The Role of Assisted Manipulation in Cognitive Development

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ABSTRACT

Objective: Motor experience plays a central role in cognitive development. Children with motor disabilities can benefit from assistive technologies that assist with manipulation. This paper explores the use of robots to this end.
Method: We reviewed studies conducted with typically developing children and children with disabilities using robots.
Results: Observation of children using robots reveals both the cognitive skills required and those demonstrated by the child. Robot use empowers children with disabilities to actively participate in learning and play activities. Integration of augmentative manipulation and communication impacts participation of children with disabilities in play and school.
Conclusion: Children can use robots as tools providing them with opportunities to reveal and further develop their cognitive skills. Research is needed to develop both physical and virtual robotic augmentative manipulation that can be accessed through communication devices and that can be used by children with disabilities for recreation and learning.

The role of motor experience in cognitive development

Motor experience plays a central role in cognitive development of typically developing children. Through manipulation, exploration and interaction with the environment a child develops cognitive and perceptual skills that will allow him or her to learn, and act on the world [1-3]. Throughout developmental theory, motor action has been related to the development of cognitive and perceptual skills [4-7]. Theories of cognitive development have described the different stages of cognition and the emergence of symbols and language through the observable motor behaviors of children at different ages [2, 8].

Identified as a landmark cognitive skill [9], object manipulation starts evolving after a few months of birth through the perception of objects and their properties and their relation with self and other's actions [10]. The exploration of objects through manipulation leads to the development of goal- oriented behaviors and early tool use within the second year of life [11] [10-13]. Tool use, the ability of the child to use an object to act on the environment to accomplish a goal [11], has been identified as a critical mechanism related to cognitive skills [14]. Further, tool use allows the child to display means-end oriented behaviors and it can also indicate that early milestones of cognitive and perceptual development have been reached [1, 15-17].

Limitations imposed by motor disabilities

The ability to grasp an object in a skilled manner enables humans to perform a variety of complex manipulative movements to use tools [18, 19]. Children with motor impairments have particular difficulty with object manipulation [20] and may miss opportunities for meaningful exploration or manipulation in the early stages of their development [21]. The child may thus have difficulty learning new concepts and using tools to act on objects.

If they cannot manipulate the environment, children with disabilities are often limited to the observation of others' manipulation behaviors. Motor impairments can also result in too few opportunities for the child to demonstrate understanding of cognitive skills. This impacts participation in school, play, and social interaction.

Nevertheless, studies on cognitive- perceptual development have revealed that even though experience is a critical mechanism for cognitive development and learning, the latter can also occur as a result of observation and perception [22, 23]. In this sense, Gibson & Gibson [24] described a distinction between two ways of learning: learning to perceive or perceiving to learn. Providing children who have disabilities with tools for aiding manipulation and the opportunities to use them can promote exploration and discovery and promote cognitive development. Such tools can also reveal cognitive skills.

Robotics - the technology for manipulation

In theory, robots are ideal devices for augmentative manipulation. A robot is defined as “An automatically controlled, reprogrammable, multipurpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications." [25]. Although this definition emphasizes manipulators for industrial applications, robots can assume different shapes and are widely used in other areas including rehabilitation involving restoration of function, the reduction of physical, sensory and cognitive limitations, and functional assistance (e.g., eating, self-care) for persons with disabilities [26].

The major objective in pediatric augmented manipulation is to create a learning environment for young disabled children that mimics the world of the non-disabled child as closely as possible. It is important to involve the child in this environment at a very young age, and robotic manipulation of objects can play a key developmental role.

Robots as tools

Manipulation through a robot is not the same as direct manipulation so considerations regarding children's developmental understanding of tool-use and the requirements to control the robots are needed. The use of another object as a tool to achieve a goal or reach a targeted event or object, implies certain cognitive skills that have been studied and observed in typically developing children [2, 11, 27, 28].

As an observable outcome of these skills, tool use implies several processes. The first is causal inference, the understanding of how something causes something else, or the ability of the child to determine that a certain event causes a particular effect, also known as causality [15] [29]. A more refined form of cause- effect is the means- ends analysis, which implies the comparison of a goal with the current situation or configuration of objects or events, and reducing the difference between both of them through the most efficient path [15, 16]. Other cognitive processes involved are the coordination of multiple frames of reference, which is the ability to coordinate the object that acts as a tool in relation to the frame of reference of the target object [17] and route planning, the planning of the more efficient path or sequence of events to reach a goal or destination [30]. As a result, the use of tools has been linked to problem solving skills and spatial relations, since it not only involves understanding and perceiving properties of objects in relation to self-goals and needs, but the understanding of object properties in relation to each other [2, 12].

According to Lockman [17], the use of tools by children is rooted in the perception- action behaviors that the child explores in order to gain information about his/her environment. In his analysis of tool use development, Lockman found that use of tools and manipulations also allow the child to develop cultural and social awareness and related behavior. Also, he analyzed how the development of tool use is not only related to direct manipulation but depends on the ability of the child to understand and realize the relation of objects and also the ability of the child to detect affordances. Because in the use of a tool, there’s more than one object interacting with the person, and also there’s interaction between objects, the complexity of the task increases and higher level of cognitive and perceptual abilities is required.

Robots, when used as tools, can assist the user who does not have all the prerequisite skills by performing more or less of the task. Robots can be programmed to exhibit different levels of autonomy with respect to the user [31]. In one extreme, the robot can accept high level commands specifying a task to be accomplished (e.g., get milk glass), and be able to perform that task making whatever decisions are necessary without requesting any human intervention (fully autonomous). At the other end of the scale, the user has direct control over the robot movements (teleoperated). Multiple controls are then necessary to operate the various robot movements, e.g. up/down/left/right/forward/back rotate/grip for a robot arm.

Cognitive skills required to control the robot

As a consequence of the discussion in the previous paragraph, there are a number of skills required to control a robot in order to be able to use it as a tool to perform a task. These skills can be presented to the child in a way that facilitates cognitive understanding by enabling a progression in skill. For example, with the basic robot movement of reaching for an object and bringing it to the child, the following progression of skills can occur [32].

- Initially, the system can be programmed to perform the entire movement to bring an object of interest to the child when the child hits the switch (one-hit mode or - autonomous robot). Children who understand **cause and effect** can use the robot in this way.

- At the next level, the movement will continue only as long as the switch is pressed and stop if it is released (continuous or press and hold mode). This requires that the child understands the need to maintain or repeat switch action and that he/she needs to **inhibit** the desire to press the switch (i.e., release it) so that the robot stops at the correct location.
- When these steps are mastered additional switches can be added that produce opposite results. For example, one switch that turns the robot to the right and one that turns it to the left. This requires an understanding of **binary relations or choice making.**
- Subsequently, movements can also be broken down into multiple parts and the robot can be programmed to carry out each part of the movement. For example: 1) move to the object, and 2) grasp and bring the object to the child, each movement activated by separate switches, or 1) move forward and 2) turn to the right. These tasks require recognition that the movement cannot be completed by only one action, and that the order of the child's action is important to task completion (**sequencing of actions**).
- Additional switch controlled movements can be added. For a robotic vehicle this could be left, right, forward, back. For a robotic arm, the movements might be open, close, up, down. In lieu of additional switches, keys on expanded keyboards can be used to accommodate for motor limitations. These additions permit full teleoperated control over the robot for exploration and discovery.

In this paper we will refer to our previous studies. These are summarized in Table I. The short titles are italicized and used throughout the paper. Figures 1- 3 show the robots used in these studies.

Table I: Summary of Robotic Use By Children

Short Title	**Robot**	**Participant population**	**Access Method**	**Task**
Typical children [33]	Hero 2000	1 to 3 y.o.	switches	Increasingly cognitively complex tasks
Typical children robot skills [27]	Lego car	18 children 3, 4, and 5 y.o.	1 to 3 switches	Knocking over blocks, but in increasingly cognitively complex tasks (from cause and effect, to sequencing)
Infant study [35]	Microbot	6 disabled 3 non-disabled <39 months	1 switch	Bring toy or cracker closer
Lego study [36]	Lego car and arm	10 with disabilities	1 to 4 switches	Exploration and discovery
Sequencing study [38]	Rhino	12 disabled 6 to 14 y.o.	1-3 switches	Three step container play task
Lego robot via AAC study [40] [41]	Lego car	12 y.o. girl	2 head switches	Following pathways and generating speech in educational activities Board games, puzzles, numbered dot to dot drawings, acting out a myth
Lego robot via computer-usability [44]	Lego arm and car	5 adult experts	direct access on tablet computer	Pick and place activity with zoo animals
Lego robot via computer [43]	Lego Roverbot (car) and a toy truck	6 w/out , 3 w/ disabilities	tablet computer	Zoo play scenario to feed or water animal w/truck or robot

Figure 1 Robots used in reported studies. Clockwise from top left: MiniMover, Lego Minstroms Arm, Lego Roverbot car, Rhino.

How do typically developing children understand and interact with robots?

In order for robots to assist in the development of early cognitive concepts they must be accessible to very young children. Thus, an important question underlying the use of robotic augmented manipulation is what happens when young typically developing children are exposed to robots? There have been a few studies where researchers have categorized, identified and labeled some skills that were demonstrated by the children while observing them using robots.

In a study of three to seven year olds using a robot construction kit, RobotixTM, children demonstrated five problem solving skills: cause and effect (termed "causality" by the author), coordination of multiple variables, reflectivity, binary relations (termed binary logic), and spatial relations [29]. The ability of children to demonstrate understanding of these specific robot skills varied with age. Stanger and Cook [33] studied typically developing children one to three years of age using a Hero 2000 robot in a series of increasingly cognitively complex tasks. Cognitive skills investigated included cause and effect, and completing a task by means of a series of movements (sequencing). All the children demonstrated cause and effect, while only the older children were able to complete the sequencing task.

In the *typical children study, we* evaluated eighteen typically developing children aged three, four and five years using a Lego robot to complete tasks based on the cognitive concepts of causality (cause and effect), negation (inhibition), binary logic (binary relations) and sequencing [27]. Participants at all ages demonstrated understanding of cause and effect. Three year olds had difficulty understanding the concept of inhibition, but the four and five years old mastered this concept. Most of the four and five year old participants succeeded at the binary relations task (choosing between left and right). None of the three year olds were able to consistently use a two-step sequence to accomplish a task. Four year olds displayed greater understanding of the sequencing task than younger children, while five year olds had no problem in accomplishing the task. This study also verified that the cognitive skills to control the robot vary with age for typically developing children.

Robot Use by Children with Disabilities

Robots have been used successfully to allow children to participate in play and school-based tasks that would otherwise be closed to them. A summary of robot studies where robots were used by children with disabilities as tools to manipulate play and education items can be found in Cook, Encarnação and Adams [26]. These studies were primarily case studies to examine the feasibility of using a robot to provide access to play and education activities, or to examine the effectiveness of the Human Robot Interface. The majority of previous studies did not report an analysis of the cognitive skills required to control the robot. Our work in this area is summarized is the following sections.

Robot use and cognitive skills

The cognitive skills identified by Forman [29], Stanger and Cook [33] and Poletz et al. [27] are shown in Table II organized by the youngest age at which they were evident in typically developing children. The initial tasks in Table II establish cause and effect and the understanding of the switch operation of the robot. The table also lists skills that were identified in other studies where older children with disabilities used robots. The robot tasks shown as examples at each of the 6 levels in Table II represent tasks developed using various combinations of the child-directed activities. The skills listed in the table are representative of those required for problem solving. In the table included in Cook, et al. [34] we used terminology consistent with Forman [29]. The terminology in Table II has been modified to reflect current usage in cognitive psychology, and it provides framework for examination of the cognitive skills of children with disabilities. The underlying idea is that child's performance on robot tasks can reveal their cognitive understanding by comparing it to the level of typically developing children. This can be useful since it is difficult to obtain developmental age from standardized tests because they rely on verbal and/or physical responses. The following discussion describes salient examples where children with disabilities demonstrated cognitive skills in our studies using robots as tools for manipulation.

Table II. Robot–Related Skills

	Skill	Definition for robot use	Age Considerations (typically developing children) [19]	Lego Robot Examples
0	No interaction	Child displays no interest in the robot or its actions	NA	NA
1	Cause and effect [Causality]	Understanding the relationship between a switch and a resulting effect	<3 action is in switch, tried to use disconnected switches >4 yrs understood switch made robot move	Use switch to drive robot, knocking over blocks with robot, drawing circles on paper by holding a switch down and turning robot
2	Inhibition [Negation]	An action can be negated by its opposite	4 yrs: begin to understand that switch release stops robot	Releasing switch to stop robot
3	Binary Relations [Binary Logic]	Two opposite effects such as on and not on	5-6 yrs: understood rocker switch had two opposite effects.	2 switches turning robot right/left, or go and stop
4	Sequencing [Coordination of multiple variable Spatial concepts-multiple dimension]	Movement in more than one dimension to meet a functional goal	age 5: Could fine tune a movement by reversing to compensate for overshoot, etc	Moving roverbot to a specific location in two dimensions
5	Symbolic Play	Make believe with real, miniature or imaginary props [28]	6 yrs: Child ID action in robot not switch, planning of tasks is possible	Interactive play with pretense, i.e. serving at tea party, exchanging toys with friends, pretending to feed animals all using robot
6	Problem solving	Problem solving with a plan - not trial and error, generation of multiple possible solutions	7 yrs. Designed robot and thought about coordinated effects, planning was possible, can understand simple programs and debug	Changing strategies to solve a problem such as avoid an obstacle, changing task to meet the child's own goal, simple programming

Cause and effect

Robot use in a playback mode requires an understanding of cause and effect - an action by the child (pressing a switch) results in a corresponding response by the robot (movement). In the *infant study,* a robot brought an object (e.g., a cracker or a cup containing a toy) to a child when they pressed a switch [35]. Children with and without disabilities who were at a developmental age of 8 months and older demonstrated an understanding of this cause and effect relationship. None of the children in this study appeared to enjoy passively watching the arm complete what we thought would be interesting and novel movements, e.g. shaking a rattle, tipping over blocks. When the arm was trained to bring an object to the child (e.g., a cracker or a cup containing a toy), the children would actively participate for relatively long periods of time (up to one hour in most sessions). This result is positive in terms of children using a robotic arm system as a manipulative tool to accomplish desired ends.

Older children with severe disabilities have also demonstrated an understanding of cause and effect in the *Lego study* through free play with a car-like Lego robot. Participants used single switch activation to activate pre-stored movements such as a robot dancing, knocking over a stack of blocks, or drawing circles on a large piece of paper [34]. Ten children ages 4 to 10 participated in that study where they used the robot to perform various tasks of increasing complexity. They controlled the robot with switches which were accessed with either hand movement, head movement or a combination of the two. Both single play (the entire movement is played back with a single switch press) and continuous play (the switch must be maintained to continue the movement) modes have been used successfully by these children.

Inhibition

Inhibition is the understanding that stopping an action (e.g., releasing a switch) results in a response from the robot (stopping its movement). In the *infant study*, a cracker was placed in the robot arm and the child was given a switch [35]. When the switch was pressed, the arm brought the cracker closer to the child as long as they pressed the switch. If the switch was released, the arm stopped and the child was able to reach for the cracker. Children learned that the release of the switch (inhibition) led to an opportunity for them to reach to see if they could touch the cracker. If not they repeated the switch activation/release sequence to bring it closer.

In the *Lego study* an understanding of inhibition was demonstrated by the child's ability to stop the robot at a specified location by releasing the switch [27]. In order to assess the level of understanding of inhibition by the children the number and type of errors (e.g., overshooting a target) were recorded. A high number of errors were taken as indications of lack of understanding of this skill, and a decrease in errors was taken as an indication of understanding of the skill.

Binary relations

"Binary relations" refers to two opposite results – left/right, up/down, forward/back. In successful demonstration of understanding of binary relations in the *Lego study*, the child would typically hit the correct switch required to complete a task [27]. Errors in switch activation (e.g., hitting the right switch when the left turn was required to complete the task) indicated lack of understanding of this concept. For participants who demonstrated understanding of binary relations, the task was expanded to include four possible movements (typically left/right and forward/stop), controlled by four switches. Three-direction control presented the opportunity for the participant to engage in an unconstrained discovery activity in which the robot could be driven to various locations to explore (e.g., going behind a barrier, crashing into a wall, knocking over other objects).

Coordination of multiple variables

Forman [29] considered this task in terms of robot arm movement to lift a full glass of water. If the elbow of the arm was flexed, the wrist needed to be extended to prevent spilling fluid. Younger typically developing children accomplished this task in two steps-first flex the elbow then compensate by extending the wrist. Older typically developing children were able to accomplish the two movements more smoothly and simultaneously. This is directly applicable to assistive robots for daily living tasks such as eating. Due to the limitations in the access method for children with disabilities, they cannot perform two movements simultaneously. They must perform movements in sequential steps.

Sequencing

In the *sequencing study* Cook et al. [36] used a robot arm programmed for three tasks to evaluate sequencing. A large tub of dry macaroni noodles was used as the medium for burying objects. The first task required the child to press a switch (#1) to cause the robot to dump a glass filled with dry macaroni. The second task had two switches each controlling one step: (1) press switch #2 to dig an object out of a tub of macaroni, and (2) press switch #1 to dump the eggs) that were buried in the macaroni and discovered by the child using the robotic arm. Twelve children, aged 5-10 years old who had severe physical disabilities participated in this study [36]. Goal Attainment Scaling (GAS) [37] was used to evaluate the participants' level of achievement in these three tasks. The children's reactions to the robot were very positive. All twelve of the participants were able to independently control at least two switches in the sequence. Seven of the children independently used all three switches and one used three switches with some prompting

In the *Lego robot via AAC study*, a 12 year old girl controlled a Lego robot using the infrared output on her augmentative and alternative communication (AAC) device to perform various educational activities [38, 39]. She accessed the robot control commands and her communication vocabulary on her device using the scanning access method controlled by two head switches. Before doing the educational activities, she developed her skill at sequencing of robot movements and moving in two dimensions by following pathways of greater and greater complexity (straight line, square, curves). The path taken was recorded by a pen attached to the robot and the accuracy of the movement was determined. Her accuracy was within the predetermined minimum set by the researchers.

Symbolic play

Once children have demonstrated understanding of the cognitive skills described in the first three levels of Table II, it is possible to use the robot in a more exploratory manner in which the structure is provided by the child rather than by the programming of the robot. Play has been defined as "intrinsic, spontaneous, fun, flexible, totally absorbing, vitalizing, challenging, non-literal, an end in and of itself" [40]. Play is both an important means through which children develop and know their world and the way in which they show their physical, cognitive, social and creative abilities [40]. Through play children can explore their environment and begin to understand their relationship to it.

In the *Lego study*, children controlled the Lego robot in two (robot car) or three (robot arm) dimensions to carry out unstructured, spontaneous play [26]. For example, one child was expected to bring her toy princess through obstacles (a forest) to a castle for a party using the robot car. Instead, she decided to bring one of the forest trees to her and then decorate it, thereby establishing her own agenda. Stickers were distributed about the play area, and she used them as decorations, maneuvering the robot to the pickup locations. This was the first indication that she had developed her own plan and was determined to act on it. Using a Lego robotic arm, the same child held a sushi party [34]. There were several people present for this session. Each observer chose which type of play sushi they wanted, and the participant picked it up and handed it to them. She would not have been able to do this activity without the manipulative assistance of the robot.

In the *Lego robot via computer study,* a tablet computer with infrared output to control a robot was used to study play in a semi-structured environment [41]. In addition to robot control, the computer software provided access to some vocabulary items for interacting in a zoo scenario giving the children access to manipulation through an augmentative and alternative communication method. The child participants were given the task of being a zookeeper that needed to feed and give water to a hippo and giraffe. They could attend to the animals needs for water and food in two ways: (1) using a robot controlled by the computer or (2) by giving commands via the AAC device to a research assistant (RA) to carry water or food to the animals in a toy truck. Children preferred to do activities using the robot rather than directing the RA to do it and they spontaneously talked while using the computer during play. The use of the robot gave the children a chance to play independently. Coupling the robot control with AAC gave the children a chance to also comment while playing - as typically developing children do.

Symbolic play can also have a role in academic activities. In the *Lego robot via AAC study,* the student used her AAC device to narrate a Greek play and act out the scenes using robots [38, 39]. The Greek myth Theseus and the Labyrinth_was uploaded to_the participant's AAC device. She then acted out the story by moving the robot car (Theseus) and the robot arm (Minotaur) through their positions, while saying their lines using her AAC voice output.

Problem solving

Problem solving is a sequence of cognitive and perceptual actions and processes required to achieve a certain goal [11]. It includes acting prospectively, monitoring problems in performance that need to be solved in order to achieve the goal, and changing strategies that are judged to be inefficient for achieving success. Another part of problem solving is to use spatial concepts to control the robot in multiple dimensions. In the *Lego study*, Cook et al. [26] evaluated whether the children were able to follow instructions to move the robot to a specific target or navigate through a set of obstacles without touching them or knocking them over. Other problem solving tasks included feeding animals, taking an object to class mates.

One participant had eight princess dolls that were her favorite toys and she enjoyed retrieving them from around the table and lining them up in a specified order [26]. Another problem solving activity with the princess dolls involved matching, another cognitive skill. At several locations around a table was a wooden block with a letter on it. Each of the blocks had a letter corresponding to the first letter of the name of one of the princesses. The participant carried each princess to the corresponding block using the robot car. This matching task was expanded to replace the blocks with a piece of food that began with the same letter as one of the princesses (e.g. Banana for Belle, Apple for Ariel, Rice cake for Rose). The participant accurately carried each princess to the piece of food corresponding to her name.

In the *Lego robot via AAC study*, after developing her skill on robot control, the participant did several educational tasks. Problem solving involving spatial orientation was the focus of a task involving puzzle pieces [38, 39]. Each piece of a puzzle was placed on the robot and the participant used the robot to orient the puzzle piece for correct insertion into the puzzle by the research assistant.

Not all children who successfully demonstrated one or more of the cognitive skills using the robot to accomplish a given task were able to explain the function of the switches used to control the robot. For example, children who were able to use one switch to make the robot turn 90 degrees in one direction and then another switch to make it go forward, failed to describe the function of the turn switch (they said that it made robot go to the left or to the right, instead of merely turning the robot) [27]. In fact, being able to do something is different from being able to explain how it was done. The latter is a higher order cognitive skill referred to as reflectivity [29].

Expanding the Robot Control Interface for the Child

The studies carried out with typically developing children and children with disabilities using robots have informed our approach to the human-technology interface for robot control by children. The *sequencing* and *Lego* studies included only children physically capable of operating multiple switches, with each switch controlling a different robot action. Children with more severe motor impairments require alternative access methods, such as single-switch scanning or alternative pointing methods (i.e. head pointing). Even for children who *can* physically activate three switches, unstructured play with robots requires more than three functions, so an alternative access method to utilize multiple functions would benefit them, as well. To support alternative access methods and multiple robotic functions, control of the robots via a computer and/or AAC device was implemented [38, 42].

Using Indirect Selection

Children who cannot access multiple switches may use the scanning access method [43]. In scanning, items in an array on a screen are sequentially highlighted so the user can select the item of interest using a single switch. This is a cognitively demanding task, and some children have difficulty learning to do it [44]. However, the robot skills described above are also the skills used to perform scanning.

- Cause and effect: This skill is required for automatic scanning in which the cursor moves until a switch is hit [43].
- Inhibition: An example of the importance of inhibition in assistive technology use is inverse scanning [43]. In this selection mode, choices are scanned as long as a switch is depressed. When the switch is released, the currently displayed item is selected.
- Binary relations: “Binary relations” refers to two opposite results – left/right, up/down, forward/back. Directed scanning requires that a choice be made between moving a cursor in one direction or another [43].
- Sequencing: An important skill for the use of assistive technologies is the ability to carry out a series of tasks in a specified sequence in order to accomplish a final result. An example in scanning is the use of two switch row column scanning in which the child must first move through rows by hitting a switch and then choose a row by hitting a second switch [43].

Since the same skills are used in robot control and scanning, learning to control the robot can be beneficial to children who are trying to learn the scanning access method

Integrating robot control and communication

The robot skills discussed above are also beneficial in language development. It is important that movements are labeled with symbols or words to help the child develop cognitive and linguistic concepts while using the robots. The labeling of switches can also be used to give the child a way of relating robot action to an individual switch. Spatial concepts such as bring, get, under, behind can be taught using the robot. Scanning skills developed using the robot can be directly applied to Augmentative and Alternative Communication (AAC) [43]. AAC often depends on binary relations like choosing between yes and no or between two other activities (e.g., listening to music or playing with a toy) or objects (e.g., a ball or doll). Sequencing is also an important skill for language development, for example, in using multiple word utterances and developing grammatical structures.

In our studies, some children had communication devices which had to be removed in order to use their switches to control the robots. This is in contrast to typically developing children who talk and play at the same time. By using the AAC device to control the robot (via the built in infrared control) they could use the same access method to control their AAC and a robot, and have an integrated communication and manipulation system. This addresses the known problem identified with AAC device use that children have to disengage from play in order to communicate and vice-versa [45].

To investigate effective methods to integrate robotic play and communication, a testing platform was developed along with several integrated communication and robotic play human-technology interfaces in the *Lego robot via computer usability study* [42]. The interfaces included vocabulary output and robot control commands and were accessed on a touch screen. Five "expert" users: speech-language pathologist (AAC), rehabilitation engineer (computer access), psychologist (human factors), psychologist (pediatrics) and adult user of AAC, tested the interfaces. After making iterative improvements to the interfaces, six children without disabilities (female age 3, male aged 3, female aged 5, male aged 5, male aged 7, and female aged 7) and three children with disabilities (two males aged 5, one female aged 5) used the interfaces in a zoo play scenario [46]. Older children were better able to direct the robot movements through independent control of left, right and forward. Younger children and children with disabilities benefited from having pre-stored robot movements (e.g., “get water”, “get food”). Children could talk and control the robot with all functions on one screen page or by linked screen pages - one for talking and the others for robot or truck control. When the talking and robot controls were on one page, the younger children and children with disabilities produced more vocabulary output.

The *Lego robot via AAC study* investigated using a scanning access method on a commercial AAC device and language system as an interface to control the robot [38, 39]. This system was proven to be functional for the child to demonstrate manipulative, cognitive, and communicative skills in various educational activities. This is in contrast to several robot studies where researchers have found it difficult to provide scanning robot control (see, for example, [47]).

In the *Lego robot via AAC study*, the robot control and talking pages were linked, and once on the robot control page, the participant was seldom motivated to independently switch to the talking page [38]. Despite being older (12) than the children in the *Lego robot via computer study*, she had little experience with AAC, and so providing the vocabulary and robot commands all on one page was beneficial to her. In another study where children were involved in designing their own robot control interface, the older children who had several years of experience using their devices (5 years or more) chose to have linked pages, and they often independently switched between robot control and talking modes [48].

Teachers’ perceptions of robot use by children with disabilities

One of the most important general results in all of the studies related to cognitive function and development described above is that overall teachers’ and parents’ perception of the competence of the children increased after successful use of the robots. In the *sequencing study*, teachers initially thought that the researchers had overestimated the skills of the children, but at the end of the study they were surprised at the level of accomplishment of the children [36]. Teachers also reported that overall responsiveness of the children in class increased as did the amount of vocalization (during robot tasks and in class afterward) and interest (i.e., increased attention to tasks) [49]. The increase in vocalization was similar to that reported for children who were provided with early wheeled mobility [50, 51].

How do children who have disabilities understand and interact with robots?

Developing skills to control assistive technology for children with physical disabilities is important so that they can participate in developmental and learning activities and grow to become active members in society. Universally, the children enjoyed using the robots and anticipated the robot sessions. The use of robots also gave the children a chance to demonstrate a range of cognitive skills while also providing a versatile tool for presentation of tasks, problems and learning opportunities to the child. Understanding children’s performance using the robots requires insight into how the children perceive the robots and robot actions.

The focus of attention control for the child in single switch controlled robots varies by developmental level. Younger children believe that the action is in the switch they pressed and they are unable to associate the switch activation with robot movement (Forman’s [29]). In the *typically children robot skills study*, young children were given the task of turning the robot with one switch and then driving it forward with a switch that had previously driven the robot away from them [27]. Since the function of the forward switch was unchanged, but the frame of reference of the robot was changed, some children were unable to understand that the forward switch still drove the robot forward ***relative to the frame of reference of the robot***. Some children turned the forward switch in an attempt to re-direct the robot. As the child begins to view the robot as tool the focus of attention is on the task and five year old children are successful in the two step sequence of turn and go forward to knock over blocks.

When a child was not able to turn the robot and move forward to knock over a stack of blocks it could have been because he/she did not understand sequencing of actions or because he/she cannot relate to the frame of reference of the robot, a critical aspect of using the robot as a tool to perform the task [17]. As we have discussed, a cognitive skill associated with tool use is managing the frame of reference of the tool relative to the task goal or destination [30]. Children's difficulty with this task has been demonstrated in several ways. One of these is the challenge of left and right switch use when the robot is moving either away or toward the child. We tried to address this problem by labeling the switches with a color and then placing labels (colored arms) on the robot in an attempt to avoid left and right designations (indicated by arrows on the switches) that change with robot orientation. We had hoped that children would then always hit the blue switch to turn the robot in the blue direction and the yellow switch to turn in the yellow direction. This appeared to help some children. However, in practice most of the typically developing children appeared to use the separation of left and right switches, labeled with arrows and located on its corresponding side as indicators.

The physical separation appeared to be of more value to the children than the arrows [27]. Forman [29] used one rocker switch with two directions of movement rather that two separate switches, and he found that only children older than four demonstrated the binary logic concept (as indicated under Binary Relations Table II). When the switches were separated physically, even the youngest of our participants succeeded on most trials. The additional spatial cue may have led to greater success [27].

When children using AAC devices to control the robot were given the opportunity to develop their own user interface - a display page of symbols for robot control - they all chose to use the color coding on the symbols for turning the robot left and right [48]. They also put the blue turn left symbol to the left of the yellow turn right symbol. The co-location on the selection screen is not as distinctive as having switches physically separated in space, so the color coding was more beneficial to the AAC users than it was to children using separate switches to control the robots.

Children also reveal other characteristics as they use the robots. As we have described, in the *infant study* the robot brought an object to a child when he or she pressed a switch [35]. Several children without disabilities gave the object back to the robotic arm at the completion of a movement. In contrast none of the children with disabilities presented the toy to the robot. By offering the object to the robot, the children without disabilities may have been requesting a repeat of the sequence or at least more movement by the arm. This type of interaction is typical of cooperative play, and its absence in the disabled children may be indicative of a more passive and adult-dominated participation in play.

In the *Lego robot via AAC study*, the child and the research team created a movie that she submitted as her class project in social studies. In the making of the move she perceived the robot to have human traits, for example, she demonstrated understanding of some social skills by independently ensuring that Theseus (the robot car) was face-to-face with other characters when he was about to speak to them. This was interesting because she relies on others to propel her manual wheelchair and she doesn't have an opportunity to orient herself face-to-face for a conversation.

Future work

A virtual robot

Physical robots are relatively expensive and even state of the art robots have limitations in performing simple tasks as well as a human would do (e.g., designing a gripper that can pick any object like a human hand is an active topic of research, encompassing problems of posture adaptation to the object or haptic feedback to regulate the gripping force). One alternative would be to design virtual robots to manipulate virtual environments, though it is still not clear if the experiences of using a physical robot to manipulate physical objects or a virtual robot to manipulate a virtual environment will be equivalent for the child.

Typically developing children directly manipulate the physical world; with the physical robot, children with disabilities can manipulate the physical world through a tool; with the virtual robot, children with disabilities will be manipulating a virtual world through a tool (a virtual robot) – will that be the same as manipulating the real world? Will the only difference be their perception of the world from a 3D image (with the physical robot) or from a 2D image (with the virtual robot), assuming the virtual world has the same physical properties as the physical one?

Computer games have been widely used with children with disabilities [52]. With today commercially available assistive technology, computers can be made accessible for most children, even with severe disabilities. One can easily find computer games and activities appropriate for every age and that can be played using several different access methods. However, few studies have been conducted on the effectiveness of computer use on children's play, communication and development [53]. Early findings indicate that computers can have a positive effect on the emergence of reading and writing skills, and on the development of language, prosocial behaviors, and higher order cognitive skills (please refer to [52] and the references therein). When compared to traditional methods, a study reported in [54] revealed that children with disabilities involved in the study exhibited more sophisticated levels of play behaviors and more positive, interactive social behaviors in computer-assisted interventions. Another comparative study showed that computer software might be a more effective means of skill building than classroom manipulatives for young children diagnosed with early childhood learning impairment [55]. Concerns on using computer games include isolation and loss of focus of interest, if children get stuck in computer activities without interest in doing anything else. Though these can be serious risks with adolescents, they seem a bit exaggerated for children since few prefer to play all their time by themselves instead of playing with friends, and observation shows that children use their imagination to keep changing games and activities all time [53]. Barriers identified to computer use in school settings are availability and funding of hardware and software, training and technical assistance, and time constraints [52].

A current study by the authors under project COMPSAR[1] is comparing the performance of children with and without disabilities in executing the same play activities with a physical and a virtual robot. The virtual robot and virtual environment were designed to match the physical scenario with a Lego Mindstorms NXT 2.0 Tri Bot [56]. Participants use both robots in the same structured play activities as those used by Poletz et al. [27] and their success rates are registered for comparison. Preliminary results show that participants' performance with both robots was similar [57]. These results indicate that virtual robots might constitute an alternative to physical robots.

Academic tasks

The *Lego robot via AAC study* results has led to the consideration of the use of robotic systems in the academic curriculum - moving beyond simply providing access to activities. The teachers of the student in the study reported that the participant demonstrated her abilities and connected with the curriculum and other students more fully using the robot than with only her AAC device. In the study, the student moved from being the outsider in the class to be the focus of attention. She and the research team created a movie of her Greek myth play that she submitted as her class project in social studies. The movie was shown to her classmates and one commented, "I wish I did that with my robot". Prior to this study, all of her classmates were learning how to program Lego robots but she was not involved. Once the student had the commands to initiate robot programs from her AAC device, she was able to test programs for her classmates, again becoming the focus of attention [58]. Additional studies underway have expanded the scope into academic tasks such as math in an integrated way (doing to build and demonstrate skills, and talking to express concepts) [59]. This research has shown that user performance and understanding of concepts beyond robot control can be assessed.

Specially designed robots

Cook, Encarnação and Adams [26], reviewed key robot characteristics for use by children with disabilities. Among the most important are reliability and accuracy to avoid confusion by children, safety and cost. It is primarily at the human-robot interface level that special attention is necessary when developing robots for children with disabilities. Augmentative manipulation robots for children must accommodate for a variety of disabilities, be easily learned, and should include simple and comfortable access to input devices. It is also desirable for the robot to have varying levels of autonomy from complete control by the child to simple playback of stored movements [26]. In an ideal case, the robot would automatically adapt its level of autonomy according to user performance.

Robotic systems for children should also be appealing to the child to attract children's attention and play mates [36, 60-63]. Children between the ages of seven and eleven perceived robots as having geometric forms with human features in their faces and feet for walking, placed them in familiar settings and social contexts, and attributed free will to them [64]. Children also tended to overestimate the capabilities of the robots. Examples of ways to make robots appealing to children are the use of bright colors, replication of well known children's themes (e.g., cartoon or book characters), incorporating amusing movements or actions, and allowing for easy personalization to match the child's preferences

Conclusions

The use of robotic systems by children can provide insight into their cognitive skills. The use of the robot avoids dependence on standardized test administration, such as verbal response or physical manipulation of objects – skills often limited in the case of severe motor disabilities. Children can demonstrate integrated manipulative, communicative and cognitive skills when communication and robot control are integrated into play and education activities. Participation and interest by the child are also increased when augmentative manipulation and augmentative communication are merged. The results of studies with both typically developing children and children who have disabilities demonstrate the importance of children having access to augmentative manipulations for both

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[1] www.compsar.anditec.pt

play and education. The studies also provide a framework for the characterization of existing rehabilitation robotic systems, and suitability of the development of commercially available robots for use by children who have disabilities.

The impact on the children was amply summarized by one of the participants in response to the question “What did you like best about the robot?” she responded, “I can do it myself”. This sense of independence in play and learning is a major outcome for the children. The 27 year old AAC user with complex communication needs who participated in the *Lego Robot via computer study* summed up the situation for many children with complex communication needs: “This is my first actual time playing with stuff. [Before] I just watched my sister play [with] her toys.” Robots for children with motor disabilities can convert them from observers to participants.

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