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Access to hands-on mathematics measurement activities using robots controlled via speech generating devices: Three case studies

Abstract

Purpose: To examine how using a robot controlled via a speech generating device (SGD) influences the ways students with physical and communication limitations can demonstrate their knowledge in math measurement activities.

Method: Three children with severe physical disabilities and complex communication needs used the robot and SGD system to perform four math measurement lessons in comparing, sorting, and ordering objects. The performance of the participants was measured and the process of using the system was described in terms of manipulation and communication events. Stakeholder opinions were solicited regarding robot use.

Results: Robot use revealed some gaps in the procedural knowledge of the participants. Access to both the robot and SGD was shown to provide several benefits. Stakeholders thought the intervention was important and feasible for a classroom environment.

Conclusions: The participants were able to participate actively in the hands-on and communicative measurement activities and thus meet the demands of current math instruction methods.

Keywords: Lego robots, mathematics skills, augmentative and alternative communication

Introduction

Students with motor disabilities such as cerebral palsy (CP) are at risk for inadequate development of mathematics skills. A review of the research, scant as it is, showed that elementary school children with CP are often delayed in performing simple arithmetic operations compared with typically developing peers [1]. Students who also have complex communication needs (CCN) may find that limited skills in mathematics leads to restrictions in their daily living activities and employment opportunities [2, 3]. Adults with CP and CCN who use augmentative and alternative communication (AAC) methods recognize education as a key to successful employment but criticize the education they received, citing low expectations on the part of the educators [4].

The amount of mathematics instruction can strongly effect the mathematical proficiency of young children [5]; unfortunately, students with disabilities participate in math less often than their non-disabled peers [6]. One reason for reduced participation may be the time required for the personal care and therapy of such students [7]. Another reason may be limited access - physical and linguistic - to the learning materials and strategies associated with mathematics instruction.

Current mathematics pedagogy recommends that young students both participate interactively with hands-on activities and communicate reflectively about the concepts they have learned [8, 9]. However, students with severe motor disabilities may not be able to touch or grasp objects in hands-on activities. Although students with CCN can use AAC devices and strategies to communicate in classrooms, these devices may have a limited selection of vocabulary related to math, and severe motor limitations that require use of the scanning access method can significantly reduce the speed of message creation.

Object manipulation for the development of mathematical thinking is well supported in educational literature [10]. Ginsburg asserts that children ‘learn about number by performing “experiments” on physical objects, . . . even fingers are an acceptable tool for conducting such investigations and for promoting mathematical thinking’ [10] (p. 439). Research with able-bodied students has shown that the use of physical manipulatives led to improved outcomes for those who had difficulties in learning math. Grade three students improved their performance solving word problems when they used Cuisenaire rods (coloured cubes that can connect into lengths of 10; ETA hand2mind, Vernon Hills, IL) [11]. Grade one students who used TouchMath (cards with numbers composed of raised dots; Innovative Learning Concepts Inc., Colorado Springs, CO) were able to overcome their math difficulties [12]. TouchMath also led to improved outcomes for students with intellectual disabilities [13] and those with minor physical disabilities [14]. Whereas these studies attest to the benefits of direct object manipulation for math learning, similar benefits may be achieved through indirect (virtual) object manipulation.

Using virtual manipulatives for learning math concepts is an evidence-based approach that has been demonstrated with able-bodied students. For example, students in grade three improved their conceptual and procedural knowledge about using fractions after using virtual manipulatives [15]. Many virtual manipulatives programs are available (e.g. at the National Library of Virtual Manipulatives at Utah State University; http://nlvm.usu.edu/). Virtual manipulatives may improve access to math activities for those students with adequate mousing skills. However, for students with severe motor limitations, indirect access to virtual objects in the computer environment may be as challenging as direct access to real objects in the physical environment. People who have severe motor limitations need to use alternative mouse access methods, typically the scanning access method. Scanning is cognitively demanding and physically laborious for the user, especially in graphical programs with numerous small targets. In addition, web-based graphical interfaces may not always interface well with alternative access methods.

Specialized computer programs are available that can allow people with physical disabilities to perform math: e.g. IntelliMathics and MathPad (both sold by IntelliTools, Natick, MA). These programs have built-in capabilities for alternative access methods such as scanning and flexible scanning array layouts. Stanger, Symington, Miller, and Johns [16] performed a case study with four students of differing physical, cognitive and math skill levels using IntelliMathics 'Number Concepts 2'. The students accessed the software, with either an enlarged keyboard or a mouse, for 3.5 to 15 hours over a four-month time span. The scores of these students increased from the pre-test to the post-test in every activity except one. A benefit to the teachers was that they were able to use the software to track student progress, whereas previously they were 'challenged by assessing when [a student] has learned something' [16] (p. 66).

Virtual manipulatives are potentially accessible to students with severe disabilities, but the educational literature generally supports the sequence originally proposed by Bruner [17]: children best work with concepts by first manipulating concrete objects, then creating images of the concept, and finally adopting a symbolic notation to represent the concept [18]. Some researchers also suggest that concrete and virtual objects be used together as long as instructors show how the objects relate to the abstract concepts [19]. Providing a means for students with severe disabilities to manipulate concrete objects in learning math concepts is clearly important, and assistive robots may be a feasible option.

Robots arms have been used in science, including bringing items closer for sensory inspection [20, 21], putting a glass over a burning candle to extinguish it [22], mixing solutions, planting seeds, and plugging in electrical wires to make a radio [23]. Another study addressed school-based art activities, such as using a robot arm to paste items onto an art collage [23]. In one study, a child used a specialized robot to draw lines that matched questions and answers on a math worksheet [24]. Children controlled these robots through various access methods: a five-slot switch [20], three push buttons [22], two joysticks [23], and (for the math study) a switch for scanning [24]. The participants ranged in number from one to seven and in age from seven to 29 years. The participants had moderate to severe orthopaedic disabilities, arthrogryposis, muscular dystrophy, and CP. The studies were generally observational trials to examine the feasibility of using the particular robot in those tasks. Some studies tracked robot and user performance variables. For example, Howell and Hay [20] tracked the number of interactions, accuracy, and response time; Eberhart and Osborne [23] tracked the time to perform tasks and number of external operator interventions required. Only Howell et al. [21] examined curriculum concept attainment, in this case by measuring the pre- and post-trial performance of the students on sensory curriculum concepts and the degree of transferral of scientific inquiry skills to another science topic (the weight of objects). Pre-trial tests were already at maximum levels, so no improvements in sensory curriculum concepts were detected, but scientific inquiry skills did indeed transfer to the other topic.

The high cost of these robotic systems, ranging from $12 000 to $30 000, made them unaffordable for most people, and hence they were not widely used. Recent studies have instead used low-cost Lego Mindstorms robots (The Lego Group, Billund, Denmark) in play activities, resulting in children making gains (e.g. increased motivation and better learning of sequences) similar to those seen in previous studies with more expensive robots [25]. Students with disabilities could use these low-cost Lego robots to manipulate objects in various early learning activities.

Being able to communicate while performing math is also important so students can ‘verbalize to internalize’ [26] (p. 145), ask for help, or talk aloud so teachers can ascertain their level of understanding [10]. Participation in educational activities by students who use AAC can be quite low [27, 28], so studies have been conducted on the effects of training teachers to involve such children in math activities. One approach was to train teachers and support staff in the use of AAC methods so that the student could direct others in handling manipulatives in math activities. After training, a 10-year-old boy who had CCN and used an AAC device participated in a math measurement activity by telling his group-mates what to measure and then communicating whether the measurement was shorter or longer than a metre (the group-mates did the physical measuring and recording) [28]. Another approach was to train teaching staff in adapting to the math activities. For example, staff were shown how an AAC user with severe physical disabilities could access math activities on a computer by using a head-pointing device [29]. The authors reported increased participation and improvements in math performance as a result of the training intervention.

A further study examined whether using writing software along with math measurement manipulatives would influence communication by students about math. Symington and Stanger [30] described experience of a teacher in the use of IntelliTalk software (an accessible program that enables writing by children with physical disabilities; IntelliTools, Natick, MA) in a classroom with a mixed group of children, some of whom used AAC devices. The teacher used 'Measure It!' (a kit of manipulatives for determining the length, weight, and volume of items) and the students then wrote about their math discoveries using the auditory and graphical features of IntelliTalk. The students who had verbal abilities showed improvements in expressive language skills and vocabulary as well as enrichments in the usage of measurement concepts. The students who used AAC devices did not have as many gains, but did learn vocabulary such as 'more', 'less', and 'weigh'.

If students could control a robot from their AAC device, they could not only perform the hands-on activities themselves but also communicate about the concepts. Since most speech generating devices (SGDs) are equipped with infrared (IR) or Bluetooth output, they can be used with IR- or Bluetooth-controlled Lego robots. Students who have severe disabilities can therefore use an integrated access method (the switches connected to their SGDs) to control the robot for hands-on activities and the SGD to communicate. Being able to use their own SGDs as the access method addresses a limitation of the aforementioned robot studies, in which the control methods for the robots could not be used effectively by children with severe physical disabilities.

Not being able to access both manipulation and communication in play activities has been identified as a problem for child AAC users, since they have to stop using play items to say something via their AAC device [31]. Some play-based projects have begun to address this issue using symbol cards integrated into the play environment [31]. Children with more severe physical limitations have controlled infrared toys from their SGDs in activities that can motivate the development of language (i.e. 'come' 'go', 'in' 'out', 'my turn', and 'your turn') [32]. However, infrared robots have potential learning advantages because they can be reprogrammed to keep the interest of the child, present increased challenges, and perform functional tasks such as math manipulations.

With an integrated communication and robotic manipulation system, students with disabilities can engage in the integrated pedagogy of math instruction and 'work with objects to construct ideas of number, devise your own problems, think about what you are doing, and express what you have learned' [10] (p. 440). Students can 'work with' objects by controlling a Lego robot and at the same time 'express' themselves using their SGD. Increasing the active component of the learning experience for students with disabilities by providing access to manipulation and communication has the potential to benefit the education of such students significantly. However, to increase the potential for these interventions to be adopted, the social significance of the goals, methods, and outcomes of interventions should be evaluated by stakeholders [33].

In this study, a low-cost robot system controlled via SGDs was used by students with severe physical and communication limitations to do hands-on math lessons. Measurement of length was chosen as an activity, since it could be performed using a Lego robot car that was used in previous studies [25] and because other studies had already reported on the use of AAC in length measurement activities [28, 30]. The research questions addressed were the following:

1. Can using an SGD-controlled Lego robot contribute to how well students with severe physical and communication perform hands-on and communicative mathematics measurement activities?
2. Do the stakeholders consider robot use in these activities to be important and feasible?

Methods

Previous reports on robotic use in academic activities have all been case studies examining robot usability, and none had experimental control. Only one of these prior studies measured academic outcomes [21], but the chosen measure did not detect change. However, the math measurement curriculum lends itself well to the descriptive case study methodology, because it encourages individualized teaching in which teachers observe and evaluate students while the students perform hands-on activities and reflect on them. We used a series of three descriptive case studies to examine the chosen research questions.

<u>Participants</u>

A non-random convenience sample of three children with cerebral palsy participated in the study. Participants were seen in the following order: a 14-year-old girl, a 10-year-old boy, and a 12-year-old girl. The pseudonyms Emily, Doug, and Jane will be used here for these participants. All three participants were diagnosed with spastic athetoid quadriparetic CP leading to severe physical limitations in reaching and grasping, and they all had CCN. Each participant used a

Vanguard II SGD (Prentke Romich Co., Wooster, OH, USA) mounted to the wheelchair and operated using head movements detected by two Specs switches (AbleNet, Roseville, MN, USA) located on either side of the wheelchair headrest. The scanning technique, language system, and number of years of experience with the SGD are shown in table 1 for each participant. None had visual impairments (as reported by their mothers), except for Doug who wore glasses.

---- Insert table 1 about here ----

Emily was in a self-contained junior high school classroom with students who had various disabilities. In her previous elementary school, she had been in an integrated setting. Although she had not been at the same academic level as her age-matched peers in the regular-stream classroom, her program had included some integrated classes with differentiated instruction via a personal educational assistant (EA). In her junior high school, she was placed in a life skills programme, and an EA provided academic and personal assistance to Emily and another student. Emily performed individualized reading, writing, and math activities with her EA. Her EA reported that Emily understood counting numbers up to 20, was working on addition, and had probably not been exposed to math measurement activities previous to this study. Prior to receiving her SGD at age 10, Emily had had no means for spoken or written communication; hence, her communication skills were delayed.

Doug and Jane were in integrated regular-stream classrooms, where they received differentiated instruction. They each had a dedicated EA who had been with each of them for at least 5 years and who provided personal assistance and academic facilitation. As reported by their EAs, Doug and Jane had both done math measurement lessons within the past two years where their EAs had manipulated the objects.

At the end of the study, we interviewed the mother and the EA (or teacher, in the case of Emily) of each participant as well as their common assistive technology (AT) team (the same occupational therapist, speech language pathologist, and teacher for all three participants).

Materials

The Level 1 Math Makes Sense curriculum resource [34] was used for this study. This resource includes four lessons on measurement: in the Launch component, students compare the length of objects with each other; in Lesson 1, students compare a referent to several objects and sort the objects into ‘shorter than’, ‘same as’, and ‘longer than’ bins; in Lesson 2, students drop three toy cars down a ramp, measure the distance the cars travelled with string, and then order them from shortest to farthest; and in Lesson 3, students apply what they learned in a problem-based activity to find out which animal in a picture went the farthest. Table 2 summarizes the focal concept, the problem to solve, and suggested materials for each lesson.

---- Insert table 2 about here ----

A task analysis of the manipulative portions of the lessons resulted in the tabulation of a distribution of manipulative tasks that could be accomplished with a Lego RCX infrared-controlled robot (and some attachments), with assistance from a teacher, or with an environmental adaptation. All the tasks were designed to be performed on a table so the participant could see them while seated in a wheelchair. Table 2 summarizes for each lesson the environment or robot adaptations as well as the manipulative tasks that the participant was expected to do with the robot, including what the teacher needed to facilitate. The key requirements for the robot were a flat surface on which to mount referent objects, a gripper, and a spindle to hold a spool of string (figure 1). The key feature of the environment was to mount the objects to be manipulated on a small 1.5" foam block, so that the objects were at the same distance off the table as the referent item on the robot and so that the robot could grasp the block with the gripper (also shown in figure 1). Yellow and blue arms were added to the robot to distinguish its left and right sides. This colour coding was expected to help the participants to base movements on the frame of reference of the robot and not that of the participant.

---- Insert figure 1 about here ----

The participants used their own SGDs to control the robot via the IR output of the SGD (the manual supplied by the manufacturer provided instructions). The participants were involved in the decisions about how their SGD interface for controlling the robot should look and behave [35]. Their differing skills and preferences resulted in interfaces that varied in navigation system, symbol type, and organization (figure 2).

---- Insert figure 2 about here ----

<u>Setting</u>

The session for Emily took place during the school year at her school in a large room that was occasionally shared with other students using computers. Doug and Jane were involved in the study during the summer break. Doug was seen at a day care, with sessions taking place in a large foyer area. Jane was seen at various locations (e.g. in her home or in laboratory space at a university or hospital). Her mother was present during the sessions.

<u>Procedure</u>

Several measures were made prior to beginning the math lessons to establish the skills and abilities of the participant. First, a test of the speed and accuracy of scanning by the participants on their SGDs was performed [36]. In this test, the participants selected target dots (not letters, words or robot commands) that were manually placed by the investigator on a blank SGD display. This method allowed evaluation of the motor accuracy and efficiency of the participant at selecting targets independent of the cognitive demands of communicating with the SGD or of manipulating objects with the robot. Next, a speech language pathologist evaluated receptive language using the Peabody Picture Vocabulary Test, Fourth edition (PPVT-4) [37], and also ascertained the general level of communicative competence of the participant using a nonstandardized protocol [38]. A narrative re-tell task [39] and interview were used with the InterAACt framework Dynamic AAC Goal Grid [40] to evaluate the level of AAC skills of each participant on grid items that were deemed applicable to doing the math activities.

Finally, because the participants had varying experience using robots, training in the control of the robot to bring the participants to sufficient levels of competence was included [41]. Emily had four training sessions in one week, Doug had four sessions over two weeks, and Jane had three sessions over two weeks. All sessions were approximately 60 minutes. Robot control, manipulation of items, and switching between manipulation and communication were introduced individually. During the training sessions, participants controlled the robot in slalom course activities with the same spatial resolution required in the math activities (e.g. pathway curvature), and the participants practiced manipulating the items that were needed in the subsequent math activities (e.g. gripping blocks or unwinding string).

The measurement lessons were taught by a special education teacher. The lesson plans from the Math Makes Sense Teacher Guide [34] were revised to include a reduced number of questions and manipulative activities. For example, the original Launch had 11 suggested background questions for the students, whereas the revised lesson plan reduced this to five. Likewise, the original Launch had the children compare several items, whereas the revised lesson plan reduced this to three. Each lesson was composed of the following parts: introducing the problem, asking the participant for potential strategies, providing instructions, doing the activity, and reporting on the results (including asking participants about their reasoning for their answers). Each participant performed the math measurement lessons in video-recorded sessions of 30 to 90 minutes (Emily had seven sessions, Doug had five, and Jane had three).

Prompts when the participant was reporting about the math activity were provided as necessary by the teacher, and followed a question hierarchy from high level down to yes/no (e.g.

'What can you tell me about your measurements?', 'Which string is longest?', 'The yellow string is ______?', and 'Is the yellow string longest?'). Whenever needed, prompts regarding finding symbol pathways for vocabulary on the SGD were provided to the participant by the teacher. The emphasis in this study was to use the core vocabulary available in the language system of the device [42, 43], so specific math words were not added to the SGDs of the participant. Instead, 'is it the same' was used instead of 'compare', 'how long' was used for 'length', and 'match up' was used for 'baseline' (defined as the imaginary line used to line up the ends of two objects for comparison). A Word Wall board (3' × 4') was available during the session to show the symbol pathways to the math vocabulary. Vantage-Vanguard PASS software (Prentke Romich Co., Wooster, OH, USA) on a tablet computer was also used to look up symbol pathways. Prompts regarding robot control were provided by the teacher or investigator in a high to low level heirarchy (e.g. 'What do you think you need to do now?', 'You need to open the gripper', and 'To open the gripper, you press this symbol').

The mother and the EA of each participant were interviewed together, with the participant present. They were all shown photographs of each of the activities, a video of the participant doing an activity with the robot, and data collection documents regarding participant performance. In addition, they were asked for their opinions about using the robot for the math activities and the feasibility of being able to use it on their own in the classroom. On a separate day, the AT team also viewed the photographs, videos, and artefacts, and they were interviewed about participant performance and feasibility in the classroom.

<u>Data collection</u>

Research question 1 was examined by assessing participant performance in the math measurement lessons and by describing the process of using the system in terms of manipulation and communication events. The teacher assessed participant performance while watching the video immediately after the session. A rubric based on the Math Makes Sense resource was used where students are rated as ‘Not yet adequate’, ‘Adequate’, ‘Proficient’ or ‘Excellent’ in conceptual understanding, procedural knowledge, and communication. If the teacher assessed that a participant was not firmly ‘Adequate’ in a lesson, then the participant performed practice activities. To establish the reliability of the teacher assessments, 33% of the math sessions were assessed by a second special education teacher (referred to as the external teacher in the results) using the same rubric. The reliability sample included one session of each lesson, with the participant chosen randomly. Percentage agreement over the total number of ratings was calculated.

To obtain descriptions of the manipulation and communication events made by the participants during the lessons, videos of each lesson were observed and coded. Picture-in-picture videos were used, showing the SGD screen of the participant within a wide view of that participant doing the tasks. The occasions when the participant performed the manipulative tasks identified in the task analysis (table 2) were marked. What the participant did with the robot was described in detail, particularly if a participant did not perform a task as expected. The qualitative analysis software NVivo (QSR International, Doncaster, Victoria, Australia) was used for marking and describing the manipulation events. The data were summarized by determining how quickly participants ‘got it’ (i.e. whether the participant performed the task appropriately on the first try, after one or two prompts, or did not perform the task appropriately even after prompting).

Communicative events were tracked using two methods. First, the built-in SGD automated data logging feature, which gives a record of all of the words spoken and buttons pressed, was turned on at the beginning of each session and turned off at the end. Second, all session videos were observed and the communication events coded by two research assistants who were not involved in the intervention. This coding was based on a framework advocated by Clarke and Kirton [44]. Communication events were coded as an 'Initiation' or a 'Response' along with the mode utilized for communication (SGD output or non-verbal gesture). A qualitative note was attached to each event to describe the utterance spoken (cross-checking with the logfile output) and the situation or question that resulted in the utterance. Morae usability software (TechSmith, Okemos, MI, USA) was used to code and summarize the number and modes of the communication events. Twenty per cent of the communicative event data in the main lessons was reviewed to establish inter-rater reliability of coding and percentage agreement was calculated.

The interviews with the EAs and the AT team informed research question 1 by providing more detail about participant performance and they informed research question 2 by providing data regarding importance and feasibility in the classroom. The interviews were transcribed, coded for themes, and summarized by the first author.

Results

The measures done prior to the math sessions established the skills and abilities of the participants and hence helped to gauge what could be expected of the participants. From the operational accuracy results [36], the teacher expected that Doug and Jane would be almost 100% accurate in using their selection method. Thus, if they had problems performing the manipulation or communication tasks, the lack of success would likely be due to some sort of demand of the task rather than operational skill. Emily had around 75% accuracy, so it was expected that she would sometimes be inaccurate in using her selection method, resulting in unintended manipulation or communication events.

All participants had a minimum receptive language level of grade 2 on the PPVT receptive vocabulary test (Emily received a score of '2;4' grade equivalent, Doug received '2;9', and Jane received '3;7'). Hence, it could be assumed that the language level in the Level 1 math lessons was likely appropriate for the participants. Participants were told to ask if they did not understand words or instructions. The story re-tell protocol [38] identified a spread of linguistic abilities across the participants. The social openers that the participants made to let their listener know they were going to tell their listener a story are shown in table 1. Doug and Jane were able to re-tell the story effectively; therefore, the teacher expected that if they had difficulty communicating about math concepts, it would likely be due to problems with the concepts and not linguistic limitations. However, Emily had difficulty expressing herself on the re-tell task, so it was expected that she would have more problems expressing her thoughts regarding math concepts. All participants showed that they had skills to correct misunderstandings or request clarification or help when needed.

Robot training results showed that the participants were able to manipulate the items adequately [41]. However, Emily and Jane had limits in their ability to manoeuvre within the spatial resolution that would have been required for the original drawing created for Lesson 3 (table 2). Therefore, the three-animal-tracks pathway was replaced with a different activity (from the Math Makes Sense resources) in which a boy and a girl followed two different sidewalks [34].

Math sessions

The assessments by the teacher of the conceptual understanding, procedural knowledge, and communication of the participants are shown in table 3. Any ratings that were assessed as 'Not Yet Adequate' or 'Adequate' are marked with comments made by the teacher. The percentage agreement between the assessments of the teacher and the external teacher on the four-level scale was 55%. The percentage agreement of ratings within one level of each other was 100%. Emily required two practice activities in Lesson 2: Practice 1 was a repeat of Lesson

2 with different characters driving the cars, and Practice 2 required her to use the robot to place three straws of differing lengths in order from shortest to longest (an activity from the Math Makes Sense Activity Bank [34]). The straws were attached to foam blocks so they could be grasped by the robot gripper. A few minor differences from the proposed procedure occurred. First, the robot was not available for Doug at his Launch lesson, so he manipulated the items by directing the teacher what to do based on situations that she set up for him to evaluate and repair. For example, for ‘place items parallel’, the teacher placed the items so they were not parallel to each other and said ‘I could put the items like this’, and Doug responded with ‘Move it straighter’. Second, because of the modification in Lesson 3 to have two pathways instead of three, ordering could not be assessed as intended. Also in Lesson 3, the teacher decided to leave the strings taped to the start position so that participants only had to pull the strings straight to compare them, thus the procedure of lining them up on the baseline could not be assessed. Finally, Doug did both the two- and three-pathway activities, but only the former is presented.

---- Insert table 3 about here ----

Manipulation events

Table 4 shows the summary of each manipulative task with an indication of how quickly each participant ‘got it’. The participants did not always ‘get’ the task right away, or they sometimes performed tasks in unexpected ways. Only Emily had trouble with the task ‘place items parallel’. Instead of moving the robot to make the item on top of the robot parallel to the comparison item in the Launch, she tried to grasp the block under the comparison item. After prompting to compare by lining up the ends, she made the tips of the items touch (i.e. at an angle rather than parallel). None of the participants ‘lined up the ends’ of the items as expected in the Launch. Emily and Jane needed reminders to line up the ends, and Doug lined up the centres, rather than the ends. In Lesson 1 Doug lined up the back end of the referent on the robot and the comparison item, not the front end as expected, and through questioning the teacher eventually understood what he was doing. Emily and Jane needed reminders to line up the ends in Lesson 1 and in Lesson 2.

---- Insert table 4 about here ----

The other events in which participants did not ‘get’ right away occurred during the tasks that allowed the participant to carry out the activity, but these difficulties were not specifically with the measurement procedures. ‘Unwind string’ was problematic for Emily in Lesson 2 because she began to unwind the string between the tape marks for the stop locations rather than from the end of the ramp to each stop mark. In Lesson 3 Jane had problems backing up the robot to get back on the path. ‘Grasp block under comparison item’ was difficult for Jane since she did not approach the blocks from an appropriate angle, resulting in parts of the item preventing the robot’s gripper from getting close to the block.

Communicative events

Table 5 shows the duration of the ‘talking’ portions (‘Introduction’, ‘Suggest potential strategies’, and ‘Report results’) and the ‘doing’ portions (‘Manipulate with robot’) of the main lessons and the rate in events/minute of each communication mode. Because of the initial low inter-rater agreement (72% for Emily, 80% for Doug, and 71% for Jane), discrepancies in coding were investigated. Differences in initiations versus responses were found, so only the sum is presented.

The coders identified some instances where they felt the participants were using the robot to communicate. Doug moved the robot backwards to tease the teacher as she was about to lift it, and he closed the gripper in response to the question ‘Do you want the card in your gripper, or not?’ Jane began to move the robot in response to the question ‘If you had to measure the rake, what would you do?’ Finally, because the robot happened to be powered on when the teacher asked for potential strategies in Lesson 2, Jane responded by moving the robot to demonstrate her idea.

---- Insert table 5 about here ----

In the introduction portion of the lesson, participants reviewed concepts and vocabulary from prior lessons. The participants were asked to suggest potential problem-solving strategies, but they primarily agreed with those eventually suggested by the teacher. Doug and Jane suggested one strategy in Lesson 3: they said to use string to solve the pathways problem reasoning that string was a good tool to use because ‘it bends’.

Examples of utterances made by the participants during the reporting portion of the lessons are shown in table 1. Emily’s responses were incorrect at first, but became more accurate in subsequent lessons. Emily and Jane did not give reasoning for their answers when asked, but they responded appropriately to fill-in-the-blank and yes/no questions from the teacher. Doug’s first response to the teacher’s question ‘Do you know what that means?’ in Lesson 2 was ‘He is the fastest’. After a reminder to use the word ‘farthest’, he said, ‘He is the farthest and long string.’ The teacher verified with yes/no questions that he understood that the longest string meant the farthest distance.

Social validity

The parents and EAs thought that the goal of improving the participation of these students in length measurement activities was important, because they found it challenging to involve children with disabilities in that unit. Being able to do the ‘hands-on’ portions was important to them because they said the students would be more motivated to solve a problem. The parents and EAs felt it was appropriate to involve these older children in grade 1 level math because, through the study, gaps had been identified in their math knowledge. They also thought the manipulative tasks that were not specifically part of a measurement procedure were important for the participants to do (e.g. drop car down ramp). The AT team teacher put it this way, ‘These kids haven’t gotten to do those things, it’s their first time experiencing that stuff, so that’s good.’ All three participants said they preferred using the robot over watching the teacher do the manipulation.

The EAs thought the cost of the robots was reasonable, and that they would be able to use them in the classroom. They said that it was easy to program the AAC device to send the robot commands and to adapt the objects for robot manipulation by attaching them on top of blocks. They recommended providing a pre-packaged kit with instructions and some prepared materials, and they thought that teachers and EAs who became used to the system would be able to make their own adaptations for new lessons. The EAs also suggested some classroom activities in which the robot could be used, such as during small-group activities, as a demonstration at the beginning of a class, or as a video taken of the student using the robot in a one-on-one session (which could be shown to the whole class as an instructional video). They felt the robot would promote interaction and collaborative learning between the children in the classroom.

Discussion

Having access to a robot enabled the participants to perform the manipulative tasks and allowed the teacher to assess the procedural knowledge of each student about comparing objects. The teacher ratings of ‘Not Yet Adequate’ and ‘Adequate’ as well as the comments about not lining up on the baseline (table 3) correspond roughly with the occasions when the participants did not immediately ‘get’ the ‘line up ends of the items’ task with the robot (table 4). One important gap discovered in the procedural knowledge of the participant was that none of them came to the study knowing that they had to ‘line up ends of items’ to compare objects. Even though Doug and Jane had been exposed to some math measurement activities previously, they had not learned this basic concept. The EAs and AT team attributed this to them doing the procedure for the students and not explaining the need to establish the common baseline. Doug's EA said 'I always did the hands-on for him so that it would always go at the end, and I probably never said you have to line up at the end' and the AT team teacher confirmed by saying 'We do these things for these kids all the time, forgetting that [doing it] is a big part of learning.'

Another gap identified because they participants did the hands-on activity themselves was the difficulty of Emily and Jane in generalizing the baseline concept from Lesson 1 (where they lined up two objects) to Lesson 2 (where they lined up three strings). The AT team teacher noted that this is understandable given the limited experience of the participants in working with this concept in various contexts, and that they would need extra reinforcement. Typically developing children would have had multiple opportunities to apply the concept in the lessons and outside the classroom, whereas in this study the participants only experienced two contexts (objects and strings). On a related note, the EAs and the AT team were not surprised that the participants did not offer potential strategies to solve problems, saying that students who use AAC do not often have the expectation that they will be asked to offer solutions, and they lack experience and confidence. However, this study shows the potential for students to gain experience in developing such strategies.

Having access to their SGDs during the activities was important for the participants because they could report and reflect on the concepts: the things the participant said, along with their non-verbal responses, allowed the teacher to assess the conceptual understanding of the participants. Each participant's use of language to report their measurement results was consistent with their performance on the story re-tell (i.e. Emily used 1-word utterances, Doug used articulate sentences, and Jane used short sentences); however, they were not as strong at explaining their reasoning as they were at reporting. Their lack of responses may indicate that they did not have good reasoning for the math concepts covered in the study.

Similar to the results of Symington and Stanger [30] and Anderson [32], these students were found to use language in motivating activities and gained some skills. Emily in particular gained experience in learning to use labels correctly and had the opportunity to practise two- and three-word utterances. Both Emily and Jane got to practise the appropriate use of the word ‘middle’ (see table 3).

Having both the robot and an SGD available offered other benefits as well, which were validated as being important - indeed, key - in the AT team interview. First, the participants had multiple ways available to demonstrate their understanding of concepts. For example, the teacher assessed sorting in Lesson 1 by observing into which bin the participants placed the objects with the robot, not from SGD vocal output. Allowing children to show instead of explain is a suggested technique in the Math Makes Sense resource for children who are struggling to express themselves because English is their second language [34]. Conversely, the teacher assessed ordering in Lessons 2 and 3 by what the participants said rather than expecting them to use the robot to put the strings in order from shortest to longest. From their communication, it was clear that Doug and Jane understood ordering and did not need to physically put the strings in order. However, Emily needed the extra reinforcement of physically placing objects in order, so she actually did the practice activity of using the robot to order the straws.

Second, robot manipulation and communication augmented each other. Verbal and non-verbal communication techniques were used to clarify robot usage. The non-verbal communication during the ‘doing’ portions seen in table 5 were the teacher verifying the intentions of the participants. As the AT team pointed out, the teacher may not have given Doug credit for knowing the baseline concept if he could not communicate that he was lining up the back ends of the referent and comparison objects rather than the front ends. On the other hand, the robot was used to enhance communication. Doug and Jane used the robot as if to point and say ‘not there, here’ and also ‘let me do it’. When Doug teased the teacher by moving the robot when she was going to reach for it, he showed his sense of humour in using a trick that typical children like to play on others.

Previous studies involved students who used AAC in choice making or in reporting portions of math measurement activities [28, 30], whereas this study also actively involved students in the hands-on activities. Adapting the math activities to be performed by a Lego robot was achievable and was found to be flexible enough to perform multiple functions, giving the participants experience in several activities. The EAs and the AT team were positive about the social validity of the intervention, indicating that access to ‘hands-on’ activities was important and that the robot materials and methods were suitable for use in a classroom with some minor modifications and instructions.

However, some limitations were observed. First, the degree of operational skill of the students with disabilities in controlling the robot will affect how much the activities can be adapted while still testing the targeted concepts. For example, because of the limits of Emily and Jane in controlling the robot, ordering could not be evaluated for them in Lesson 3. Conversely, because Doug had very good control of the robot, he was able to perform the three-pathway activity proposed originally. Given the problems faced by Emily and Jane, the robot training routine should have included more practice with driving the robot, unwinding string, and grasping the blocks under objects. Second, environmental factors such as the amount of space available will also play a part in ability to adapt the lessons to test the target procedures. For example, the teacher taped the strings to the start position in Lesson 3 because no room was available to pull the long strings along a table, making it impossible to assess lining up the ends. The EAs pointed out that finding two large tables on which to use the robot could be a problem in a classroom, and they suggested adapting the activities to the size of one or two desks. Finally, the mechanical limitations of this robot, such as not going in a straight line, were not addressed in this paper, but they do contribute to the effectiveness of this robot as a tool in these activities.

This study had inherent limitations because no experimental control was included, so no inferences regarding the specific role of the robot in the learning of the concepts by the participants can be made. Treatment integrity could also be questioned, because the teacher did not administer each lesson in an identical way with each participant; instead, she used individualized teaching principles to tailor the lesson to each participant. However, this process has social validity, because it resembles how lessons would be tailored to the varied levels of ability of the children in a classroom. The low inter-rater reliability between the teacher and the external teacher for the exact rating on the assessments occurred because the two teachers sometimes rated the concepts and procedures interchangeably. The rubric provided did not give definitions for these terms; thus, such definitions must be more explicit in future studies.

Future studies will implement the recommendation of providing a kit so that school staff can adapt the activities on their own. Also, strategies for inclusion of this technology in group or full-classroom activities will be examined. This study provided an opportunity to begin to observe the differences between modes of manipulation for measurement procedures, such as observation of teacher demonstration and direction of the teacher via the SGD. The differences of these modes from robot manipulation should be examined in more detail in future studies. Also, utilizing a robot to perform grade two (measurement with non-standard units) and grade three (standard units) activities will be examined.

Conclusion

Providing students who have severe physical disabilities and complex communication needs with a way to control a Lego robot through their SGDs allowed them to demonstrate and explain their understanding of math concepts. Some gaps in their knowledge were revealed. The

EAs felt these gaps were caused by lack of experience in doing the activities independently. Having access to both the SGD and robot was beneficial because they could use whatever method was most effective for demonstrating or explaining, they could augment one method with the other, and both modes were always available rather than having to switch between them. Actively using all these options is more like the way that typically developing children perform problem-based math lessons: they actively participate in hands-on activities and communicate ideas to express what they have learned. Use of this inexpensive robotic system could contribute to the learning of early math concepts for students with severe physical disabilities and complex communication needs, and it could also lead to improvements in learning the higher math skills they will need as adults.

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References

1. Van Rooijen M, Verhoeven L, Steenbergen B. Early numeracy in cerebral palsy: Review and future research (Review). Dev Med Child Neurol 2011;53(3):202–209.
2. Meyer LA, Loncke FT. Factors contributing to success or failure in vocational evaluation by users of augmentative and alternative communication devices. Clinical AAC Research Conference; 2008 Sept 25–27; Charlottesville, VA.

3. Bryen DN, Potts BB, Carey AC. So you want to work? What employers say about job skills, recruitment and hiring employees who rely on AAC. Augment Altern Commun 2007;23(2):126–139.

4. McNaughton D, Light J, Arnold KB. “Getting your wheel in the door”: Successful full-time employment experiences of individuals with cerebral palsy who use augmentative and alternative communication. Augment Altern Commun 2002;18:59–76.

5. Bisanz J, Sherman JL, Rasmussen C, Ho E. Development of arithmetic skills and knowledge in preschool children. In: Campbell JID, editor. Handbook of mathematical cognition. New York: Taylor & Francis; 2005. p 143–162.

6. Eriksson L, Welander J, Granlund M. Participation in everyday school activities for children with and without disabilities. J Dev Phys Disabil 2007;19:485–502.

7. Jenks KM, de Moor J, van Lieshout EC, Maathuis KG, Keus I, Gorter JW. The effect of cerebral palsy on arithmetic accuracy is mediated by working memory, intelligence, early numeracy, and instruction time. Dev Neuropsychol 2007;32(3):861–879.

8. Van De Walle JA, Karp KS, Bay-Williams JM. Elementary and middle school mathematics: Teaching developmentally. Boston: Allyn and Bacon; 2010.

9. Western Canadian Protocol for Collaboration in Basic Education. 2006. The common curriculum framework for K–9 mathematics. <http://www.wncp.ca/math/ccfkto9.pdf>. Accessed 2008 Mar 21.

10. Ginsburg HP, Klein A, Starkey P. The development of children’s mathematical thinking: Connecting research with practice. In: Siegel IE, Renninger KA, editors. Handbook of child psychology, Volume 4: Child psychology in practice. 5th ed. New York: John Wiley and Sons; 1998. p 401–476.

11. Marsh LG, Cooke NL. The effects of using manipulatives in teaching math problem solving to students with learning disabilities. Learn Disabil Res Pract 1996;11(1):58–65.

12. Dev OC, Doyle BA, Valente B. Labels needn't stick: "At-risk" first graders rescued with appropriate intervention. J Educ Students Placed At Risk 2002;7:327–332.

13. Wisniewski Z, Smith D. How effective is touch math for improving students with special needs academic achievement on math addition mad minute timed tests? Lanhang, MD: ERIC Document Reproduction Service; 2002.

14. Avant MJT, Heller KW. Examining the effectiveness of touchmath with students with physical disabilities. Remedial Spec Educ 2011;32(4):309–321.

15. Reimer K, Moyer PS. Third-graders learn about fractions using virtual manipulatives: A classroom study. J Comput Math Sci Teach 2005;24(1):5–25.

16. Stanger C, Symington L, Miller H, Johns S. Teaching number concepts to all students. Teach Except Child 2000;33(1):65–69.

17. Bruner JS. Toward a theory of instruction. Cambridge, MA: Belknap Press of Harvard University Press; 1966.

18. Maccini P, Mulcahy CA, Wilson MG. A follow-up of mathematics interventions for secondary students with learning disabilities. Learn Disabil Res Pract 2007;22(1):58–74.

19. McNeil NM, Uttal DH. Rethinking the use of concrete materials in learning: Perspectives from development and education. Child Dev Perspect 2009;3(3):137–139.

20. Howell R, Hay K. Software-based access and control of robotic manipulators for severely physically disabled students. J Artif Intell Educ 1989;1(1):53–72.

21. Howell R, Martz S, Stanger CA. Classroom applications of educational robots for inclusive teams of students with and without disabilities. Technol Disabil 1996;5:139–150.

22. Kwee H, Quaedackers J. POCUS project: Adapting the control of the MANUS manipulator for persons with cerebral palsy. ICORR '99: International Conference on Rehabilitation Robotics. 1999; Stanford, California. p 106–114.

23. Eberhart SP, Osborne J, Rahman T. Classroom evaluation of the Arlyn Arm robotic workstation. Assist Technol 2000;12:132–143.

24. Smith J, Topping M. The introduction of a robotic aid to drawing into a school for physically handicapped children: A case study. Br J Occup Ther 1996;59(12):565–9.

25. Cook A, Adams K, Volden J, Harbottle N, Harbottle C. Using Lego robots to estimate cognitive ability in children who have severe physical disabilities. Disabil Rehabil Assist Technol 2011;6(4):338–46.

26. Bley NS, Thornton CA. Accommodating special needs. In: Thornton CA, Bley NS, editors. Windows of opportunity: Mathematics for students with special needs. Reston, VA: National Council of Teachers of Mathematics; 1994. p 137–166.

27. Olsson C. Participation of adolescents with complex communication needs at school: Considerations from public health issues. 14th International Society for Augmentative and Alternative Communication (ISAAC) Conference; 26–29 July 2010; Barcelona, Spain.

28. Schlosser R, McGhie-Richmond D, Blackstien-Adler S, Mirenda P, Antonius K, Janzen P. Training a school team to integrate technology meaningfully into the curriculum: Effects on student participation. J Special Educ Technol 2000;15(1):31–44.

29. Hunt P, Soto G, Maier J, Muller E, Goetz L. Collaborative teaming to support students with augmentative and alternative communication needs in general education classrooms. Augment Altern Commun 2002;18:20–35.

30. Symington L, Stanger C. Math = success. Teach Except Child 2000;32(4):28–32.

31. Light JC, Drager KDR. Improving the design of augmentative and alternative technologies for young children. Assist Technol 2002;14:17–32.

32. Anderson A. Learning language using infrared toys. 18th "Technology and Persons with Disabilities" Conference; 2002; Los Angeles, California.

33. Schlosser RW. Social validation of interventions in augmentative and alternative communication. Augment Altern Commun 1999;15:234–247.

34. Pearson Education Canada. Math makes sense 1. Toronto, Ontario: Pearson Education Canada; 2007.

35. Adams K. Involving users in the design of a speech generating device interface for Lego robot control. Annual RESNA [Rehabilitation Engineering and Assistive Technology Society of North America] Conference; 2011; Toronto, ON.

36. Adams K, Cook A. Measuring user accuracy and speed with scanning access on dynamic display speech generating devices. 14th International Society of Augmentative and Alternative Communication (ISAAC) Conference; 26–29 July 2010; Barcelona, Spain.

37. Dunn L, Dunn L. Peabody Picture Vocabulary Test. 1997

38. Adams K, Helmbold B, Lucky K. "I tell you a story": Using narrative re-tell to assess AAC competencies. 14th International Society of Augmentative and Alternative Communication (ISAAC) Conferenc;. 26–29 July 2010; Barcelona, Spain.

39. Glasgow C, Cowley J. The Renfrew Bus Story – American Edition. Centreville, DE: The Centreville School; 1994.

40. Clarke V, Schneider H. InterAACT Framework: Dynamic AAC goals planning guide. Pittsburgh, PA: DynaVox Mayer-Johnson; 2008. <http://ca.dynavoxtech.com/training/toolkit/details.aspx?id=32>. Accessed 2009 Nov 27,.

41. Adams K, Encarnação P. A Training protocol for controlling Lego robots via speech generating devices. In: Gelderblom G, Soede M, Adriaens L, Miesenberger K, editors. 11th European Conference for the Advancement of Assistive Technology. Volume: Everyday technology for independence and care – AAATE 2011 Assistive Technology Research Series. 2011; Maastricht, The Netherlands.

42. Baker B, Hill K, Devylder R. Core vocabulary is the same across environments. Technology and Persons with Disabilities Conference; 2000; Northridge, CA.

43. Caputo Boruta M, Bidstrup K. Making it a reality: Using standards-based general education science and math curriculum to teach vocabulary and language structures to students who use AAC. Perspect Augment Altern Commun 2012;21:99–104.

44. Clarke M, Kirton A. Patterns of interaction between children with physical disabilities using augmentative and alternative communication systems and their peers. Child Lang Teach Ther 2003;19:135–151.

Figures and tables

Table 1: Participant demographics, pre-existing language skills, and utterances made during the measurement lessons.

		Emily	Doug	Jane
Demographics	**Grade in school**	8	4	6
	Scanning technique	Two-switch row-column step scanning	Two-switch row-column step scanning	Two-switch group-row-column step scanning
	Language system	Unity 45 Full	Unity 45 Full	Unity 84 Sequenced
	SGD experience	2 years	5 years	5 years
Pre-existing language skill	**Social opener on re-tell task**	'Alice you <?. That's interesting tell me more.> Listens.' [a]	'I'm going to tell you a story.'	'I tell you a story.'
Sample utterances made during the lessons	**Launch**	'shorter', 'long'	'The stick is longer than the other one.'	'It is longer.'
	Lesson 2	'farthest', 'green' In the practice activity: 'red taller green' (with scaffolding from the teacher)	'Y [b] is the longest string.'	'The blue went the furthest.'
	Lesson 3	'blue longs'	'B [b] went farther than Y.'	'The red is shortest.'

[a] 'Alice' is a pseudonym for Emily's EA, and the section marked with < > indicates a selection made and then deleted by Emily.
[b] 'Y' and 'B' were the first letters of the names of the 'drivers' of the toy cars.

Table 2: Description of the lesson focus, the problem to solve, the materials, (all from Math Makes Sense 1 [34]), the adaptations of the robot or the environment, and the manipulative tasks expected of the participant (using the robot).

	Launch	Lesson 1	Lesson 2	Lesson 3
Concept of focus	Demonstrate prior knowledge of measurement.	Compare objects to one common referent.	Order objects according to length.	Apply concepts from earlier lessons.
The problem to solve	Choose two objects and compare them.	Find objects around the classroom that are about as long as the pencil and sort them into 'shorter', 'longer', or 'same as' bins.	How can you find out which of three toy cars travels the farthest past the ramp?	How can you find which animal went the farthest?
Materials	Various classroom objects.	Various objects, pencil as referent.	Ramp, three toy cars, string, tape, pens.	A drawing of three pathways of tracks of different animals.
Environment or robot adaptation	- Object 1 was affixed to the top of a 1.5" square block. - Object 2 was placed on top of the robot.	- Objects were affixed to the top of blocks and spread around the table. - The pencil was placed on top of the robot. - Three bins were hung off the edge of the table. - A gripper was attached at front of robot (to grasp and release the blocks).	- Robot gripper was available to grasp and release the toy car. - A spool of string on a spindle was attached to back of robot.	- Drawing was enlarged to 2' × 3'. - A spool of string on a spindle was attached to back of robot.
Manipulative tasks the participant was expected to do with the robot (with teacher facilitation)	Drive robot forward, backward, left and right to <u>- place the objects side by side as well as parallel,</u> and <u>- line up the ends of the objects.</u>	Drive robot forward, backward, left and right to <u>- place the objects side by side and parallel,</u> <u>- line up the ends of the objects,</u> <u>- grasp the second object</u> with the gripper, and <u>- push it into the appropriate bin.</u>	<u>- Release the car</u> at the top of the ramp by opening gripper. - Drive robot from the bottom of the ramp to the place the car stopped (where teacher placed a piece of tape) while <u>unwinding the string</u> (teacher helped if string got tangled). - (Teacher attached string to robot first.) One at a time, drive robot to ○ <u>pull each string side by side and parallel, and</u> ○ <u>line up the ends of the strings.</u>	Drive robot along each pathway while <u>unwinding the string</u> and asking to tape it down (teacher taped down the string). Drive robot to <u>- pull the strings side by side and parallel and</u> <u>- line up the ends of the strings.</u>

Table 3: Teacher assessments in main lessons (M) and practices (P).

			Emily						Doug				Jane				Comments
		Lesson	0	1	2			3	0 [a]	1	2	3	0	1	2	3	[a] Robot not present during this session.
		Activity	M	M	M	P1	P2	M	M	M	M	M	M	M	M	M	
Conceptual understanding	**Compare**	Excellent	x					x	x			x					
		Proficient											x			x	
		Adequate															
		Not yet adequate															
	Sort	Excellent		x						x							
		Proficient												x			
		Adequate															
		Not yet adequate															
	Order	Excellent						Not scored			x	Not scored				Not scored	[b] Did not get that string represented distance.
		Proficient													x		[c] Needed explanation three times that string represented distance.
		Adequate				x [c]	x [d]										
		Not yet adequate			x [b]												[d] Able to do it after demonstration.
Procedural knowledge	**Compare**	Excellent		x									x				
		Proficient	x						x								
		Adequate															
		Not yet adequate															
	Sort	Excellent		x													
		Proficient								x				x			
		Adequate															
		Not yet adequate															
	Order	Excellent						Not scored			x	Not scored				Not scored	[e] Did not understand baseline.
		Proficient					x								x [g]		[f] Did not use baseline until third try.
		Adequate				x [f]											[g] Did not use baseline at first.
		Not yet adequate			x [e]												
Communication		Excellent	x	x					x	x	x	x		x			[h] Called middle string 'middle', even though it was shortest.
		Proficient				x	x	x					x		x [i]	x	[i] Trouble using words 'medium' and 'middle'.
		Adequate															
		Not yet adequate			x [h]												

Table 4: Tasks with an indication of how quickly participants 'got it':

+ Participant performed the task appropriately on the first try.

○ Participant performed the task appropriately after one or two prompts.

− Participant did not perform the task appropriately even after prompting.

A shaded cell means that the task was not part of that lesson.

Manipulative Task	Participant	Launch	Lesson 1	Lesson 2	Lesson 3
Release car	Emily			+	
	Doug			+	
	Jane			+	
Unwind string	Emily			○	+
	Doug			+	+
	Jane			+	○
Place item parallel [a]	Emily	○	+	+	+
	Doug	+	+	+	+
	Jane	+	+	+	+
Line up ends of the items [a]	Emily	○	○	−	NA-taped
	Doug	○	+	+	
	Jane	○	○	−	
Grasp block under comparison item	Emily		+		
	Doug		+		
	Jane		−		
Put item in appropriate bin [a]	Emily		+		
	Doug		+		
	Jane		+		

[a] Tasks that were specifically part of a measurement procedure.

Table 5: Time in each portion of 'Introduction', 'Asking strategies', 'Manipulating the robot' to do the activity, and 'Reporting' (the talking parts). Communication rate is given in events/min for SGDs (event = utterance), non-verbal communication (event = gesture), and communications via the robot (i.e. using the robot to communicate a concept).

		Introduction				Suggest strategies				Manipulate with robot				Report results			
		Launch	Lesson 1	Lesson 2	Lesson 3	Launch	Lesson 1	Lesson 2	Lesson 3	Launch	Lesson 1	Lesson 2	Lesson 3	Launch	Lesson 1	Lesson 2	Lesson 3
Emily	Time (h:min)	0:09	0:02	0:06	0:04			0:01		0:09	0:18	0:16	0:13		0:01	0:05	0:05
	SGD	0.8		0.3						0.3		0.1	0.2			0.5	1.7
(events/ min)	Non-verbal	0.1			0.2			1.4		0.3	0.2	0.7	0.2		1.7	0.7	1.3
	Robot																
Doug	Time (h:min)	0:03	0:01	0:02	0:08	0:08		0:13	0:04		0:46	0:31	0:26	0:00		0:21	0:15
	SGD	2.1	1.0	1.4	0.4	0.3		0.3	0.4	NA				3.1		0.7	0.3
(events/ min)	Non-verbal	0.3	1.0	0.7	1.3	0.6		0.9	0.6	NA	0.2	0.8	0.9	3.1		0.5	0.5
	Robot									NA		0.1	0.1				
Jane	Time (h:min)	0:06	0:02	0:13				0:10	0:07	0:06	0:40	0:24	0:34	0:13		0:15	0:20
	SGD	0.2		0.7					0.3			0.1	0.0	0.5		0.3	0.2
(events/ min)	Non-verbal	0.2	0.7	0.2				0.6	0.4	0.5	0.4	0.8	0.1	0.4		0.2	0.2
	Robot							0.1		0.2							

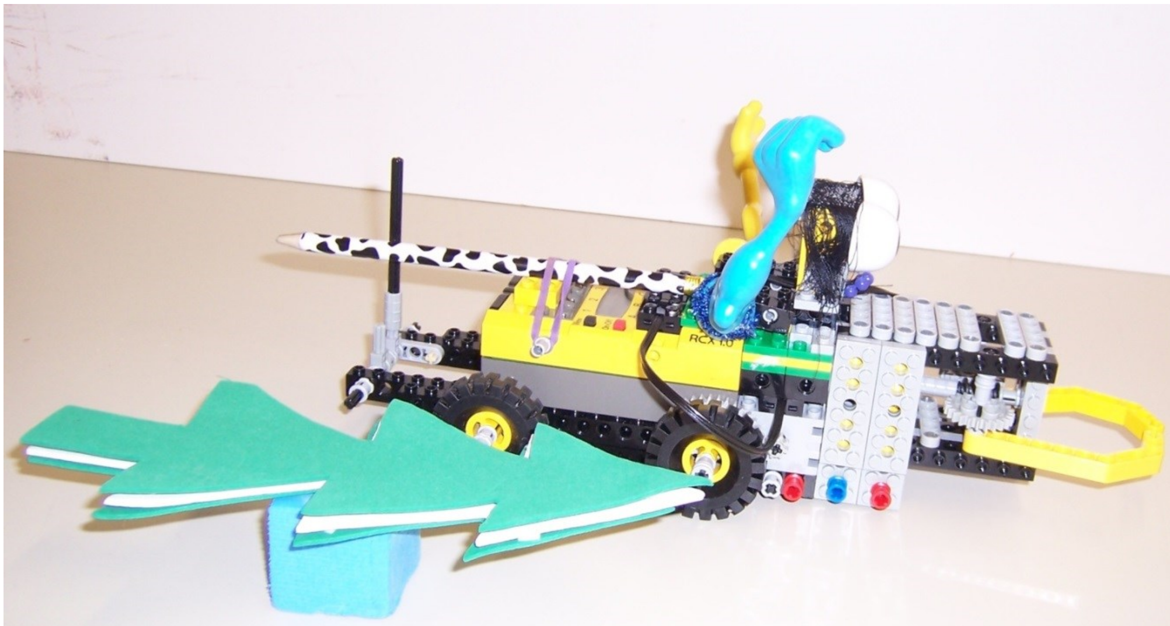
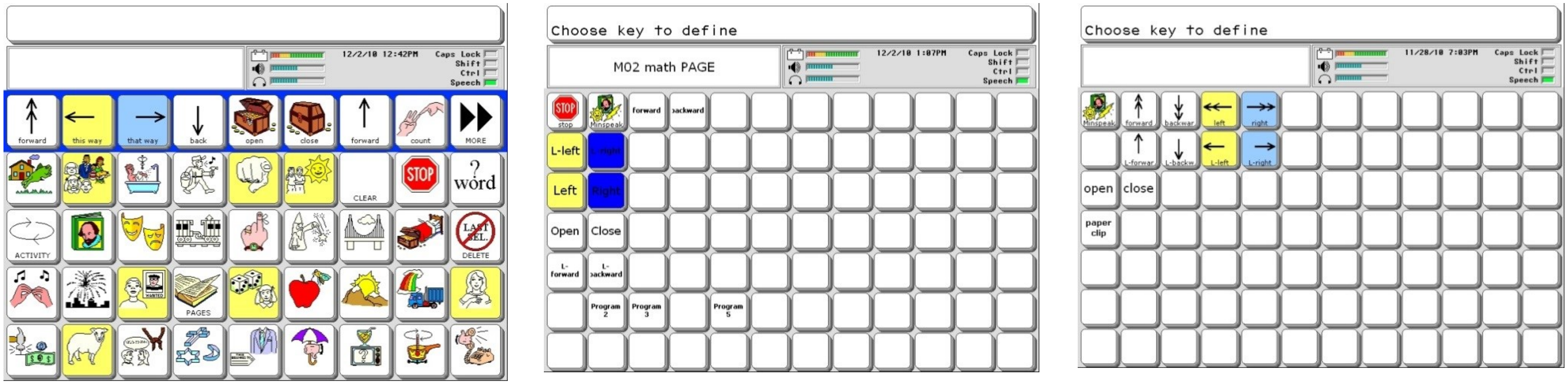


Figure 1: Robot with flat surface (on top of robot) and a rubber band to secure objects, a pencil referent in this case. The comparison object, a toy tree, is secured to a foam block so that it is the same height off the table as the referent item and can be grasped by the robot gripper.



(a) **(b)** **(c)**

Figure 2: SGD interfaces. Emily (a) used the top row on her SGD interface for robot commands, whereas Doug (b) and Jane (c) used separate pages for communication and robot commands. Each interface had robot commands for forward, left, right, backward (and Doug and Jane also have 'little' [L] forward, left, right, and backward commands as well), gripper open and close, and some programs. Left and right cells were colour coordinated with the left and right arms of the robot. The cell to switch to the core vocabulary (Minspeak) was located near the top left of the page in the interfaces of Doug and Jane.