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Research Article

Development and Preliminary Investigation of a Semiautonomous Socially Assistive Robot (SAR) Designed to Elicit Communication, Motor Skills, Emotion, and Visual Regard (Engagement) from Young Children with Complex Cerebral Palsy: A Pilot Comparative Trial

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Through play, typically developing children manipulate objects and interact with peers to establish and develop physical, cognitive, language, and social skills. However, children with complex disabilities and/or developmental delays have limited play experiences, thus compromising the quality of play and acquisition of skills. Assistive technologies have been developed to increase opportunities and level of interaction for children with disabilities to facilitate learning and development. One type of technology, Socially Assistive Robotics, is designed to assist the human user through social interaction while creating measurable growth in learning and rehabilitation. The investigators in this study designed, developed, and validated a semiautonomous Socially Assistive Robot to compare with a switch-adapted toy to determine robot effectiveness in quantity of, changes in, and differences in engagement. After interacting with both systems for three sessions each, five of the eight subjects showed a greater level of positive engagement with the robot than the switch-adapted toy, while the remaining three subjects showed slightly higher positive engagement with the toy. The preliminary results of the study suggest that Socially Assistive Robots specifically designed for children with complex cerebral palsy should be further researched and utilized to enrich play interactions and skill development for this population.

1. Introduction

Play is essential to child development by offering young children the opportunity to create, imitate, imagine, and practice while interacting with their environment. Through this interaction, children develop physical, cognitive, language, and social skills, thus enhancing their sense of autonomy, self-confidence, and achievement of critical developmental milestones [1, 2]. Play also introduces repeated experiences, which provide children with sensory feedback through exploration [3]. These repeated experiences also facilitate learning due to an increase in association between neural processes and an overall increase in "efficacy of synaptic transmission along specific brain pathways" [4].

Participating in play is crucial for all children, but children with complex disabilities and/or developmental delays cannot always access the same opportunities as typically developing children. The delays may be in any skill set, which may result in a lack of the physical ability to reach for a toy as well as diminished awareness of a toy due to visual or hearing deficits [5]. Due to the physical, cognitive, and sensory limitations in this population, manipulation of objects or environmental exploration is difficult, and the quality of play and learning of skills may be compromised, particularly for children with complex cerebral palsy [5]. In a seminal article, Brodin (1999) recognized that limited playing abilities and opportunities for interaction with the environment result in children with complex cerebral palsy often not developing skills and abilities as well as, or as easily as, their typically developing peers [6]. Without these play experiences, a child may have difficulties reaching certain developmental milestones, which in turn can prevent them from reaching their full potential.

All children learn through play and play often involves a toy [7]. Toys perform an essential role in enhancing development since children are naturally attracted to them. Occupational and physical therapists as well as speech language pathologists have long used play-like activities to engage children in therapeutic interventions. Motor skills such as reaching and grasping, language development activities involving play scenarios, and the use of toys to enhance overall engagement in therapeutic behaviors are just a few examples [8–12]. It has been suggested that toys may have a greater impact for children with severe disabilities when they have educational value; however, young children with disabilities are less likely to actively engage with objects or other people, which results in the need for more frequent and exciting play opportunities [6, 10]. To meet this need, toys specifically adapted for better educational access and greater interaction—to provide multisensory input and allow for repetitive interaction—have been developed for children with all kinds of disabilities [13–16]. Additionally, assistive technologies designed for adapted play and social interaction can prove to be fundamental in enabling children with physical disabilities to play, as well as facilitate learning in those with cognitive disabilities [9, 17].

Recently, the term "Socially Assistive Robots" (SAR) has entered the literature to describe a unique cross section between Assistive Robots (AR), designed to directly support the needs of a patient, and Socially Interactive Robots (SIR), designed to entertain or to form a social bond with an individual. SAR are designed to assist the human user through social interaction, while creating measurable growth in learning and rehabilitation. Defining what features characterize "socially assistive" emphasizes the importance of the human participant and of assistance to human users, similar to AR. This distinction also specifies that the assistance is through social interaction, similar to SIR [18]. Feil-Seifer and Mataric proposed a formal definition of SAR as "robotics systems whose primary purpose is to provide assistance and measurable progress in rehabilitation, learning or convalescence through the establishment of close and effective interaction" [18]. Put simply, a SAR seeks to replicate, but not replace, the therapeutic and educational benefits that stem from the relationship between a caregiver and an individual with a disability. Overall, an effective SAR must understand and interact with its environment, exhibit social behavior, and focus its attention and communication on the user to help him or her achieve desired goals [19]. This definition sets the foundation for the socially assistive robotic device prototype designed for this study focused on providing therapeutic benefit to children with complex cerebral palsy.

Thus far, SAR have been predominantly used for increasing social interaction for children with autism spectrum disorder (ASD) [16, 20–23]. Children with ASD may struggle with emotion detection or affect recognition, and they often have limited verbal communication, visual tracking impairment, and fine motor deficiency. Some of the more common humanoid SAR used in ASD therapy—KASPAR, NAO, and Zeno—provide affective feedback through facial or postural expressions, while other systems, such as the Huggable, use speech and tone to express affective conditions [13, 15, 24, 25]. Using a SAR to mediate interactions between children with ASD and their peers, or their clinicians, has been shown to increase social interaction abilities and a diverse range of therapeutic intentions [26].

The goal of this research project was to develop a semiautonomous SAR for children with complex cerebral palsy providing information useful in the future development of a fully autonomous SAR to increase effectiveness of rehabilitation therapy as it improves independence in daily activities, while also improving quality of life and reducing caregiver burden. An adaptive SAR designed for a specific developmental delay, or set of developmental delays, can be used in a home or community setting. Such a system may also be effective in assisting children with complex cerebral palsy to reach developmental milestones during the most critical time of neural development: birth to three years of age [4].

This study was designed as a preliminary step towards development of a fully autonomous SAR to be used as a therapeutic augmentation tool for children with complex cerebral palsy. This first phase was designed to determine which features of the SAR were attractive to this population and if the SAR itself elicited a higher level of engagement than a typically available switch-adapted toy. Simple switch-adapted toys are the current standard of practice in clinical play therapy for children unable to use their hands to manipulate objects. For example, toys are used to facilitate gross motor movement patterns such as reaching. Reaching towards the switch to activate the toy accomplishes the goal of motor pattern movement and activating the toy (and causing it to move) serves as the positive reinforcement. The goal with the SAR is to elicit this type of therapeutic motion—reaching—through playful interaction, which can stimulate not only physical skill progress, but also cognitive and social skills as well. Further research will incorporate these results to design an autonomous system that can respond appropriately to the child in a clinical setting, with a final goal of creating an information-relaying SAR to be deployed at home to increase therapeutic interactions.

2. Materials and Methods

2.1. Semiautonomous SAR Development. This study incorporated a within-subject crossover design comparing a control condition (standard, switch-adapted toy) with an experimental condition (SAR, dynamic robotic prototype). The SAR developed and used in this study was built on the m3pi

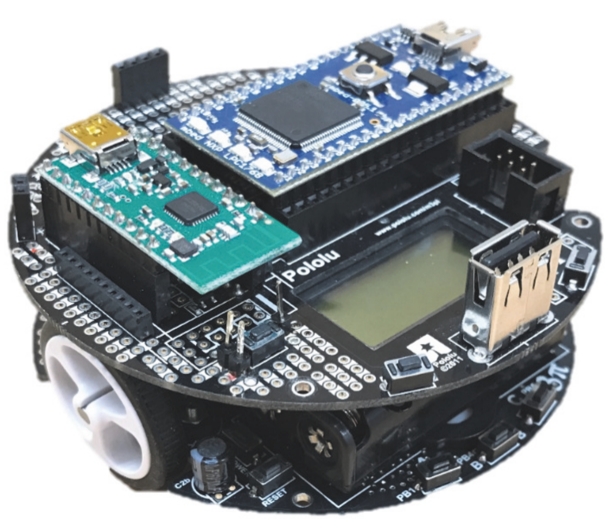

Figure 1: The m3pi hobbyist robotic platform, which was the foundation of the SAR developed for this study.

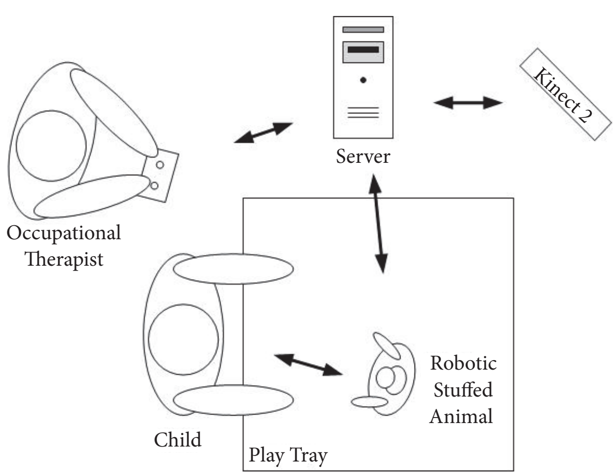

Figure 2: Diagram of the communication between hardware components when using the SAR during this study. The child interacts only with the SAR, which is controlled by the investigator in the room through commands sent to an external server.

hobbyist robotic platform; see Figure 1. The platform was 3.7 inches in diameter and 1.25 inches high. Movements and sounds of the system were performed by activating the embedded electronics that controlled the two motors driving the onboard wheels, as determined through a remote control managed by the investigator conducting the study. These wireless communications were enabled by the addition of a Wixel 2.4 GHz radio to the m3pi.

The diagram in Figure 2 shows the communication among hardware components of the system. The investigator drove the SAR using a wireless Xbox controller, which sent commands to the server by use of a dongle and then wirelessly to the SAR via a serial com port connected to the Wixel radio. The server sent commands for the SAR to perform the next action with the associated behavior; available commands

Figure 3: Completely dressed SAR used during SAR-child interactions in this study.

included forward, backward, left, right, and audio commands. Kinect 2 was also hardwired to the server to gather xyz coordinate information about the SAR's center and child's upper body appendages, which was sent to the server. Sensing the local environment was completed through an onboard SONAR sensor and current battery status; this information originated by the robot served as event inputs for the control system.

To protect the electronic hardware and provide structural support to the fabric covering, a 3D printed exoskeleton was mounted on top of the m3pi base. The dressed version of the SAR covered the entire base and increased the overall diameter to 4 inches, allowing the wheels to be completely covered. The final height and weight of the SAR were 8 inches and less than 20 oz. Figure 3 shows the completed SAR with its visually stimulating stuffed animal exterior.

The entire management system is executed externally from the SAR. The actual memory on the m3pi is limited, so the investigators decided that it was best to move this software to a more powerful computer. The computer was a laptop attached to Microsoft Kinect 2, the Xbox wireless adapter, and the Wixel radio. The system received inputs from these devices and the information flowed up the stack to execute commands and store the appropriate data. In wizard mode, the SAR received commands directly from the Xbox wireless controller, allowing for nonautonomous testing. Table 1 lists the drive commands and sounds available with the robotic toy.

2.2. Eligibility, Recruitment, and Consent. This study focused on children with complex cerebral palsy, which is a condition prevalent in approximately two out of every 1000 births worldwide [27]. This diagnosis covers a range of nonprogressive motor impairment disorders resulting from malformations or injuries during early brain development [28]. The severity of impairment in gross motor skills for each child in this study can by placed at a Gross Motor Function

Table 1: Controller commands for the SAR.

Button	Command
Start	Restart robot and control program
Left Control Stick	Drive robot forward, backward, left, or right
Directional Pad	Drive robot forward, backward, left, or right
A	Chatter sound 1
B	Chatter sound 2
X	Chirping sound
Y	Excited sound
Left Bumper	In sound
Right Bumper	Out sound
Right Thumbstick Click	Yoo-Hoo sound

Classification System (GMFCS) level of V, which represents severe limitations of posture and self-mobility [29]. Voluntary control of motor movements and the ability to maintain most head and trunk postures are restricted, and there is no means of independent mobility.

Children between 18 months and 5 years of age with complex cerebral palsy and, thus, severe developmental disabilities in the areas of motor function, cognitive development, and communication were recruited for this study. Each participant had significantly limited motor ability, resulting in minimal ability to physically interact with their environment. Additionally, their ability to communicate was limited to vocalizations or very few word approximations. The precise list of inclusion and exclusion criteria can be found in Table 2. Each child was recruited from the Denver Metro area and surrounding communities, regardless of race and gender. Fifteen children were enrolled in the study, with 8 eligible participants completing the study for an attrition rate of approximately 40%.

When the parents of an interested and eligible research participant contacted the investigators, they were invited to the study site at Assistive Technology Partners (ATP), Department of Bioengineering—a specialized assistive technology facility with comprehensive clinical and research programs focused on the assistive technology needs of people with disabilities—for the consenting procedures and eligibility verification. Investigators had separate conversations with each family to determine the ideal location for the study to take place, with the three optional places being ATP's early childhood room, the participant's home, or the participant's school. The chosen location depended on the ease of mobility for the participant as well as the schedule of the participant and the family. The consenting process took place in the chosen location, and this room was also used during the experimental sessions allowing the child and parent or legally authorized representative (LAR) to have the opportunity to become familiar with the environment prior to the initial experimental session. A trained research staff member then described the entire protocol and consent form in detail, which the parent or legally authorized representative was asked to sign. Signing only occurred if the parent or representative understood the information presented. Due to age, limited cognitive development, and impaired communication of the study population, the parent or representative provided consent for the participant. Parents were also asked to sign a HIPAA Authorization, Health Records Release Form, and a Photo, Video, and Sound Recording Release and Consent Form. Signed and dated copies of all forms were provided to the parents or LAR.

Eligibility verification was determined through demographic and health history information, as well as two prescreening measures of early development, one focused on early communication and one focused on early motor skills. The Receptive-Expressive Emergent Language Test-Third Edition (REEL-3) – Expressive Language Subtest was used to inform inclusion/exclusion based on the participant's communication ability. Similarly, motor and cognitive subsections from the Assessment, Evaluation, and Programming System for Infants and Children (AEPS) were used to describe the physical and cognitive skills of each patient.

These eligible participants were then asked to schedule additional sessions for the experimental portion of the study. These experimental sessions ranged in date and location for each subject enrolled in the study and continued for up to 12 weeks.

2.3. Experimental Design. Each enrolled subject was randomized to one of two orders: (1) interacting with the switch-adapted toy first or (2) interacting with the semiautonomous SAR first. After three sessions with the first device, each child then had three sessions with the second device. Each participant completed six individual sessions, each lasting no more than 30 minutes.

The study included a total of seven visits per participant, over a 12-week period; there were one visit for consent/eligibility and six experimental visits. The length of time to complete the experimental visits accounted for scheduling, transportation, and health-related issues that had an impact on attendance. Participant schedules were kept as consistent as possible with allowances made to accommodate family and participant needs.

2.4. Intervention. During the initial experimental visit, ATP's pediatric occupational therapist worked with the parent, legal representative, or treating therapist to identify the ideal seating and positioning options for proper support, alignment, safety, and comfort of the participant to maximize the child's ability to interact with the SAR or switch-adapted toy. Once positioning was established, it remained consistent for the subsequent visits for each participant, unless changes were needed for comfort and/or stability.

Before each of the six experimental visits, the investigator administered a previsit checklist to the parent or legal representative to determine the child's health, mood, and level of arousal. During this time, the child had an opportunity to become acquainted with their surroundings. The investigator then familiarized the child with the switch-adapted toy or SAR to ensure they were familiar with the device's operation and would not become startled by its movement or sounds. The device was then placed on a supporting surface within the child's visual field, close enough to touch, as described

Table 2: Inclusion and exclusion criteria for recruited subjects.

Inclusion Criteria	Children between the chronological ages of 18 months and 5 years, regardless of race/ethnicity or gender. Children that have significant motor and communication disabilities/delays. Children with a raw score of 42 or less on the Expressive Subtest of the Receptive-Expressive Emergent Language Test (REEL-3). Children with no unresolved medical issues. Vision within gross normal limits (functional) with or without correction. Hearing within gross normal limits (functional) with or without correction. Children who live in homes where English is the primary spoken language. Children without a seizure disorder or with a well-controlled seizure disorder. If taking medication, children who have been on a stable medication regime for the past 12 weeks. Children at Level V of GMFCS.
Exclusion Criteria	Children younger than the chronological age 18 months and older than 5 years. Children that do not have significant motor and communication disabilities/delays. Children with a raw score of 43 or more on the Expressive Subtest of the Receptive-Expressive Emergent Language Test (REEL-3). Children with unresolved medical issues. Children who are blind or have low vision (nonfunctional). Children who are deaf or hearing is not within gross normal limits (nonfunctional). Children who live in homes where English is not the primary spoken language. Children with an uncontrolled seizure disorder. Children who have not been on a stable medication regime for the past 12 weeks. Children at Level I, II, III, or IV of GMFCS.

in the previous design layout in Figure 2. The child was left to interact with the toy on their own, but the investigator remained in the room, mostly out of the child's field of vision, to ensure ongoing optimal positioning and to control movements and sounds from the SAR when it was employed. Each interaction lasted approximately ten to fifteen minutes and was video-recorded from two front-facing views for later analysis.

For each experimental visit, the child was given approximately ten minutes to interact with the switch-adapted toy or SAR. This length of time was chosen as optimal when taking into consideration the age and attention spans of young children with complex cerebral palsy. With the switch-adapted toy, the child had to initiate touching a large red button to make a firefighter character move up and down a one-foot tall ladder; the movement of the character is accompanied by a mechanical noise from the toy's simple motor system. Without this button being pushed, the character would not move, and the toy itself did not make a distinguishable sound. Interactions with the semiautonomous SAR involved the investigator staying out of sight and manipulating the SAR through a push-button controller. The SAR moved and emitted sound in response to the therapist's desired actions using a remote-control system. This allowed the system to respond in a therapeutic manner to the child's actions. The specific movements controlled and implemented by the investigator were determined by current clinical intervention; the investigator moved the robot in a such a way that it would mimic play-like interactions the child experiences in the clinic, thus acting out how the autonomous SAR will move with clinical benefit in future work. Figure 4 shows this interaction between a study participant and the SAR.

Figure 4: A sample interaction with the fully fabricated robotic toy. The child in the photo is representative of the study's target population (with permission).

2.5. Data Collection and Analysis. Collected video (including digital audio) following each session was immediately

Table 3: Definitions of coded behaviors and actions for child and SAR.

Behaviors and Actions	**Definition**	**Behaviors Incorporated From Every Move Counts**
Visual Regard	Child looks at the toy/SAR	Visual Contact (with Object); Visually Tracks
Vocalization(+)	Child makes any vocalization that cannot be interpreted as an emotion (i.e., crying, laughing)	Vocalizes; Verbalizes
Vocalization(-)	Child is able to verbalize and give a “Negative” vocalization to the toy/SAR (i.e., “No,” “Stop”)	
Reach	Child reaches towards the toy/SAR	Unilateral Reach with Contact; Bilateral Reach with Contact; Unilateral Reach; Bilateral Reach
Push	Child pushes the toy/SAR away	
Grasp	Child grasps towards the toy/SAR or physically grasps the object	Hand Opening; Unilateral Grasp; Bilateral Grasp
Emotion(+)	Child elicits a Positive Emotion to the toy/SAR, not a clinician, parent, or other individual in the room	Laugh; Smile
Emotion(-)	Child elicits a Negative Emotion to the toy/SAR, not a clinician, parent, or other individual in the room	Cry; Frown
Noise	Toy/SAR makes any noise	
Movement (+)	Toy exhibits any movement/SAR moves towards the child	
Movement (-)	SAR moves away from the child	
Spin	SAR makes a complete 360° spin	

transferred to a secure, HIPAA compliant, research network server hosted by the University of Colorado. Following secure transfer, the camera storage was wiped clean and prepared for the next subject visit. After all experimental visits were completed for each participant, the captured video data was edited, sorted, and analyzed using the Morae™ usability software suite from Tech Smith Inc.

Prior to initiating the study, investigators extensively interviewed a group of seven subject-matter experts (pediatric occupational and physical therapists and speech language pathologists) to define behaviors suggestive of engagement by the population selected for this study. These subject-matter experts had a combined 187 years of experience working with children with severe disabilities as well as the assistive and rehabilitation technologies used by and for these children. Due to the complex and atypical physical, sensory, and/or communicative interactions presented by this population, the subject-matter experts recommended defining engagement as “maintained visual regard towards the object accompanied by motor movements and vocalizations present during play therapy.” This definition was adapted from “Every Move Counts,” a program focused on communication development for children with severe sensory, cognitive, and motor impairments [30]. It is widely used by clinicians as a standard of practice to document child behaviors during therapeutic interventions and is representative of the fine detail needed to establish baseline measures as well as incremental changes in functional performance over time for children with such limited movement and communication patterns.

Visual Regard, Vocalization, Gross Motor Movements (Reach), Fine Motor Movements (Grasp), and Emotion were established as significant aspects in determining participant involvement in toy interaction, as defined in Table 3. Vocalization, Reach, and Emotion were separated into positive and negative codes (Reach is divided into “Reach” and “Push”) to provide a more cohesive picture of overall child behaviors during interaction. The negative codes were included as a form of disengagement with either system, or a wish to disengage.

These behaviors are similar to those seen in a previous study used to define and code engagement [31]. The 2018 study by Perugia et al. focused on measuring engagement-related behaviors across activities and then using these behaviors to establish a coding system for engagement; the behaviors listed included those similar to the behaviors established by the investigators for this study, including gaze (visual regard) and reach. While Perugia et al. also incorporated leaning during their research, we could not because our subjects had little to no trunk support and were mostly incapable of leaning towards the toys [31]. A summation of visual regard and the selected behaviors were selected to measure the level of engagement, each behavior having a specific weight depending on the child and dependent on their interaction (motor/visual/communication) abilities.

Codes were determined per partial interval recording techniques; videos were divided into 30-second intervals, and each interval was listed as having a specific behavior or action if that behavior or action was present at any point in the interval. Thus, a ten-minute video would consist of 20 total intervals, and each behavior or action could only be listed as present no more than 20 possible times. The frequencies of behaviors and actions were divided by the total number of intervals to determine a percentage of occurrence, which was then related to the percent of overall engagement expressed by the child, as determined by clinicians and

Table 4: Demographic table for study subjects.

Subject	Location of Intervention	Official Diagnosis	Motor Skills	Interventionist Notes
1	ATP	N/A	Limited fine and gross motor movements; no trunk movement and support	Responds to sensory stimuli and follows by visual tracking; limited response to causality
2	Home	N/A	Consistent fine and gross motor movements; sufficient trunk and neck support	Responds to visual and tactile stimuli; no response to causality
3	ATP	STxBP1 West syndrome	Limited fine motor movements and consistent gross motor movements	Limited response to sensory stimuli; no response to causality; limited communication through sign language
4	ATP	Seizures; infantile spasms	General fine motor movements and limited gross motor movements; no trunk and neck support	Limited response to sensory stimuli; limited response to causality
5	Home	Ohtahara syndrome with controlled seizures; cortical visual impairment	Limited fine and gross motor movements; no trunk support or balance	Responds to sensory stimuli; limited visual tracking; responds to causality
6	School	Petit mal seizures (well-controlled)	Limited fine motor movements and consistent gross motor movements; trunk and neck support present	Responds to sensory stimuli; good vision; no response to causality
7	School	Spinal muscular atrophy type 2	Consistent fine motor movements and limited gross motor movements; no trunk and neck support	Responds to sensory stimuli; limited speech; good vision; follows one- and two-step directional cues
8	School	Cerebral palsy; seizures	Consistent gross motor movements and limited fine motor movements; no trunk support and limited head support	Responds to sensory stimuli; good vision; no response to causality; limited following of one-step directions

previously available research. Based on the behaviors selected from the Every Move Counts program, the investigators were able to determine levels of engagement by using the overall summation of the behaviors present during each interval.

Prior to analysis of the data, interrater reliability was assessed. Ten of the 48 videos were randomly selected to compare coding values to determine the degree of agreement using Krippendorff's alpha with a reliability cutoff value of $\alpha = 0.80$. This minimum acceptable coefficient value is relied on by social scientists to verify that quantified analysis does not significantly deviate from perfect agreement. Alpha values greater than the cutoff ensure that coders were interpreting behaviors appropriately; any value less than that required coders to go over the individual video and collaborate to identify and label specific behaviors and actions [32]. This method ensured that a child's behaviors were marked as objectively and accurately as possible for the study.

3. Results and Discussion

3.1. Results. The subject demographics provided in Table 4 show most children had difficulty with controlling fine motor movement, using trunk support to maintain a sitting position, and following one- and two-step directions with contextual cues to complete activities. The investigators, in watching all of the videos, noted that several children did not have the ability to grasp. Additionally, the primary behaviors exhibited by all subjects, which accounted for over 80% of listed behaviors, were Visual Regard, Vocalization, and Gross

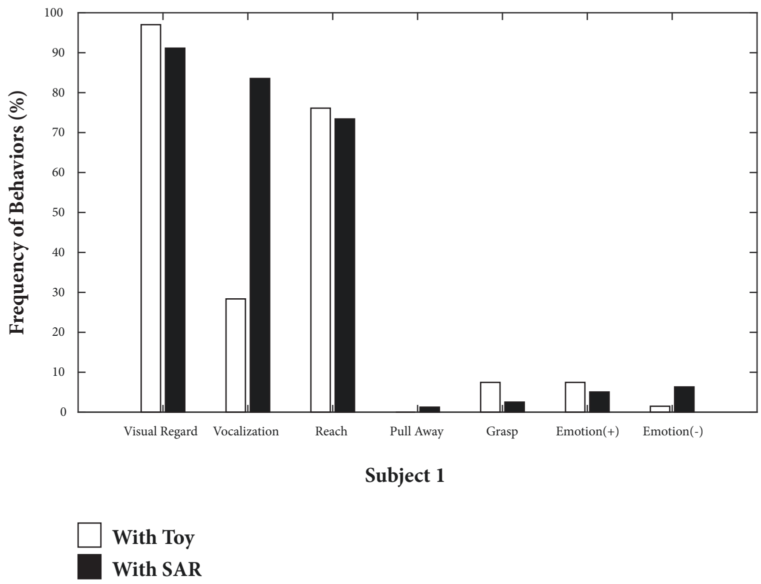

Figure 5: Results for Subject 1, which show a higher level of interaction with the SAR over the switch-adapted toy, shown most clearly in frequency of Vocalization.

Motor Movements (Reach and Push). Due to the prevalence of these behaviors across all subjects, level of engagement with the systems incorporated these behaviors first, and then the remaining behaviors (Grasp and Emotion) were considered if a preference for the SAR or switch-adapted toy was not clear. With this breakdown of behaviors in effect, investigators noticed 5 of the 8 subjects—Subjects 1, 2, 3, 6, and 7—had a higher level of overall engagement with the SAR over the switch-adapted toy.

Subject 1 had only slightly differing variations in Visual Regard and Gross Motor Movements for both the SAR and switch-adapted toy, as seen in Figure 5, so the behavior that determined level of engagement for this subject became Vocalization. Subject 1 was more vocal with the SAR, with a large number of sounds being made in response to the SAR's bell tones, which would keep the child interested approximately 10-15 seconds at a time before a new sound was needed to maintain interest.

Subject 2 showed similar behavior frequencies as Subject 1, as shown in Figure 6. However, Subject 2 only had slightly higher Vocalizations, but there was also a slightly higher level of Reach. The final contributor in deciding Subject 2 was more engaged with the SAR was the need for investigator intervention with the switch-adapted toy; in each session with the switch-adapted toy, the investigator had to initiate engagement by placing the child's hand directly on the button to elicit any type of response from the child. Even though the study investigator was controlling the SAR during each session, the movements and sounds created were not listed as prompting for the child, because the investigator did not physically or visually intervene during SAR sessions. Engagement initiated directly by the investigator only occurred with the switch-button toy across all subjects, when the investigator had to interact directly with the child and act as a mediator.

Figure 7 shows the results for Subject 3, who had similar frequencies of behaviors to Subject 2, and investigator intervention was also needed at the beginning of each switch-adapted toy session to initiate any kind of engagement. Additionally, Subject 3 had a higher frequency of grasping with the switch-adapted toy; however, during video analysis, subject-matter experts concluded these movements were due to a preference of the smoothness of the button because grasping did not coincide with Visual Regard from the child or movement and sound from the switch-adapted toy.

Subject 6 only had a noticeable difference in frequency of Gross Motor Movements and little variation in Visual Regard and Vocalization, shown in Figure 8. However, this difference was accompanied by a higher level of Positive Emotion with the SAR and greater Negative Emotion with the switch-adapted toy. While Emotion was not considered a primary behavior to indicate engagement by investigators, it was noted that Subject 6's emotions did coincide with active engagement during video analysis. Thus, incorporating Positive and Negative Emotion frequency was used in determining toy preference for this subject.

As shown in the demographics table, Subject 7 was capable of making verbal commands and presented more like typically developing peers than any other subject in this study. Because of the subject's ability to voice commands, Vocalization was divided into Positive and Negative, as defined in Table 4. Overall, Visual Regard, Vocalization, Reach, and Pulling Away for Subject 7 were higher in response to the SAR than the switch-adapted toy, making it clear that the subject was more engaged with the SAR, shown in Figure 9. This was also apparent throughout the recordings of the video sessions; the initial session with the SAR required investigator and teacher intervention to ensure the child was comfortable, and, by the end of the final session with the SAR, the subject asked the SAR, "Are we friends?"

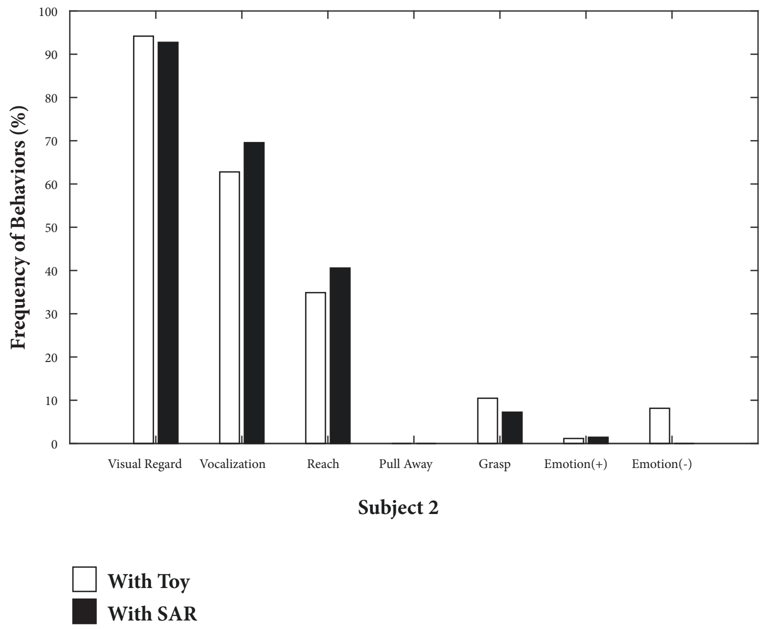

Figure 6: Results for Subject 2, which show a higher level of interaction with the SAR over the switch-adapted toy in both frequency of Vocalization and Reach.

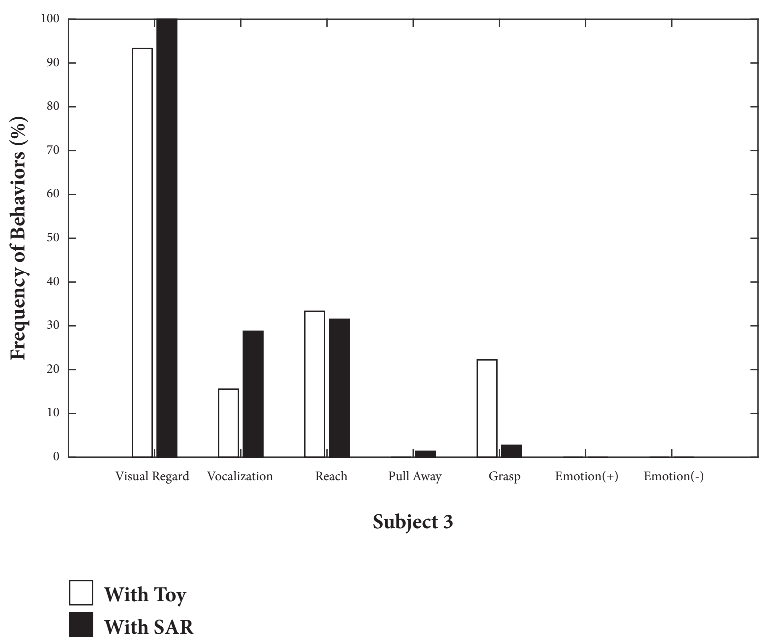

Figure 7: Results for Subject 3, which show a higher level of interaction with the SAR over the switch-adapted toy when considering the primary behaviors of Visual Regard, Vocalization, and Gross Motor Movements.

Throughout the SAR sessions, it was evident that the subject became increasingly comfortable with the SAR and enjoyed interacting and providing instruction ("Stop!" "Over here!" etc.). Conversely, interaction with the switch-adapted toy was limited to less frequent reaching movements and decreased interest ("I done now"). Subject 7 had the greatest difference in frequency of behaviors between the switch-adapted toy and the SAR.

Subjects 4, 5, and 8 did not express higher levels of Visual Regard, Vocalization, and Gross Motor Movements with the SAR over the switch-adapted toy, which can be seen in Figure 10. While Subject 4 did have a greater frequency of Gross Motor Movements and Fine Motor Movements with the SAR, there was a marked decrease in Visual Regard and Vocalization. Emotion was also considered with Subject 4 to help determine which sessions provided a higher level of

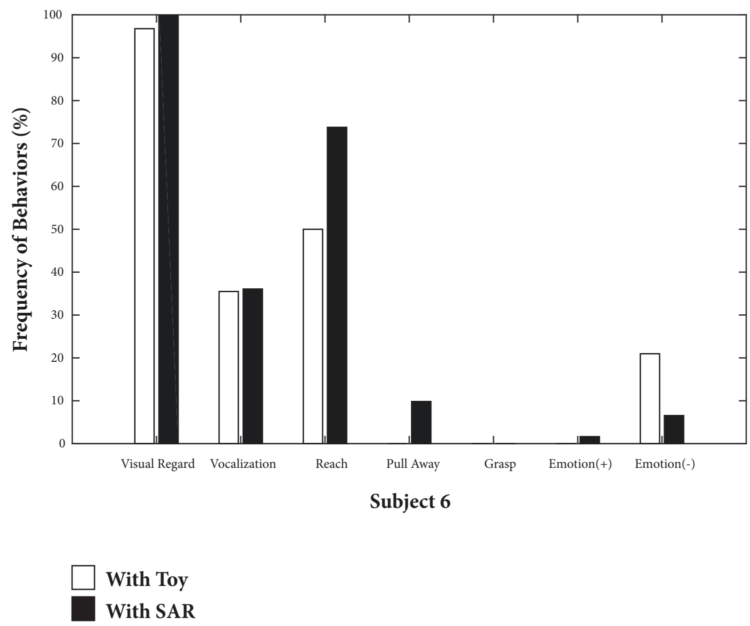

Figure 8: Results for Subject 6, which show a higher level of interaction with the SAR over the switch-adapted toy when considering the primary behaviors as well as Positive and Negative Emotion.

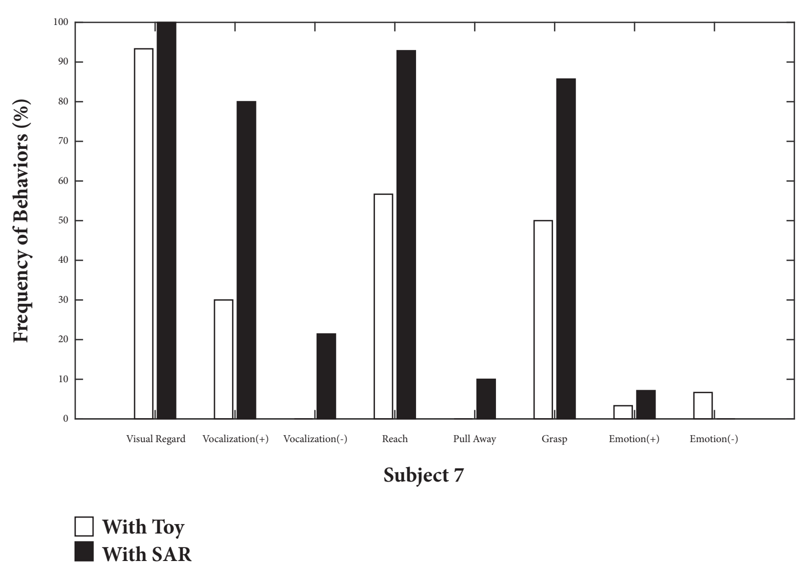

Figure 9: Results for Subject 7, which show a higher level of interaction with the SAR over the switch-adapted toy. Subject 7 was the only child capable of giving vocal commands, so a behavior for Negative Vocalizations was considered when the subject said "No!" or "Stop!" Even though this behavior was considered "negative," subject-matter experts determined it showed a higher level of overall engagement.

engagement, as there was greater Positive Emotion with the switch-adapted toy and greater Negative Emotion with the SAR.

Subject 5 had a greater frequency of both Vocalization and Reach with the switch-adapted toy, suggesting higher engagement with the switch-adapted toy. However, the child became increasingly comfortable with the SAR over time; in the last session with the SAR, the child stuck out their tongue twice to obtain a response from the SAR. Investigators suggested additional sessions with this subject may have shown increased engagement with the SAR over time.

It was difficult to determine engagement levels for Subject 8, as this subject cried for the majority of every session with both the switch-adapted toy and SAR. Investigators made attempts throughout each session to console Subject 8, but the child continued to be upset. Due to the higher frequency of Vocalization and Grasp with the switch-adapted toy and only Pulling Away with the SAR, subject-matter experts noticed

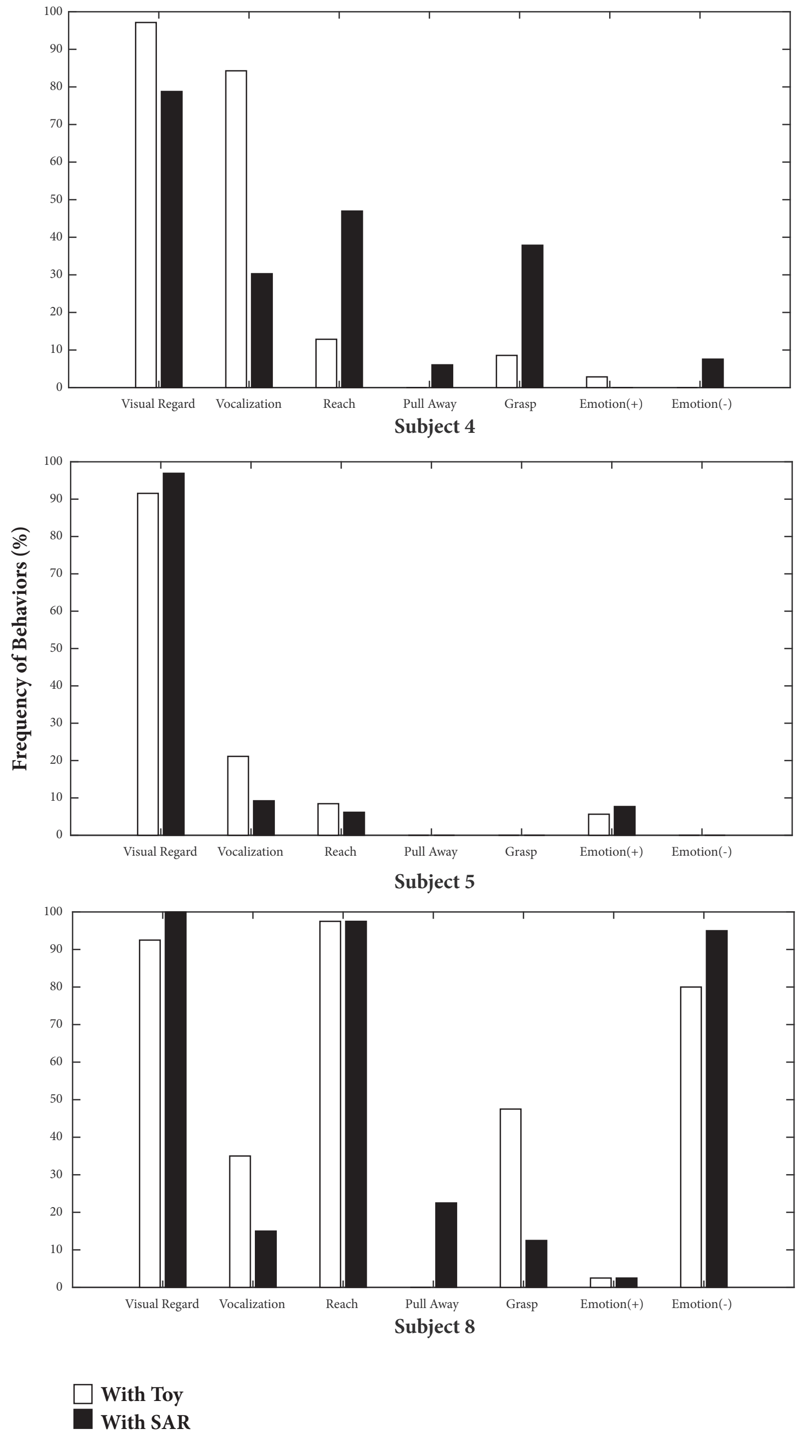

Figure 10: Results for Subjects 4, 5, and 8, which show a higher level of interaction with the switch-adapted toy over the SAR for all three children.

that behaviors indicated that the switch-adapted toy provided more positive engagement with this subject.

3.2. Discussion. Using a crossover methodology with repeated observations with the switch-adapted toy and SAR addressed both the limited population of potential participants in geographic proximity to our facility and the fluctuations in mood and/or level of arousal common in these populations. The study appropriately addressed this heterogeneity of participants via its use of a crossover design. Since each subject served as their own control, the impact of heterogeneity on the findings is mitigated although the impact on generalizability remains. Additionally, the repeated observation of a participant increased the precision with which each participant's response was measured. This approach mitigated the impact of a child having a "bad day" while, at the same time, it allowed for assessing the impact of repeated exposure.

Repeated exposure to the SAR proved to be beneficial in increasing engagement, as most children became more comfortable with the SAR over time. This increased the sense of familiarity with the SAR, and interactive design of the system did influence the overall engagement of each child, providing them with a positive difference in quality of play. One of the limitations of this study was the limited number of sessions allowed per participant. For example, investigators determined that it took a varying amount of time for subjects to become comfortable with the SAR, and some subjects may have needed more time than others.

Across all subjects, the quality of engagement remained consistent with the standard switch-adapted toy; some children did need to be prompted by having their hand placed on the button by investigators, and this needed to be performed for each session. Additional limitations that investigators had to consider during setup and result analysis were the small number of children available for the study and the use of in situ environments sometimes becoming distracting. However, there was significant assistance from subject-matter experts to aid internal validity of the study, given the shortcomings. Because of their input, any external validity completed for this study will need to work with supplementary subject-matter experts.

Overall, interaction with the SAR provided varying levels of engagement that increased in quality and quantity over time, as shown by the greater frequency of engagement with the SAR for five of the eight subjects. If the sessions were to continue, investigators speculated they would most likely have seen increased engagement among the remaining three participants as well. Thus, introducing the SAR as a source of playful engagement for children with complex cerebral palsy proved that a greater quantity and quality of engagement can be achieved than with a standard switch-adapted toy.

4. Conclusions

Children with complex cerebral palsy often experience limitations in their quantity and quality of play, as compared to their typically developing peers. Because children learn through play and therapists use play as an aid to meaningful clinical intervention, maintaining engagement is critical, especially therapeutic engagement. Introducing a SAR designed primarily for children with complex cerebral palsy holds promise for augmenting clinical intervention activities. This pilot study provided crucial information: Do these children respond positively to this type of engagement? The results show that yes, across multiple exposures with the SAR, children with complex cerebral palsy became more comfortable with the SAR and began to interact more openly and without interference. Children were engaged with the SAR's movements and sounds and responded mostly appropriately and positively to the SAR's actions.

Expanding on this newfound knowledge will focus the next stage of development of a fully autonomous SAR that can be used as an augment to a child's current therapies. This will first be accomplished by expanding on this study by addressing some of the limitations. Further research will include higher numbers of study participants, more sessions with both the SAR and switch-adapted toy, a familiarization session with the SAR prior to the intervention phase, and a controlled environment that all children can access. From there, investigators can also relate the direct movements and sounds of the SAR under their control with responses from the participants to determine which features are most appealing to this population.

To create the autonomous system, the SAR will be equipped with vision and auditory systems to obtain data about the movements and noises made by the child as they work towards a chosen therapeutic goal. Developing a SAR for this population is difficult, especially with clinical intent, so it is pertinent to include subject-matter experts. Current research is being done to design the vision system specifically to recognize the specific, often repetitive movements of children with complex cerebral palsy. Additional work will incorporate the vision system into a fully functional autonomous SAR, allowing the SAR itself to obtain important information about how the child reacts to certain behaviors and then respond appropriately to elicit a desired reaction.

Complex cerebral palsy encompasses a wide range of both developmental and physical disabilities and affects two out of every 1000 children. Providing quality therapeutic intervention with opportunities to practice clinical objectives during play is critical in supporting the advancement of crucial developmental milestones and thus increase of overall quality of life. A very simple SAR has shown increased engagement, and an autonomous system designed specifically for interaction with these children will ideally increase the quality and quantity of engagement further.

Data Availability

The primary data used to support the findings of this study are included within the article as integers representing the total frequencies of each behavior.

Disclosure

This paper was presented at RESNA (July, 2018) Annual Conference, Arlington, VA.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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