School-Based Use of a Robotic Arm System by Children With Disabilities

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***Abstract*—A robotic arm system was developed for use by children who had very severe motor disabilities and varying levels of cognitive and language skills. The children used the robot in a three-task sequence routine to dig objects from a tub of dry macaroni. The robotic system was used in the child's school for 12–15 sessions over a period of four weeks. Goal attainment scaling indicated improvement in all children in operational competence of the robot, and varying levels of gain in functional skill development with the robot and in carryover to the classroom from the robot experiments. Teacher interviews revealed gains in classroom participation, expressive language (vocalizations, symbolic communication), and a high degree of interest by the children in the robot tasks. The teachers also recommended that the robot should have more color, contrast and character, as well as generating sounds and/or music for student cues. They also felt that the robotic system accuracy should be increased so that teacher assistance is not necessary to complete the task.**

***Index Terms*—Assistive technology, cerebral palsy, disabled children, physical disabilities, play, robotics, special education.**

I. Introduction

Typically, developing children learn cognitive and linguistic skills through manipulation of objects, often in a play context. Power [1] has described play as a distinct motivational/behavioral system through which children "learn about their environments, establish relationships with others, and create or refine skills needed for success in later life." Children integrate sensory, motor, and affective components in an intensely active manner. Enjoying the play activity itself is the primary motivation for cognitive, social, and motor growth, as opposed to routine learning and memory [1]. When children play they are relaxed in the present, intrinsically motivated, and actively engaged, all behaviors that are conducive to learning [2]. Neuroscience research suggests that play behavior may be important to brain development and that play behaviors enable us to actively seek out or create appropriate experiences for learning [3].

Because children with disabilities typically engage in adult-chosen play activities, the quality of their play may be compromised [4]. Also, because children with disabilities may take longer to respond and make less obvious responses, adults often assume the role of entertainer and director of the play. Blanche [5] discusses "play based" therapy sessions for children with cerebral palsy. She calls the process of *entertaining* directing the play experience by "doing to" rather than the conversationalist method of "doing with."

Children who are unable to independently manipulate objects due to physical disabilities may not be able to demonstrate their learning level through independent play, and may be perceived as being more developmentally delayed than they actually are. Adapted robotic systems may allow these children to independently demonstrate their cognitive and social skill levels. Robots provide an opportunity for them to choose how to interact with their environment, to exert some control over the activity, and to manipulate three-dimensional objects. Children with disabilities will engage in play if the stimulus is adequate (i.e., the toy is "interesting" to the child) and the toy is physically accessible to them [6]. Adapted robotic devices meet both of these criteria.

Kwee and Quaedackers [7] used an adapted robot controlled by single switch scanning with children with severe disabilities. One-switch-activation was used to select the direction of movement, and then the same switch controlled arm movement in the chosen direction. Significant training was required to understand the cognitive aspects involved in the tasks (e.g., pouring water from a glass, eating a cookie). In another study, children with severe disabilities used a robotic arm to draw [8]. The color of a pen and then the position the pen up or down (draw) was selected using single switch scanning. A subsequent scanning choice moved the pen to draw. The three subjects in this study had widely varying levels of success with this task.

A five-position switch and a computer were used to control a robot system developed for use in elementary schools [9]. Operational modes included: demonstration of the arm to the student, execution of prestored tasks, unstructured movement controlled by the student, and student programming and storage of movements for later playback. Special software and hardware features were necessary to accomplish these tasks [10]. These included easy physical and cognitive access and fast interaction speed; understandable, powerful and complete learner control features; and the definition of robot motions that are useful in the classroom. This robotic system was applied to science instruction at the elementary school level [11]. Important issues

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raised by this study were the need for the student to be able focus on the learning task not on robot control, the training methodology, and curricular applications. Harwin, Ginige, and Jackson [12] developed another system for classroom use. This system included a vision component that allowed the system to be used for three tasks: 1) stacking and knocking down blocks with two switches (yes/no); 2) sorting articles by shape and/or color with four switches (one for each feature) or two switches (yes/no); and 3) a stacking game with five switches (left, middle, right, pickup, release). Children with motor disabilities who used this system enjoyed it and were able to successfully complete the tasks that they could not otherwise do.

Nof, Karlan, and Widmer [13] used a two level system for developing a child's interaction with a robotic arm. At the first level, the arm functioned to carry out complete classroom tasks. Nof, Karlan, and Widmer [13] also used one and two-step sequences to break the overall tasks into component steps. At the second level, the robotic arm allowed the child to control component actions and incorporate these into more complex sequences to complete the tasks. The Aryln Arm robotic work station was developed specifically for educational applications [14]. It has a portable base and a six degree-of-freedom arm. A two joystick control system is used to position the arm, control the end effector (a "pseudo hand") and direct the moveable base. There is also a built-in vacuum system. Eberhardt *et al.*, [14] used the arm with five subjects who had disabilities preventing participation in science and the arts. Using the arm system, these subjects completed projects in these two subject areas. Robots have also been used as tools in therapeutic play activities [15]. In this approach, a series of sensors are attached to a child to detect arm, finger, or head movement. Those signals are then used to control a robot. A storytelling robot was employed to address cognitive, language, and emotional rehabilitation needs in children with disabilities.

Cook, Liu, and Hosseit [16] evaluated how very young children would interact with a small computer-controlled robotic arm [17]. All of the children with a cognitive developmental age of 7–9 months or greater used the arm as a tool to obtain objects out of reach. Success in using the robotic arm was most closely related to developmental levels in cognitive and language areas. Cook and Cavalier [18] provided guidelines for use of assistive robotics in the classroom including hardware and space needs as well as training of both students and teachers and the balance between computer-driven and student-directed robot-assisted activities The work reported here is based on an earlier feasibility study using an industrial robot in a clinical setting [19]. The robot was adapted to allow control by children with severe disabilities [20]. The system was programmed to: 1) carry out preprogrammed movements when the child hit a switch; 2) execute three-dimensional Cartesian coordinate movements when activated by one of six switches or keyboard keys; and 3) move any of the six degrees of freedom and open or close the gripper when one of 14 switches or keyboard keys was pressed. Enlarged keyboards that reduced the physical demands for high-resolution movements by the child could be used instead of single switches. In this study, we focused on container play in a large tub of dry macaroni (e.g., scooping and dumping) using a robotic arm controlled by a set of three switches activated by the child. The robotic arm was programmed to carry out pre-programmed tasks when the child pressed any one of three switches in a specified sequence. Each of the four children in the pilot study had only brief exposure to the system. The current study differed in two important respects: 1) the robot system was located in the child's school rather than a clinical setting

TABLE I
SUBJECT PROFILES

	Age	Diagnosis	Physical skill	Cognitive skill	Social skill	Educational setting
P1	6	Spastic-athetoid quadriplegia,	Limited grasp, difficulty crossing midline, functional but poor head control	Good receptive, limited expressive language	Age appropriate play skills, needs lots of physical assistance	Segregated classroom
P2	8	Spastic quadriplegia, West syndrome, seizure disorder	No hand dominance, reach extends to limits of lap tray, lateral grasp with Left & Right hands	Language skill not measurable, limited vocalizations (no words)	Responds to greetings, makes eye contact, responds to manipulative materials	Included classroom and individualized instruction
P3	13	Spastic quadriplegia,	Very limited hand control; poor but functional head control	Severe speech and language impairment	Initially withdrawn, but eventually responded to researchers with smiles and vocalizations	Segregated classroom
P4	14	Spastic quadriplegia,	Left Hand dominance; can grasp & cross mid-line	Unknown (not measurable)	More social with familiar people than with researchers	Segregated classroom
P5	10	Spastic quadriplegia, visual impairment, G-tube	Right hand dominance, functional grasp, crosses midline	Some vocalizations (no words)	Very cheerful, smiles often	Segregated classroom
P6	10	Spastic quadriplegia, G-tube	Hand-over hand assist for grasping, voluntary head control	Indicates likes & dislikes, vocalizations (new words), expressive body language	Smiles, tolerates loud noises and music	Segregated classroom
P7	10	Spastic quadriplegia	Left hand reach & grasp	10 words expressive and receptive language,	Initiates greetings, occasional recess participation	Included classroom and Individualized instruction
P8	5	Spastic quadriplegia, seizure disorder	Palmer grasp, can't cross midline, good head control	Receptive language-not measured; uses a few words appropriately	Very social, enjoys interaction with people	Segregated classroom
P9	11	Spastic quadriplegia, seizure disorder, visual impairment	Functional hand and head control, can grasp large blocks, can cross midline	Unknown (not measurable)	Very social, not always appropriate, prefers human to object interaction	Segregated classroom
P10	12	Spastic quadriplegia, seizure disorder	L hand dominance, palmer grasp w/ assist; reach switches on lap tray	Strong receptive lang.; minimal vocalizations; recognizes colours, body parts, name	Greets others, friendly, laughs and smiles often	Included classroom and individualized instruction
P11	9	Spastic quadriplegia, G-tube	Both hands functional, good grasp and reach	Some words (<10), recognition of name	Outgoing and interactive with researchers	Segregated classroom
P12	11	Spastic quadriplegia,	Right hand dominance, functional reach and grasp	Limited receptive language (1-words)	Some vocalizations when greeting, interested in robot	Segregated classroom

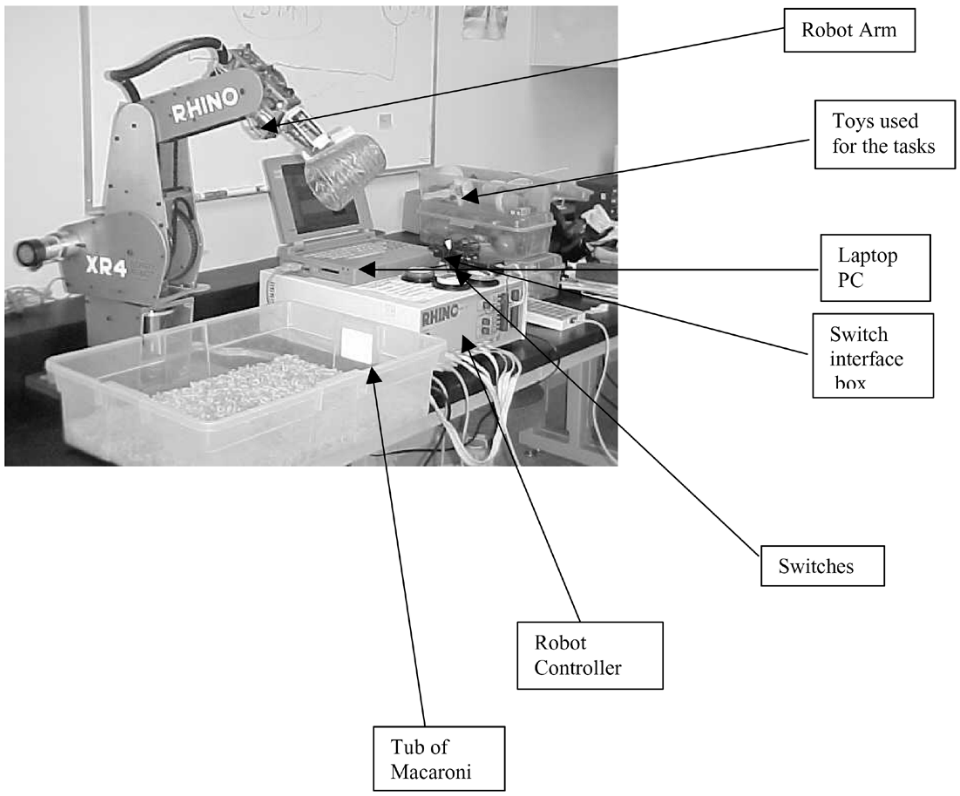

Fig. 1. Rhino XR-4 Robot Arm.

and 2) the children used the system for a period of four weeks, rather just one or two sessions.

A. Subjects

Twelve children with severe physical disabilities, ranging in age from 6 to 14, participated in this study. The functional anatomical sites used by the children for switch control included head and hand movement. The children were unable to engage in play or educational activities independently or with other children or adults. Subject profiles are shown in Table I.

II. Methods

A. Objectives

1) To evaluate how children with severe physical disabilities can physically control a robotic arm to engage in functional play tasks.
2) To determine the impact of the use of a robotic arm on children's behavior, social and academic performance, including play and emergent literacy skills.

B. Experimental System

The Rhino XR-4, shown in Fig. 1, is a five-degree-of-freedom robot arm that can move similarly to the way a human arm moves. The robot can rotate around its base, bend (flex/extend) at the shoulder, elbow and wrist, and rotate (supinate/pronate) at the wrist. It can also open and close its two-fingered gripper. The robot is mounted on an aluminum base to ensure stability when the arm is fully extended. Each of the motors on the robot has an encoder, which provides feedback to the robot controller regarding the position of each motor.

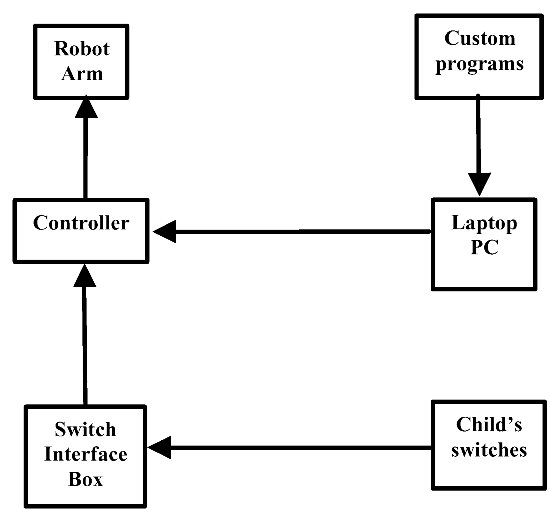

Fig. 2. Block diagram of the robotic system.

The robot is controlled using the Rhino Mark IV controller. The Mark IV can be programmed to allow the robot to perform a wide variety of movements. A custom designed switch interface box was built to interface the childrens' control switches to the robot. These switches are the means by which the child controls the robot. Software for these applications was developed using the proprietary robot programming language, RoboTalk (Rhino Robotics Ltd, Miamitown, OH). The control software was run on a laptop computer that was connected to the controller. A block diagram of the overall robot system used in this study is

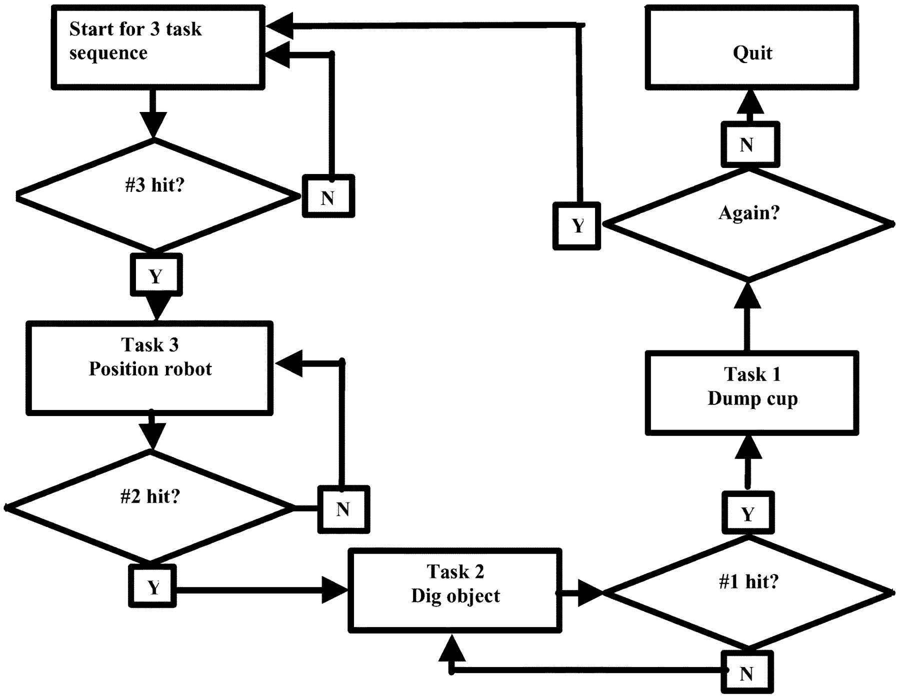

Fig. 3. Software flowchart used to control robot arm.

shown in Fig. 2. The computer allows the researcher to modify the parameters of the robot's behavior to match the abilities of individual children.

C. Tasks

Three play tasks were used.

Task 1 The adult's role was to fill up the cup with macaroni (by hand) and the child's task was to hit a switch causing the robot arm to dump the macaroni. The child then indicated that the cup should be filled again (typically by looking at the cup).

Task 2 The child used two switches to 1) dig an object (e.g., a plastic egg with some kind of small toy inside) out of the macaroni and 2) dump the macaroni and object. The adult's role was to bury the egg, catch the egg when the child dumped it out, and open the egg for the child when the child requested it (e.g., by looking at the egg).

Task 3 The child pressed a switch to move the robot to the correct position for digging. Once the child positioned the robotic arm, the second switch dug the object and the third switch dumped the cup. An additional feature was included to require the child to hit switch 3 from one to eight times to correctly position the arm for digging. The adult's role was the same as for Task 2.

Custom software was developed to control the robotic arm using a three switch array to perform the tasks. One switch controlled each task. Fig. 3 shows the flow chart for the three-task sequence. Some children began with task 2 and others began with task 1 during the course of the study.

TABLE II
SUMMARY DATA FOR GOAL ATTAINMENT SCALE RATINGS

	Mean	Max	Min
Initial T	32.50	40.87	27.18
Final T	53.42	68.26	31.74
Difference	20.92	31.95	4.56
paired T	0.0009		

III. PROCEDURE

The robot was set up at four different school sites to accommodate students participating in the study. Data collection took place over a period of four weeks at each site. At each school, the procedure was explained to teachers, who in turn choose potential students for the study. Informed consent was obtained from the parents for each student in accordance with approved ethics guidelines. Each potential participant was then screened using a switch controlled battery toy to ensure they understood cause and effect and could activate a switch. Each student used the robot an average of three times a week. One member of the study team and a student assistant directed each session, which was video taped for later analysis. The analysis consisted of counting both the number and time of occurrence for specific behaviors. Behaviors monitored included prompts (visual/auditory), incorrect switch hits (hitting the wrong switch in the three task sequence), and attention to task (looking at the robot, looking at the teacher, not attending to task). Goal attainment scaling (GAS), a criterion-referenced, individualized objective measure [21], was used to evaluate Objective 1. GAS allows the identification of multiple and individualized goals for each child. For this project, we developed individualized goals for each child in three categories: 1) operation of the robot; 2) functional task describing interaction; and 3) carryover to the classroom. Example goals are shown in the Appendix. At the conclusion of four weeks, teachers were interviewed to ascertain their impressions of the study.

IV. Results

A. Goal Attainment Scale

Goal attainment T scores were calculated using the formula [21]

$$T = 50 + 10 \cdot \left(\frac{\sum_{i=1}^{n} g_i}{\sqrt{n - R \cdot n + R \cdot n^2}} \right)$$

where

g_i outcome score $(-2 \text{ to } +2)$, for the ith goal;
n the number of goals;
$R0.30$ (a constant reflecting the estimated inter-correlation for scores on multiple goals).

This formula provides an overall score for all goals for an individual subject. It was used for pre- and post-intervention comparison. The results for all goals over all subjects are shown in Table II.

The inter-rater agreement for the determination of what outcome score was most appropriate given analyzed video data was 95.3%. All 12 children had increased goal scores for the operational goal, 83% (10 out of 12) had increased scores for the functional goal scales, and 75% (8 of 12) had increased scores for the carry over goals.

B. Behavioral Measures

A summary of selected behavioral measures is shown in Table III. The number of visual and auditory prompts was taken to be an indicator of the amount of assistance required by the student. A decreasing frequency of prompts was interpreted as the student becoming more independent in the task. These two measures were related to operational and functional goal performance, as shown in Table III. Both visual and auditory prompting increased in $1/3$ of the children, decreased for $1/3$ and remained the same for the last $1/3$ over the course of the robotic sessions. In order to access the functional goal of attending to task or attending to teacher, frequency of behaviors such as "looks at instructor," or " looks at task" were used. Only frequencies were used because duration of these behaviors was generally short (a few seconds). The noted behaviors were not inclusive of all the subjects' actions. Thus, the totals do not add to 100% for any combination of behaviors, e.g., "looking at robot," "looking at teacher," and "looking around" do not cover all of the visual attention of any subject. Increases or decreases in the frequency of these behaviors over the course of the robotic use are noted in Table III. The column labeled *trends in frequency of events* reflects changes in these parameters over all the sessions. Table IV shows typical goals.

TABLE III
SUMMARY OF GOAL ATTAINMENT SCALING, TREND, AND INTERVIEW DATA FOR THE 12 SUBJECTS

	Functional Goal Attainment [Initial/Final]	Operational Goal Attainment [Initial/Final]	Carryover Goal Attainment [Initial/Final]	Trends in Frequency of Events	Teacher Interview
P1	Anticipated turn and initiated action. [+1/+1]	3 Switches with minimum assistance, used switch 2 with no assistance. [-2/+1]	Vocalizations increased [-1/+1]	Switch 2 and 3 errors, visual, and auditory prompts decreased. No vocalization during arm use.	Confidence and interaction increased, looked forward to sessions. Used new symbols in class and interaction increased.
P2	Attended to teacher when told "my turn" [-1/+1]	Operated switch 1 and 2 in less than 10 seconds, or preservation. [-2/0]	Became excited when robot mentioned [-1/0]	Switch 1 and 2 had no errors. switch 3 errors decreased.	Robot gave student something to look forward to and became excited about.
P3	Consistent interest in the activity [-2/+1]	Used switch 1 with few prompts, and was able to use all three switches. [-2/0]	Increased vocalization in class. [-1/0]	Auditory prompts increased, visual prompts were consistent. Most prompts were for switch 3. Looked at task/instructor unchanged.	Smiled and got excited when robot mentioned in class or at home. More vocalizations in class, and was more interactive after robot use.
P4	Attended to arm [-2/-1]	Hit switches inadvertently [2/-1]	No carryover to the classroom. [-1/-1]	No switch errors and all 3 switches hit on each trial.	Seemed to look at the arm during use. No change in the classroom.
P5	Anticipated and responded to "your turn." [-1/0]	Controlled 2 switches with prompts. [-1/-1]	No carryover to the classroom. [-1/-1]	Auditory and visual prompts increased. Switch 2 errors increase. Switch 3 errors were unchanged.	Eye contact before hitting switches and excited at reaction of robot. No classroom change.
P6	Anticipated initiated and responded to "your turn". [-1/+1]	Controlled 3 switches with auditory and visual prompts. [-2/+2]	No carryover to the classroom. [-1/-1]	Auditory and visual prompts increased. Switch 2 and 3 errors increased.	On the way to robot the student anticipated what was going to happen; ability to control robot increased student's self esteem. Minimal carryover to class; slightly more outgoing behaviour.
P7	Responded to "your turn" [-2/+1]	Controlled 2 switches with no prompts [had bad days] [-2/0]	Excited when robot session was mentioned [-1/0]	Switch 2 errors unchanged. Visual prompts increased and auditory prompts were unchanged. Looked at task/ instructor increased.	The student became excited when the robot arm was mentioned in class.
P8	Anticipated and initiated turn. [-1/+1]	Controlled 3 switches without assistance, [0/+2]	Increased vocalizations. [-1/+1]	Auditory and visual prompts decreased. Looked at task was unchanged, looked at instructor decreased.	"Learned new words like crazy"; and put two words together at home and school.
P9	Did not attend to arm at all. [-2/-2]	Focused on arm with few prompts. [-2/-1]	No carryover to the classroom. [-1/-1]	Auditory prompts increased and visual prompts decreased. "Looked at task" and "looked around" were unchanged, and "looked at instructor" was decreased.	No change in the classroom.
P10	Demonstrated understanding of task. [-1/+2]	Operated 3 switches with minimum errors. [-2/0]	Discriminated colors [-1/+2]	All switch errors decreased.	Demonstrated understanding of the task which extended the student's learning experience. The student was able to show understanding of color matching using robot
P11	Understood 'your turn" [-1/+2]	Operated 3 switches with no assistance. [-2/0]	Increased vocalizations in class [-1/+1]	Looked at task increased. Auditory and visual prompts decreased.	Predicated and reacted to what happened; could do more with hands, increased self-esteem. More social and expressive; greater class participation and more vocalization, noises and laugher.
P12	Attention to task for one trial. [-2/0]	Controlled 2 switches without assistance, controlled 3rd switch with assistance [-1/+1]	Showed more enjoyment when participating in classroom activities [-2/+1]	Auditory, visual prompts and switch 3 errors remained constant. Switch 2 errors, looked around/at task/at instructor all decreased.	Indicated interest in task by tapping the tray for turn, more vocalizing and facial expressions. The robot was a challenge and helped with understanding, cause and effect and control of the environment. Student enjoyed the activity.

Fig. 4 shows an example of trends for auditory and visual prompting and incorrect switch activation for student number P1. Each task required a particular switch to be hit. Thus, if the child hit an incorrect switch for that task it was recorded as a switch error. Linear trend lines are also shown for each of the variables.

In order to evaluate attention to, and interest in the robot, parameters such as the example shown in Fig. 5 for student P8

TABLE IV
TYPICAL GOAL ATTAINMENT EXAMPLES

Score	Operational Goal Example	Functional Goal Example	Carryover Goal Example
+2	Controls 3 switches in a 4 step scoop with minimal assistance	Anticipates the outcome of the task	Unexpected gains-classroom activities
+1	Controls 3 switches in a 2 step scoop with no assistance	Anticipates and responds accordingly to her turn	Increased attention in classroom activities and increased vocalizations.
0	Controls 3 switches with out assistance	Understands "your turn" and responds appropriately	Increased vocalizations in the classroom
-1	Controls 3 switches with visual prompts	Understands turn taking with auditory and visual prompts	No change in attention, vocalizations in the classroom
-2	Controls 3 switches with visual and auditory prompts	Doesn't understand turn taking	More passive in classroom, decreased vocalizations, shorter attention span

were used. In general, a decreasing trend in "looks at instructor" was interpreted as increased independence. A decreasing trend in "looks at task" (recorded when the children looked at the robot) was interpreted as losing focus on the task.

C. Teacher Interviews

Following the final robotic session, the children's teachers were interviewed using the questions shown in the Appendix. Results of these interviews are summarized in Table III where they are related to results obtained for the functional and or carry over goals for each child.

The teachers were also asked to comment on three more general aspects of the robot and its classroom use, also shown in the Appendix. The first of these questions addressed the changes teachers would suggest with respect to the capabilities of the robot arm. The following four themes were abstracted from those comments.

1) The robot should have more color, contrast, and character.
2) The robot should be able to generate sounds and/or music for student cues and feedback for successful performance.
3) The robotic system accuracy should be increased so that teacher assistance is not necessary to complete the task.
4) The tasks should be expanded to include two or more children (nondisabled and disabled peers) in a play context using cognitive activities and training for powered mobility.

The second general question asked the teachers whether they could see ways the robotic arm would be useful in their classroom. The responses obtained from the teachers in answer to this question are summarized in the following themes.

1) The robot may increase students' independence by allowing them to do activities related to basic life skills (e.g., kitchen tasks, self care, ADL) and academics (e.g., spelling, reading, color ID, asking questions, free drawing, interaction between two objects).
2) The robot can be motivating and foster integration by allowing children with disabilities to participate more independently and contribute to class activities.
3) The robot can contribute to growth and development by assisting the child to do a variety of activities typically done by nondisabled peers.
4) The teachers also indicated that in order to be useful in the classroom, the robot system must be reliable, easy to set up, and perform as expected.

The final general question asked the teachers whether children reacted differently to the robotic arm than to other single switch tasks (e.g., toys and appliances). The responses to this question are summarized in the following four themes.

1) The robot is more stimulating, motivating, exciting, interactive, interesting and fun, and it requires more thinking on the student's part than do single on/off switch toys.
2) The robot is more challenging, satisfying and has many capabilities that hold student interest. It made other single switch activities easier for the child.
3) The robot can reveal student performance levels through exploration, multiple stage tasks and cognitive and academic activities.
4) The robot is more interesting to the child than two-dimensional computer activities. It also allows for activities that contribute to eye–hand coordination.

V. DISCUSSION

As shown in Table I, all the students in the study had severe physical disabilities. Nine of them used one hand movement to control the switches and three used head rotation. All of the children were able to physically control the switches. The children fell into three cognitive/language groups labeled as Group 1 (very low functioning), Group 2 (low functioning), and Group 3 (moderate cognitive disability). Group 1 included subjects P3,

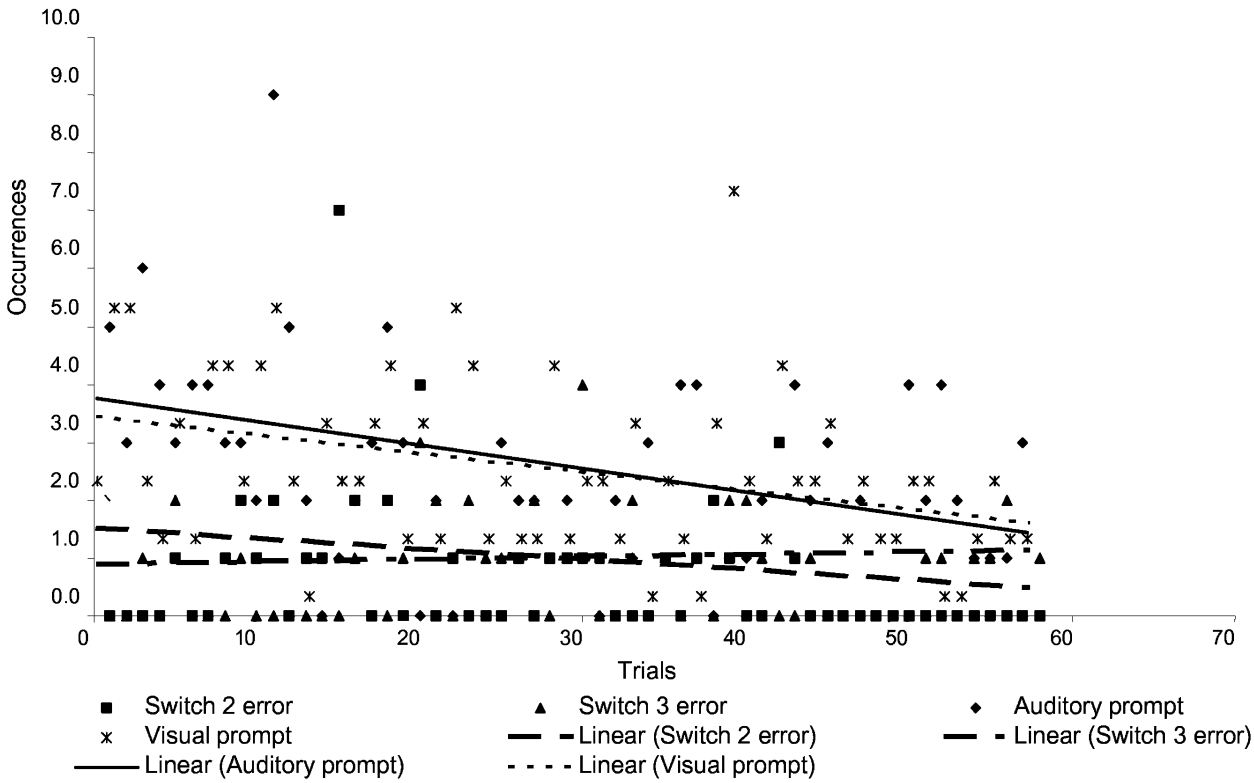

Fig. 4. Trends for auditory and visual prompting and incorrect switch hits for student P1.

P4, P9, all of whom had severe receptive and expressive speech and language delay. They also had limited social interaction and were generally passive. Group 2, subjects P2, P5, P6, P11, and P12, had some vocalization and moderate receptive skills. They also responded to greetings and were more social, both with the researchers and in their classroom environment. Group 3, P1, P7, P8, P10, all had near age-level receptive language skills. Their expressive skills were limited, but all used vocalizations and/or symbols for communication. This group was very social and out going.

All of the children reacted positively to the robot. The robot-generated tasks were more motivational for the children, and generated more interest and excitement than single switch tasks such as toys, appliances or computer-based activities. Prior to robot use, T scores were below 50 (representing the expected outcome) for all children. The majority of the children in the study had T scores greater than 50 on all scales after using the robotic arm for a period of approximately four weeks. The greatest improvement was in operational scale scores, followed by the functional scale and carryover scale scores, respectively.

There was a relationship between the three goals established for each child and their cognitive/language skills. Those in Group 1 generally had operational goals of controlling one or two switches with prompting. Those in the other two groups generally had goals relating to success in controlling three switches, and their associated tasks. For the functional goals, Group 1 was only required to show and maintain interest, Group 2 was expected to anticipate their turn, and Group 3 was expected to both know when it was their turn and initiate interaction without prompting. Finally, the greatest carryover was expected for Group 3; however, the results indicated students in all three groups had some carryover to the classroom. It was the type and amount of carryover that varied between the three groups. This spread of results is consistent with those of [8] in their use of a robot for classroom drawing. For Group 1, carryover was characterized by increased vocalization and classroom interaction. For Group 2, there was also anticipation of the robot sessions and more attention to classroom activities. The children in Group 3 achieved new learning in the classroom that was attributed to the use of the robot. For the majority of the children, vocalizations increased during robot use and this was carried over to the classroom. Butler [22] found a similar increase in vocalizations when very young children with severe physical and cognitive disabilities were given independent mobility. In general, the performance from Group 1 to Group 3 (increasing cognitive and language ability) parallels the results of Forman [23] in which nondisabled children were only able to perform more complex robot tasks at later ages. Younger children could only accomplish simpler tasks, while older children mastered more complex tasks. Our results have a similar trend, but are based on developmental level rather than chronological age.

A decrease in the number of switch activation errors was taken to reflect an increase in skill by the child. For the majority of the children, this skill development occurred. The increase in skill was greatest for Group 1, with smaller increases for Groups 2 and 3. This may have reflected the generally lower initial ability level for Group 1. A decrease in the number of prompts (physical, auditory, and visual) was interpreted as increasing independence of the part of the child. The mean number of auditory prompts was higher for the children who had visual impairments (P5, P9) and for those with severe receptive language

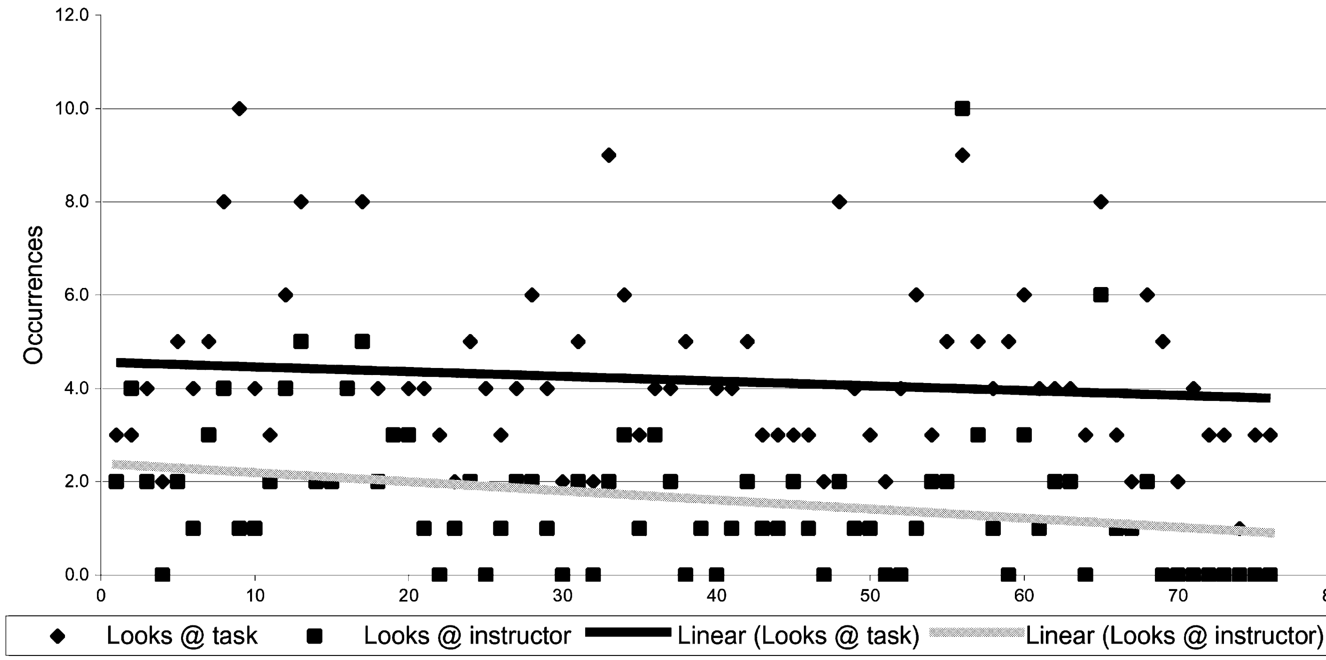

Fig. 5. Trends in looks at task and instructor for student P8 illustrating the analysis used to evaluate functional goal scoring.

limitations (P3, P4). The mean number of auditory prompts was highest for Group 1, less for Group 2, and smallest for Group 3. For all groups, the level of prompting decreased over the course of the four-week robotic interaction. This training effect is similar to that observed by [7].

At the beginning of the study, the teachers involved believed that the researchers had overestimated the skills of the children selected for this project. In contrast, at the completion of the study both the teachers and teacher assistants believed that the children had made significant accomplishments as a result of using the robot. This led to a perception that the children were more capable than had been previously thought. This perception positively affected the teachers' interaction with the children in other learning contexts in a positive way. This finding is consistent with previous robotic studies [16]. This change in perception of students' capability appears to be greater than for other assistive technology tasks. Successful use by children in tasks involving computer controlled games, educational software, and electronic aids to daily living is less surprising to teachers and teaching assistants. This may be related to the apparent problem solving skills that are demonstrated during robotic use. When these are mastered, it can alter the perception of the child in other skill areas.

VI. Conclusion

Children with severe physical disabilities are able to understand multiple step sequence tasks using a robotic arm. This robot use can also reveal information about the child's cognitive and language skills that are not easily assessed using other means. Future areas of research in this area will include paired studies of nondisabled children are matched to children with disabilities in cooperative play tasks using the robot and greater classroom use of the robotic arm.

Appendix
Examples of Goals Used in Goal Attainment Scaling

Examples of teacher questions are as follows [24].

1) How do you feel the children reacted to the robotic arm?
2) Did you notice any changes in the children's behavior during the project?
3) Did you notice any changes in the children's social skills during the course of the project?
4) Did you notice any changes in the children's language skills during the course of the project?
5) What changes would you recommend with respect to the arm and the capabilities of the arm?
6) Can you see ways that the robotic arm would be useful in your classroom?
7) Do the children react differently to the robotic arm than to other single switch tasks (e.g., toys or appliances)?

References

[1] W. L. Haight and J. E. Black, "A comparative approach to play: Cross-species and cross cultural perspectives in play development," *Hum. Develop.*, vol. 44, no. 2, pp. 228–234, 2001.

[2] D. Kleiber, *Leisure Experience and Human Development*. New York: Basic Books, 2000. 1994.

[3] J. E. Black and W. T. Greenough, "Induction of pattern in neural structure by experience: Implications for cognitive development," in *Advances in Developmental Psychology*, L. Albme and B. Rogoff, Eds. Mahwah, NJ: Laurence Erlbaum, 1986.

[4] C. Musselwhite, *Adaptive Play for Special Needs Children*. London, U.K.: College Hill, 1986.

[5] E. I. Blanche, "Doing with—Not doing to: Play and the child with cerebral palsy," in *Play in Occupational Therapy*, L. D. Parham and L. S. Fazio, Eds. St. Louis, MO: Mosby Yearbook, 1997.

[6] J. Brodin, "Play in children with severe multiple disabilities: Play with toys—A review," *Int. J. Disability Develop. Educ.*, vol. 46, no. 1, pp. 25–34, 1999.

[7] H. Kwee and J. Quaedackers, "Pocus project adapting the control of the Manus manipulator for persons with cerebral palsy," in *Proc. Int. Conf. Rehabil. Robot.*, Stanford, CA, 1999, pp. 106–114.

[8] J. Smith and M. Topping, "The introduction of a robotic aid to drawing into a school for physically handicapped children: A case study," *Br. J. Occupational Therapy*, vol. 59, no. 12, pp. 565–569, 1996.

[9] R. D. Howell, S. K. Damarin, and E. P. Post, "The use of robotic manipulators as cognitive and physical prosthetic aids," in *Proc. 10th RESNA Conf.*, 1987, pp. 770–772.

[10] R. D. Howell, K. Hay, and L. Rakocy, "Hardware and software considerations in the design of prototype educational robotic manipulator," in *Proc. 12th RESNA Conf.*, 1989, pp. 113–114.

[11] R. D. Howell, G. Mayton, and P. Baker, "Education and research issues in designing robotically-aided science education environments," in *Proc. 12th RESNA Conf.*, 1989, pp. 109–110.

[12] W. S. Harwin, A. Ginige, and R. D. Jackson, "A robot workstation for use in education of the physically handicapped," *IEEE Trans. Bio.-Med. Eng.*, vol. BME-35, pp. 127–131, 1988.

[13] S. Y. Nof, G. R. Karlan, and N. S. Widmer, "Development of a prototype interactive robotic device for use by multiply handicapped children," in *Proc. ICart*, Montreal, QC, Canada, 1988, pp. 456–457.

[14] S. P. Eberhardt, J. Osborne, and T. Rahman, "Classroom use of the Aryln arm robotic workstation," *Assist. Technol.*, vol. 12, pp. 132–143, 2000.

[15] C. Lathan, J. M. Vice, M. Tracey, C. Plaisant, A. Druin, K. Edward, and J. Montemayor, "Therapeutic play with a storytelling robot," in *Proc. Conf. Human Factors Comp. Syst.*, 2001, pp. 27–28.

[16] A. M. Cook, K. M. Liu, and P. Hoseit, "Robotic arm use by very young motorically disabled children," *Assist. Technol.*, vol. 2, pp. 51–57, 1990.

[17] A. M. Cook, P. Hoseit P, K. M. Liu, R. Y. Lee, and C. M. Zenteno, "Using a robotic arm system to facilitate learning in very young disabled children," *IEEE Trans. Bio.-Med. Eng.*, vol. BME-35, pp. 132–137, 1988.

[18] A. M. Cook and A. R. Cavalier, "Young children using robotics for discovery and control," *Teaching Exceptional Children*, vol. 31, no. 5, pp. 72–78, 1999.

[19] A. M. Cook, K. Howery, J. Gu, and M. Meng, "Robot enhanced interaction and learning for children with profound physical disabilities," *Technol. Disability*, vol. 13, no. 1, pp. 1–8, 2000.

[20] A. M. Cook, M. Q. H. Meng, J. Gu, and K. Howery, "Development of a robotic device for facilitating learning by children who have severe disabilities," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 10, no. 3, pp. 178–187, Sep. 2000.

[21] T. J. Kiresuk, A. Smith, and J. E. Cardillo, Eds., *Goal Attainment Scaling: Applications, Theory and Measurement*. Hillsdale, NJ: Erlbaum, 1994.

[22] C. Butler, "Effects of powered mobility on self-initiated behaviors of very young children with locomotor disability," *Develop. Medicine Child Neurol.*, vol. 28, pp. 325–332, 1986.

[23] G. Forman, "Observations of young children solving problems with computers and robots," *J. Res. Childhood Educ.*, vol. 1, no. 2, pp. 60–73, 1986.

[24] A. Cook, B. Bentz, C. Card, H. Y. Kim, and M. Meng, "Robot Use And Cognitive Development In Children With Cerebral Palsy," presented at the Proc. 2002 RESNA Conf., Minneapolis, MN, 2002, pp. 17–19.

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