Robot enhanced interaction and learning for children with profound physical disabilities

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The goal of this study was to explore how children who have significant physical disabilities could use a robotic arm to interact in a play and exploration activity. These children cannot manipulate toys and other objects to engage in typical play activities with adults or their peers. A robotic arm was used to provide an alternative method to engage in joint play activities. Using the robotic arm, these children were able to engage in play with an adult. For successful play experiences, this activity required manipulation of objects in sequence and turn taking with the adult. Children were able to experience, independently, the mediated manipulation of real objects in the context of a play activity. They demonstrated an ability to interact and to carryout a sequence of steps to complete a play task.

Keywords: Robotics, severe disabilities, children, play

1. Introduction

Children with severe motor disabilities cannot control their environment without assistance and have few opportunities for spontaneous exploration. They may begin to lose interest in the environment and develop 'learned helplessness' [13]. Unless they are given active opportunities to explore their surroundings by alternative methods, these children may remain passive, dependent and socially inactive [20]. Play allows development of environmental exploration.

Ruff et al. [19] studied manipulative exploration of objects by both full and pre-term infants (considered to be at risk for cognitive disabilities). They found a relationship between manipulative exploration occurring at nine months and later cognitive functioning. Their results suggest that lack of early manipulation is one way in which cognitive deficits may arise and or be maintained. They concluded that early manipulative exploration of objects can have long-term effects on the development of these abilities.

Play and development are critically inter-related concepts. Play is one of the primary occupations of childhood, and as Pierce [18] states, it is through play that "the child learns to explore, develop, and master physical and social skills". Children with physical disabilities have limited access to play activities, and because children with disabilities typically engage in adult-chosen play activities, the quality of their play may be compromised [16]. Also, because children with disabilities may take longer to respond and make less obvious responses, adults take the role of entertainer and director of the play and they may not spend enough time observing the play and taking turns with the child. The most appropriate role for the adult is as an equal partner in the play taking, turns with the child. Blanche [3] discusses "play based" therapy sessions for children with cerebral palsy. She calls the common play mode, in which the adult directs the play experience, "entertaining". A more productive alternative, in which the child and adult share responsibility for directing the play, is the "conversationalist" method. This method "doing with" rather than "doing to" the child is generally a more productive alternative and provides more opportunity for discovery and learning by the child. Play, as a context for learning and as a joyful activity, is limited in children who have cerebral palsy. These children have great difficulty engaging in activities for their sensorimotor pleasure, and their reduced exposure to this form of play may restrict their development of motor coordination and perceptual and cognitive development.

Play deprivation for children with physical disabilities can result from the impairment (primary play deprivation) or from a lack of access to substitute play activities that are analogous in form and function to the more typical play activity (secondary play deprivation). Since children with severe physical disabilities have limited opportunities to explore their environ-

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ment, computers adapted to allow access by the child have been used to simulate a range of play experiences that allow discovery and exploration. This approach requires that the child be cognitively able to control the interface (e.g., switches, mouse). Computer-mediated play ranges from simple cause and effect programs to more complex programs requiring children to make decisions and engage in more difficult control of the software. Although computers allow a mediated version of play for children with disabilities, it is not the same type of play as that which is done by a child with real objects [1].

The provision of robotic systems that the child controls to manipulate objects in a play context is attractive for children whose disability prevents or limits their ability to engage in play. Robotics provides an opportunity to choose how to interact with their environment, to exert some control over the activity, and to manipulate three-dimensional objects. This use of robotic systems differs from their use as manipulative prostheses for people with disabilities [22]. Forman [10] proposed that there were five broad areas of problem solving in which computers and robotic technology could assist development. These are causality, coordination of multiple variables, reflectivity, binary logic, and spatial relations. In order to investigate typically developing children's understanding of causality, he used a panel of switches controlling a robotic arm. Forman also used the robot to investigate the coordination of multiple variables by requiring a robotic arm movement in which the arm held a glass of water and the wrist angle had to be continually changed as the elbow was flexed in order to prevent water from spilling. Young children carried out this task as two sequential events. Older children were able to develop a control scheme that used coordination of the wrist and elbow. Only the oldest of his children demonstrated reflectivity, the ability to understand what we are doing. Binary relations were explored by using paired opposites. For example, one switch opened the robot hand and its binary pair closed it. Younger children had trouble associating the pairs of switches by function, and they were unable to understand that an action (e.g., hitting a switch) could terminate an action (e.g., stop the arm) rather than initiate an action.

Robotic systems can facilitate learning and exploration by children who have severe disabilities in several ways. If a robotic arm is sufficiently adapted [5], even very young children will interact with it and use it functionally [9]. Both typically developing children and those with disabilities used the arm as a tool to obtain objects out of reach. The common factor was a cognitive developmental age of 7 to 9 months or greater, and success in using the robotic arm was most closely related to developmental levels in cognitive and language areas rather than gross and fine motor development. Early use of a robotic arm, can lead to greater exploration and active participation in classroom tasks as the child enters school [4]. For older children, sequences of one and two-step tasks to complete the same activity can be programmed into the robotic arm system and placed under the control of the child [17]. For children who have very severe motor disabilities, robotic systems can be further adapted to allow single-switch scanning to select the direction of movement followed by switch-controlled arm movement in that direction [15]. However, these adaptations for physical performance may result in cognitive tasks that require significant amounts of training and practice in order to understand the cognitive aspects involved (e.g., pouring water from a glass, eating a cookie). Open-ended tasks such as drawing can also be carried out using single-switch scanning [21]. In this case, selection of the color of a pen and the position the pen, up (move) or down (draw), and its movement are accomplished using single switch scanning. Tasks such as these are cognitively demanding, and Smith and Topping [21] reported a wide range of success in the three subjects included in their study.

In an elementary school setting robotic systems have been used to facilitate instruction in tasks requiring manipulation [12]. Four levels of control: (1) demonstration, (2) pre-stored tasks, (3) unstructured movement, (4) student programming and storage of movements were developed using special software and hardware [13], and the system was used in science instruction at the elementary school level [14]. Inclusion of a vision system based on a television camera and image recognition software, allows more complicated manipulative tasks such as finding and stacking blocks to be successfully accomplished by students who have severe motor disabilities [11]. The common theme for all of these applications is that the robotic system allows greater interaction with and exploration of three-dimensional objects. The study reported here is an extension of that concept to a container play situation.

2. Materials and methods

The study reported here focused on both the child's performance of specific tasks and on the cooperative play interactions that the robot facilitated for the child. Container play (e.g. scooping and dumping) was chosen, as it is a play activity typically seen in early childhood. Children at approximately 15 months of age engage in container play activities, but this type of play continues into kindergarten and early grades and contributes to many learning contexts and activities, especially those in the domain of science. In the appropriate context, the robot can facilitate play activities that are analogous to typical play for children with physical disabilities, thereby giving them the ability to control the play experience and to actively participate in play with others. Preliminary reports of this work have been presented elsewhere [6–8].

2.1. Objectives

This study evaluated how young children who have physical disabilities use the robotic arm for exploration and play. The overall goal of this project was to evaluate how children with severe physical disabilities can control a robotic arm to engage in functional play tasks. Specific objectives were to determine if:

1. the child appeared to relate each switch to its corresponding action,
2. the child took a role in the play activity, and
3. the child could combine the switch actions into a three-step process.

Beyond this, the study looked at the quality of this type of play experience for children with physical abilities and whether these children would learn to engage in turn-taking behavior that involved manipulation of objects in a co-operative play situation with an adult.

2.2. Procedures

The robotic arm was used in an exploratory format in which the child was shown how the robotic arm moved by a single switch activation to replay a stored movement. A series of progressively more complex tasks reflecting both the increasing developmental level of the task and an increase in the number of switches used to control the arm was programmed for playback by the child.

As shown in Fig. 1, the play was focused around a large tub of dry macaroni to provide both sensory and motor interactions for the child. This medium allowed the child to use the robot arm to dig up the macaroni and dump it out much like typically developing children would do in early sandbox play. The medium also allowed objects to be "hidden" (buried) from the child's view so discovery could be a component of the play activities as well as manipulation of the medium.

Fig. 1. The robotic system. The robot arm is shown in the foreground. The child was able to dig and find objects hidden in a tub of dry macaroni.

We began by determining whether the child understood the function of each switch and whether he or she could combine the switch actions into a three-step sequence of motor actions and to use them to find buried objects of interest.

Each session with a child was video taped for review. One investigator engaged in play with the child. The video observation was by another investigator. The adult play partner was known to all of the children who participated in the study. Observed behaviors are described in Table 1. We also noted the type and number of prompts that were required in order for the child to successfully complete the task, and the nature of the play interaction (e.g., initiation of play by the child, the amount of interaction between the child and the adult play partner).

2.3. The experimental system

The robotic arm used for these studies is the CRS A465 that can rotate about its base, flex and extend at the elbow and shoulder, extend, flex, supinate and pronate the wrist, and open and close the gripper. Using a teaching pendant, the arm can be moved through a desired movement or portion of a movement and the movement can be stored for later playback. A specially designed interface allows single switch playback of movements. In multiple movement tasks involving more than one switch, the computer was programmed to accept only the correct switch input.

Table 1
Videotape observed behaviors and their interpretation

Examples of observed behaviors	Inferred Meaning
Looking at robotic arm	Request for activity
Looking at robotic arm after switch activation	Anticipation of arm movement
Movement toward correct switch in sequence for task 2 or 3	Intent to hit switch (used to distinguish inadvertent from purposeful switch activation)
Smiling, laughter	Positive reaction to robotic arm and/or play activity
Frowning, crying	Negative reaction to robotic arm and/or play activity
Restless	Tired or bored with task
Looking at play partner	Request for play activity
Looking at cup or looking at cup and then at adult	Request for adult to fill cup (Task one) or request for repletion of tasks (all tasks)
Looking at egg	Request for play partner to open egg and display contents
Time delay between end of robotic arm movement and child hitting the net switch in sequence	*Larger* implies more random child action *Smaller* implies more purposeful action by child

2.4. Description of tasks

Three distinct tasks were programmed to generate specific robotic arm movements.

Task 1: The arm dumped macaroni from a glass using one switch hit. In this task, the adults role was to FILL UP the cup with macaroni (by hand) the child's task was to hit the switch that would cause the robot arm to DUMP the macaroni out. The adult would catch the falling macaroni. The child would then indicate that the cup should be filled again (typically by looking at the cup) and the process was repeated.

Task 2: The child controlled the arm to (1) dig an object out of the macaroni, and (2) to dump the macaroni and object, using two switches. Here the child used a second switch to activate the robot arm to dig in the macaroni to FILL UP the cup and use the same switch as in task one to once again DUMP out the macaroni. In Task 2 the child dug up a plastic egg with some kind of small toy inside. The adult's role was to bury the egg in the macaroni, to catch the egg (and macaroni) when the child had dumped it out of the cup and, finally, to open the egg for the child when the child indicated he/she wanted it opened to see what object was inside. Typical objects were a finger puppet, a small rubber stamp or a sticker or toy ring.

Task 3: In this task the robot arm start position was changed so that before the child could dig up the egg, he/she would have to move the hand to the correct position (i.e. over the buried egg). The adult's tasks were as they were in Task 2. The child was given access to a third switch which, when activated, caused the arm to move in a horizontal direction to where the egg was buried. Once the robot hand was positioned by the child, the task become identical to task 2.

2.5. Description of children

Four children, ages 6 and 7, participated in the study. All of the children had severe cerebral palsy that limited their ability to control their limbs. None of the children were able to speak. Each child used left and right head movement for the first two movements (those in Task 1 and 2). For Task 3, the third switch was activated by the hand for two of the children, behind the left elbow for one and by the right foot for one.

All four children have had experience using single switches to operate battery-operated toys and to access simple games on the computer. Although at least one switch site has been identified for each child, exact placement of the switches has not been satisfactorily achieved for any of these children. Consistent access to switches was difficult for all four children due to the severe nature of their cerebral palsy. Only one of the four children had previous experience with the use of more than one switch, and this was in the context of powered mobility. The other three children had only been engaged in single switch activities and differentiation of multiple switch use was new learning for them.

None of these children would be able to engage in container play independently or with another child or adult without some adaptation. By parental and school report, these children were loosing interest in many of the computer activities to which they had access. This could be due to the lack of control they had over their switches or because this type of play was not meaningful to them. All the children were reported to be more interested in other people and children in the classroom than in the computer or other play activities accessible to them with simple technology.

3. Results

Overall, the results indicate that the children learned the stored tasks and how to operate them. Beyond this, the children were actively engaged in the turn-taking behavior and interaction that was encouraged by the nature of the task.

3.1. Skills students demonstrated

There was great interest by the children in the robot and no apprehension toward it. By parental report and clinician observation, children attended to task for significantly longer periods with the robot than with other activities (e.g., computer graphics programs). All of the children understood that hitting switch #1 dumped the cup and its contents. After one or two trials in which verbal and physical prompts were used, the children were able to activate the switch as soon as the adult filled the cup. The children initiated turn taking behaviors and would prompt the adult to fill up the glass by looking at the glass as a request. The children reacted very positively to this task and looked toward the arm after hitting the switch in anticipation of the cup being dumped. They also reacted with pleasure to the adult's participation in the play, and would occasionally dump the macaroni prior to the adult having completely filled the glass. They found this amusing, indicating that they had some understanding of expected timing of the turns. This phase lasted an average of 8 trials, and it served both as a physical 'warm-up' and orientation to the task for the child.

Adding a second switch with a different function led to confusion for some of the children. All of the children had to be physically prompted (moving the child's head until it contacted switch #2 (dig)) before they began to understand the task. After one or two physical prompts, three of four children learned to 'dig' (switch 2) and then 'dump' (switch 1) with only verbal prompts. For the fourth child, additional physical and verbal prompting was required for task completion. In this task it was not clear whether the children understood the nature and timing of the turn taking. It could not be determined if they consciously waited for the adult to bury the egg or if they just dug when they were cued. However, all children did appear to watch the adult bury the egg and to be aware that the task had changed from the initial one where there was no "treasure" to find in the macaroni.

Due to their severe physical disabilities, some of the children had uncontrolled body movements that led to some random switch activations (e.g., hitting the "dump" switch before the "dig" switch). Review of the videotape records did indicate that the children initiated movement toward the correct switch when required, although they sometimes hit the incorrect switch through uncontrolled body movements. Children took between 6 and 12 trials to demonstrate that they understood the two switch sequence task by completing it for three trials in a row with no prompting. All the children indicated interest in finding out what was inside the egg by looking at the egg and smiling and request that the adult open it by directing their eye gaze to the egg.

When the third switch ("move") was added (Task 3), the children required differing levels of prompting to understand its function. For one child, during one session, it was necessary to remove switches 1 and 2 and teach the function of switch 3 alone, then replace the other two switches. For the other sessions and for all sessions with the other children, the third switch was simply added to the first two. All of the children required both verbal and physical prompts in order to carry out the third part of the sequence ("move"). Children took more trials to understand this task, and each trial required more prompting. There were also many incorrect switch hits (wrong order). For the children to understand the three-switch task, they would have to have seen the burying of the egg and understand that they had to move the hand to the correct place to acquire it. There were 2 turns required by the child after the adult's first turn: (1) move the robotic hand to the place above the hidden egg, and (2) dig the egg up before the adult was required to take her turn of catching the egg. This two-part sequence proved to be the most difficult for every child. They were able to add the third switch to their repertoire, but each child needed prompting to accomplish the movement of the robotic hand by hitting the third switch. These tasks were physically demanding for the children, and exhaustion was a common occurrence by the end of a session.

4. Discussion

The use of the robot in the specified tasks allowed all children to engage in a cooperative play activity with an adult. Every child engaged in turn taking by hitting switches to control the robot's movements. They also learned how to use switches to control the robot's movements in the context of this play activity. All of the children understood the first task (dump-1 switch). In the second task (dig/dump-2 switch), three of the four children hit the proper switch to 'dig' prior to hitting the 'dump' switch after one or two prompted trials. The fourth child required additional trials and prompting to achieve success in this task.

The children were very motivated to engage in this play activity. They would often continue for periods of up to one hour or until they were physically exhausted. This was much longer than they would typically engage in other play activities, including computer-controlled games. By parental report, the children were interested in the play and appeared to be excited by the activity. This is in marked contrast to observations of their play behaviors in other adapted play activities.

Understanding of the three-step (3 switch) move, dig, and dump sequence was more difficult for all of the children. Three of the four children appeared to understand it eventually. This task was more abstract than the digging and the dumping and was less visually obvious. Children often hit one of the first two switches before they hit the "move" switch. This may be due to the extraneous movements or to a lack of understanding by the child. In the current study, the computer was programmed to accept only the correct switch input. Thus, if a child hit the wrong switch the arm did not respond. In further studies, it is important to determine if the extra switch hits are accidental due to uncontrolled movements or due to lack of understanding of the task. In order to make this determination we will use an alternative control mode in which all switches are active at all times, and the child will cause the arm to respond no matter which switch is hit. For example, if the child hits switch 2 first the arm will attempt to dig, even though it is not positioned near the buried object. This will allow us to explore what the child's reactions are to this anomaly and whether the child attempts to correct his or her actions to obtain the correct sequence. This approach can only be undertaken when it is clear that the child has control over all three switches. In our study this could not be established, and it may also be the underlying reason that others have reverted to scanning for robotic control for children who have severe motor disabilities [15,21].

It is important for the child to have more experience in moving the hand to a particular location in the context of a play activity. This movement requires spatial planning concepts that they likely have very little experience with due to their disabilities. Based on experience with battery-powered toys and computer-controlled games, all the children had more practice with the control aspects associated with the dig and dump portions of the play. This container play was the focus of each session while the movement itself received less attention. In order to evaluate the child's learning of this component of the interaction; more emphasis would need to be put on the "Hide and Seek" aspect of the activity; i.e., having the child discover what is buried in the macaroni or hidden inside a plastic egg.

Since the computer only accepted the correct switch input, it is difficult to know if all the children could correctly sequence the actions to complete the entire task in multiple action tasks. However, review of the videotapes revealed that the majority of the children appeared to be moving in the direction of the correct switch as they engaged in repeated trials of the tasks. Three of the four were able to put two operations together to complete a task. This gave a unique "window" on their ability to sequence since most were very physically limited and did not speak.

The robot arm also gave the children the opportunity to interact with the investigators by "handing" objects to them and using eye gaze to choose which object was to be buried. This type of interaction is not possible with computer graphics or battery-powered toys. Children often satiate quickly and lose interest in tasks that only emphasize cause and effect relationships with toys, or simple switch activated computer games. The three-dimensional aspect of this play activity was definitely of greater interest to the children since they could manipulate real objects. Acting on the three dimensional environment also teaches different things than the two-dimensional world of computer screens. Spatial concepts, teasing, the need for precision in manipulation are all better taught in three dimensions, and robotic systems allow this to happen.

Including a more interactive play activity in the three dimensional world was important to motivate the children to engage in switch mediated play. It was also important that the participation of both the child and the adult was necessary in order to complete the tasks. By letting the child complete his or her part of the task and continually discussing what was happening, the adult became more of a conversationalist and entertainer and less of a director of the activity [16]. Since, interaction and play activities are an integral part of learning about the world and its relationships, this type of play is valuable to the child in a more general context than the robot tasks. We found that parent's and teacher's perceptions of the abilities of these children were altered by the child's participation in this study. Following success in the robotic arm tasks, the children were perceived by parents and teachers to be more capable and more independent than when they were observed in less demanding tasks. Robot enhanced play for children with physical disabilities allows a much wider breadth of play activities for children with disabilities, and this can reduce their play deprivation and passivity in other task and situations.

It has been proposed that a human aide can accomplish the same result as the robotic arm by carrying out a child's communicated instructions. We believe that the actual use of a robotic arm differs in several ways from that of a human attendant. First, many of the children with whom we work (and those in this study) lack the communicative skills to give sufficiently clear instructions for multiple step tasks. Thus, the human aide is left to "interpret" the instructions and act accordingly. Often this leads to more adult-directed play and less child-initiated cooperative play. Second, unless the aide very literally follows the child's instructions, the child cannot "surprise" the play partner. In our study the children often surprised the adult by dumping the cup full of macaroni when the play partner wasn't ready. Their subsequent smiling or laughing indicated that they had intended this as a "surprise", especially if the adult's reaction was one of surprise. Such spontaneity is a major feature of play and can be accomplished by self-directed manipulation using a robotic arm. If the adult is controlling the actions, then the child has no opportunity to create unexpected manipulative actions and subsequent reactions of the adult in the task.

5. Conclusions and future directions

This study is part of an overall research program leading to the provision of more general play and learning opportunities for children with profound physical disabilities. Future studies include play interactions for two children together as well as other activities that require turn taking and interaction by the child and their play partner. Currently, we are studying the use of a robotic system in a school context. In contrast to the study reported here, in which the child interacted with the robotic system in a few sessions in our clinical setting, this study will place a robotic system in a child's school for a period of four weeks. This will allow the child to develop skills through regular use and will provide information regarding the child's learning and exploration using the robotic arm system. We are also exploring the two dimensional positioning of the arm by the child using head movements. This additional capability will allow the child to explore by moving the robotic arm over the tub, and then digging in the macaroni to find hidden objects. This generalization of the "move" aspect of Task 3, will facilitate the evaluation of exploration and discovery by the child.

Children with severe physical disabilities have limited opportunities to explore their environment, and they often depend on their parents or care givers to assist them with environmental interactions. Their lack of spontaneous, independent exploration and discovery of their surroundings may influence both their cognitive and social development. The behaviour of children with physical disabilities may itself shape parents' choices of environmental exploration to only a few parent-defined situations [2]. A robotic arm allows a very flexible approach to such interaction in which the child is able to exercise increasing amounts of control and is able to explore and discover objects and their properties through manipulation of real objects.

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