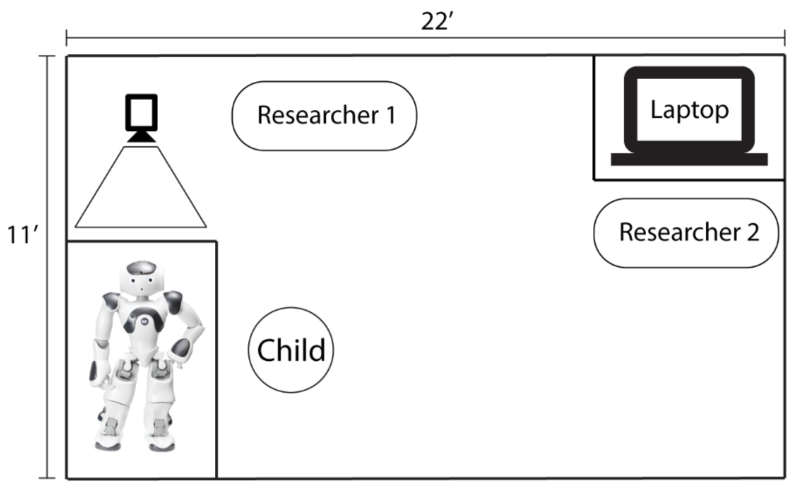


Figure 2. Layout of the private therapy room where the study was held

Materials

A humanoid Nao robot was used (See Figure 1) for this study. The Nao is 58cm in height with two degrees of freedom (DOF) in the head, five DOF in each arm, one DOF in each hand, and six DOF in each leg to enable it to produce physical movements. It contains speakers to enable it to speak verbally and an external speaker was used to amplify the sound. Furthermore, it has seven touch sensors, four bidirectional microphones, and two 2D cameras that enable the robot to sense the environment around itself. The robot was controlled remotely via a Wi-Fi connection by a Dell computer and a software program designed specifically for the study.

Experimental Design

The effects of the intraverbal wh-question answering intervention was evaluated using a single-subject multiple baseline design (MBD) across participants to investigate the acquisition of answering wh-questions using an ABA-based robot-mediated intervention. Single-subject research designs are a standard method utilized to evaluate ASD interventions in clinical research and can include only one single participant but in general will include 3-8 participants (Neuman & McCormick, 1995; Horner et al., 2005; Mesibov & Shea, 2011). Examples of such sample sizes utilized for the evaluation of interventions specifically in the field of ABA are also found in (Allan et al., 2015; Finkel & Williams, 2001; Goldsmith, et al., 2007; Miguel, et al., 2005; Vedora, et al., 2009). Single-subject designs are commonly utilized because individuals with ASD each have his/her own heterogenous skill set and level of functioning which leads to difficulty in obtaining a control sample. Namely, single-subject designs enable each participant to serve as his/her own control.

In our study, we utilize a multiple baseline single-subject design because the robot-mediated intervention focuses on teaching WH-question answering and multiple baselines are utilized when a learned skill is expected to not be reversible (Simonsen & Little, 2011). The intervention consisted of using a SAR to deliver common intraverbal wh-questions. One session of nine trials of wh-questions per day was conducted. Each session ranged in time from 202-906 seconds (μ=366, σ=152). Across the nine trials, three questions were presented randomly three times each. The teaching protocols directly mimicked standard procedures utilized from human therapists within the university-based clinic

Dependent Variable and Measurement

The primary dependent variable was the percentage of correct responses for the three intraverbal wh-questions. The targets selected included wh-questions with a common response (e.g., “Who flies a plane?”, “pilot”). Questions were designed to have a clear answer and contained 4-5 words within the question.

Correct responses were recorded as a “+” and defined as vocally answering three rotating wh-questions without prompts within five seconds of the robot’s instructions. Incorrect responses were recorded as a “-” and defined as the child responding incorrectly or not emitting a response within five seconds of the instruction. Prompted correct responses were recorded as a “+P” and defined as vocally answering a rotating wh-question within five seconds of the robot’s prompt. The prompt could be delivered immediately or two seconds after the targeted instruction. Prompted incorrect responses were recorded as a “-P” and defined as incorrectly answering or not providing a response immediately following prompt delivery.

Procedure

Baseline

The robot began interactions with the participant by engaging him/her with a conventional greeting (e.g., “How are you today?”, “Do you want to play with me?”). The purpose of this was to build rapport with the participant before presenting demands to him/her. We presented three high-probability (high-p) requests (e.g., “Clap your hands”, “A pig says…”) to ensure the child was attending and ready to participate in the intervention. High-p requests consist of presenting easy and known demands from the learner’s repertoire to increase compliance (Cooper et al., 2019). Social praise in the form of reinforcing movements and vocal statements (e.g., robot dances, “You rock!”) followed all correct responses to high-p behaviors.

Incorrect responses or no response from the participants were redirected by a different high-p request. Error corrections were not implemented for high-p requests.

Once the participant responded to three high-p behaviors, the robot presented the three wh-questions to each participant. For each participant, the three questions were presented randomly three times each for a total of nine trials. No consequences (e.g., praise) were delivered from the robot whether a participant answered a question correct or incorrect. Approximately every three questions, the robot presented three high-p requests followed by reinforcement to encourage the participant to continue responding because during baseline reinforcers were withheld for wh-questions. Wh-questions that received no correct responses were utilized during the intervention phase.

Intervention

Social interactions, conventional greetings, and high-p behaviors were implemented prior to each intervention session. Teaching procedures were immediately conducted after these components were completed. Each participant was taught three wh-questions from the robot using the following time-delay prompt hierarchy: immediate vocal prompt, two-second delay vocal prompt, four-second delay vocal prompt, and independence. The prompt hierarchy for each participant started with immediate prompts and progressed in two-second intervals until the child could answer independently. Prompts were delayed contingent on meeting mastery criteria, which was defined as 89% accuracy across two consecutive sessions. The presentation of these questions was randomized within a session to reduce the chance the participants were memorizing the order of the correct responses (Sundberg & Partington, 1998). Hence, the participants needed to comprehend the question delivered to them and then provide the correct response. This is considered one of the levels towards comprehension of wh-question answering within a standardized DTT-based language curriculum typically delivered in ABA clinics because it involves the ability to answer general and prior knowledge questions (Sundberg & Partington, 1998). Typically, there are 13 different levels of wh-question answering skills for children with ASD since the overall skill of answering wh-questions has many complex factors and cognitive processes (Sundberg & Partington, 1998; Sundberg, 2014). Decomposing wh-question answering into these levels enables a child with ASD to scaffold increasingly difficult cognitive processes so they can gradually learn the overall skill of answering novel wh-questions. Without this scaffolding and progressive development process, an individual with ASD can be faced with a skill that is too challenging for them which has the potential to lead to increased errors and decreases in motivation, and, therefore, increased time for skill acquisition or worse yet lack of skill acquisition (Sundberg & Partington, 1998; Sundberg 2014). We selected this level of wh-questions because according to the participants VB-MAPP assessments this was within their current level of functioning (Sundberg, 2014).

Social praise was delivered contingent on the participant vocally emitting the correct response to the targeted question before prompts were delivered or after prompts were delivered. Error corrections were provided when the participant incorrectly responded or did not respond at all. The error correction consisted of the following sequence of actions: 1) close the trial (e.g., "Let's try again"), 2) repeat the original question with an immediate prompt following the question, 3) social praise of the participant's correct response, and 4) continuing the original instruction. Error corrections were repeated until a correct response was emitted or up to three times.

Interobserver agreement (IOA)

IOA was scored for the collected performance data using the trial-by-trial technique where the number of trials that agreed were divided by the total number of trials and converted into a percentage. The first observer was the behavior technician that scored all participants correct and incorrect responses in-person. A second observer scored correct and incorrect responses via video recordings on 30% of sessions for each participant. Mean IOA for Marvin across all sessions was 98% with a range of 89%-100%. Mean IOA for Brandon across all sessions was 88% with a range of 82%-100%. Mean IOA for Walter across all sessions was 90% with a range of 80%-100%.

Treatment Integrity

Treatment integrity was obtained for the following steps of the robot delivering the Discrete Trial Training (DTT) procedure: presenting the target instruction to the participant; providing the required prompt during the zero second, two second, four second, and independent stages of the intervention; and providing error corrections or reinforcements if applicable. Treatment integrity was collected during 30% of the sessions on the behavior of the researcher while he/she controlled the robot using the laptop computer. Treatment integrity was scored on the occurrence or non-occurrence of the procedural steps during all of the nine presentations of the three targets each session. An average of 96% was obtained for treatment integrity with a range of 91%-98% across all participants.

Results

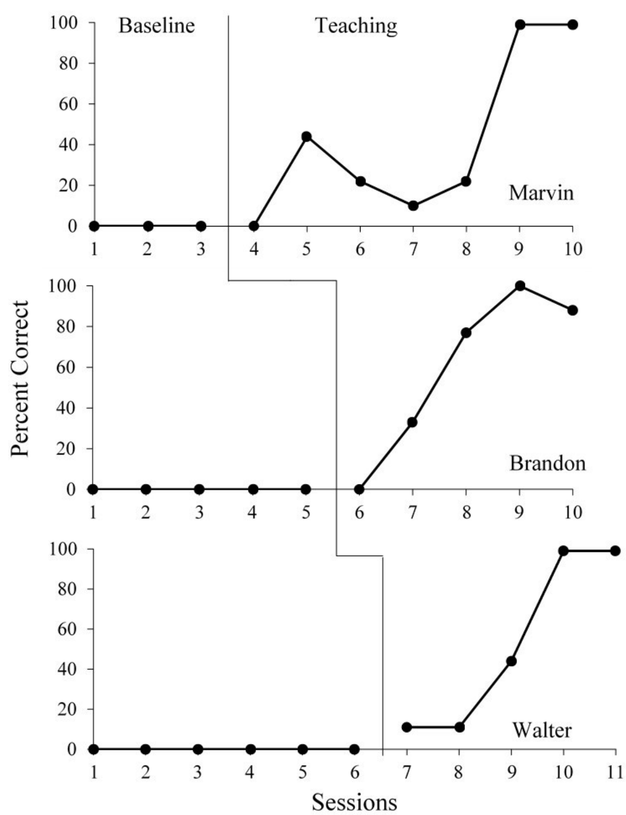
Figure 3 displays the results of intraverbal wh-questions across all three participants. Baseline data reported 0% on the targeted skills for all participants. All participants completed the intervention within five to seven sessions.

During baseline Marvin had zero correct responses on “Who repairs cars?”, “What tells time?”, and “Where do you cook?” when presented with 27 baseline trials (three sessions). During immediate prompting across two sessions and 25 trials, Marvin received 18 vocal prompts with correct responses after the prompt. He responded before the prompt with correct responses on seven trials. Marvin did not respond incorrectly to any prompted or unprompted trials during this phase. Following the two-second delay across two sessions and 19 trials, Marvin responded correctly after prompting on 16 trials and responded before the prompt on three trials. Prompts were faded and in the independent phase Marvin achieved mastery of the skill by obtaining 100% accuracy in the 18 trials presented. Marvin mastered the three intraverbal wh-questions in seven sessions.

Brandon had zero correct responses on “Who drives a tractor?”, “Who helps animals?”, and “Who flies a plane?” during 45 baseline trials (five sessions). During immediate prompting across two sessions and 18 trials, he received 13 vocal prompts with correct responses after those prompts. He responded before the prompt with correct responses on three trials and responded incorrectly on one trial even though the prompt was presented. During the two-second delay across two sessions and 18 trials, Brandon responded correctly on 16 trials, required one prompt, and emitted one error. For the independent responses only one session of nine trials was conducted. Mastery criteria of 89% for two consecutive sessions was met in 18 trials by combining the last session of the two-second delay and the final session of no prompting. Namely, Brandon responded correctly on nine out of nine trials on the last session of the two-second delayed prompting and on eight of the nine trials for the final session of the independent phase with no prompting. Brandon mastered the three intraverbal wh-questions in five sessions.

Walter had zero correct responses on “Who flies a plane?”, “Who drives a tractor?”, and “Who helps animals?” during 56 baseline trials (six sessions). During immediate prompting across two sessions and 18 trials, he responded correctly after prompting on 16 trials and responded before the prompt with correct responses on two trials. During this phase Walter did not respond incorrectly to any prompted or unprompted trials. When presented with the two-second delay across two sessions and 18 trials, he responded correctly on 13 trials and required 5 prompts. Similar to Brandon, mastery criteria of 89% for two consecutive sessions was met by combining Walter’s last session of two-second delay and his one session of the independent phase. He responded correctly for 100% of the 18 trials presented between the last session of two-second delays and the one independent phase. Walter met the mastery criteria for his three wh-questions in a total of five sessions.

Figure 3. *Participant Wh-Question Answering Performance During the Intervention*



Discussion

In this study, the robot effectively taught all the participants the skill of answering wh-questions by delivering a DTT-based intervention with a time-delay prompt. The results demonstrated that children with a diagnosis of ASD can acquire an intraverbal skill such as wh-question answering through instruction from a robot. The participants acquired the intraverbal wh-question answering skill in 5-7 sessions which is a similar acquisition rate to when humans deliver the intraverbal training procedure (Kodak et al., 2012). This also aligns with the participants' typical acquisition rates at the university-based autism clinic when intraverbal interventions were delivered by a human therapist. This research is beneficial for future researchers in the field of SARs and ASD due to the consistent acquisition rates that the subjects obtained when learning intraverbal wh-questions. This consistency is important because it emphasizes that SARs can deliver ABA-based interventions just as efficiently and effectively as a human therapist.

We also evaluated the children's ability to generalize and retain the skills after they learned wh-question answering from the robot. The evaluation was accomplished by a human re-presenting the wh-questions to a participant one-year after the intervention. Each learned question was presented three times for a total of nine questions. We measured the percentage of correct responses from the children for the three questions. Two of the children (Marvin and Walter) fully retained and generalized the three wh-questions previously mastered by answering them 100% correctly. One of the children (Brandon) retained and generalized two out of the three questions by answering them 100% correctly. The question he did not retain was answered correctly 0% of the time. The question that Brandon was unable to retain was, "Who helps animals?", with the expected response of "veterinarian". We hypothesize the retention of this question may have been more difficult because the correct response of veterinarian was more complex (i.e., number of syllables) than pilot and farmer.

In comparison to Louie et al. (2020a), our robot delivered wh-question intervention utilized standard behavioral protocols and human-like teaching behaviors that alter antecedents and consequences. This resulted in significant improvements in the acquisition rates of an intraverbal skill for children participating in robot delivered wh-question interventions. Namely, high-p requests and behaviors were utilized in this study to maintain participant engagement and compliance to responding to the robot. High-p requests are often paired with reinforcement to increase children's compliance with the targeted instruction (Lipschultz & Wilder, 2017). Although high-p requests are a common tool used in the field of ABA, SARs studies have yet to examine the use of these techniques in the delivery of interventions. Additionally, the robot emitted praise statements and engaged in preferred activities to provide positive reinforcement for prompted or independent correct responses. Praise statements and activities from the robot were effective as reinforcers because preferred stimuli were only delivered contingent on correct responses and this reinforcement strategy led to the children meeting the mastery criteria. To exhibit human-like teaching behaviors, we also followed recommendations by Louie et al. (2020b) and had the robot utilize a pre-recorded human voice with their associated prosodic behaviors (e.g., pitch, intensity, intonation, speaking rate) to deliver all verbal instructions, prompts, reinforcers, and error corrections. The robot also performed social praise such as celebrations and dances which were modelled from observations of the behaviors of the therapists from the clinic.

Our study aligns with current research that demonstrates that robots can increase language and communication skills in individuals with ASD (Husken et al. 2013; Yun et al.

2016). Namely, our study was similar to Husken et al. (2013) and Yun et al. (2017) which designed an intervention based-off the three fundamental units of a discrete trial which consists of a discriminative stimulus, targeted behavior, and consequential reinforcement. Such an intervention design is recognized to be the best practice for teaching skills to individuals diagnosed with ASD (Smith, 2001). Although Begum et al., (2015) applied the fundamental units of a discrete trial, only a single participant out of three increased their behaviors in the targeted skill. This may be attributed to the lack of assessment of the appropriate prompting strategies for the participants. In this research all the participants already had a history of successfully learning new skills with the prompting method utilized within the study and, consequently, we hypothesize this assisted in them being able to learn the skill. Our study also extends the existing literature on using robots for ABA-based robot-mediated language and communication interventions because it demonstrates that robots can not only increase these skills in children with ASD but teach a completely new skill not known apriori by the child.

In this study, we utilized a single-subject research design with a small sample size which may limit the generalizability of the results when considered independently. However, it is currently well established that in order to form an evidenced-based practice and generalize an ABA-based intervention for individuals with ASD it is necessary to replicate at minimum five single-subject studies by three different research groups across three geographical locations (Horner et al., 2005). The results of this study demonstrated that SARs could teach a skill to children with ASD with the same efficiency and efficacy as human delivered therapies. Hence, we hope this study can serve as a starting point towards building a replicable body of literature to support the use of SAR technology as an evidenced-based approach for delivering ABA-based therapies to children with ASD. Namely, for interventions to be included as an evidence-based practice, future studies should extend upon and replicate SARs research especially in clinically based settings (National Autism Center, 2009; Dickstein-Fischer et al., 2018).

The results of this study demonstrate that a robot can be utilized to teach a completely new skill to an individual with ASD when utilizing the principles of ABA and contingent reinforcements. Although the primary focus of the current study has been on the efficacy and efficiency of robot-mediated therapies for teaching children with ASD wh-question answering, it is also important to explore the use of this technology for wh-question asking as it is a socially relevant skill for individuals with ASD. In the future it is also necessary to compare the efficiency of robot delivered interventions with human delivered interventions to ensure that robots can at least deliver on par or better services to individuals with ASD. Namely, De Korte et al. (2020) and Huskens et al. (2013) found that in comparison to humans, robots can deliver better or on par ABA interventions when targeting increases in behaviors for children with ASD. Hence, it will be valuable to identify whether robots can also teach a completely new skill with the same efficacy and efficiency as a human. We will also be further developing the autonomy of SARs for them to be practically deployed in clinical settings. Such SAR development has the potential to broadly influence the delivery of care for ASD by supporting clinicians in increasing the frequency of learning opportunities presented to individuals, such as through in-home intervention delivery, when ABA clinics or related services are not accessible. Namely, access to services that are needed for these individuals' development are not always obtainable due to difficulties related to one’s economic status, social class, and location of residence (Elder et al., 2016). If SARs can autonomously provide intervention delivery, they have the potential to positively transform the delivery of these services by serving as an intermediary between the need for individualized treatment and lack of accessibility.

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