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Performing mathematics activities with non-standard units of measurement using robots controlled via speech generating devices: Three case studies

Abstract

Purpose: To examine how using a Lego robot controlled via a speech generating device can contribute to how students with physical and communication impairments perform hands-on and communicative mathematics measurement activities. This study was a follow-up to Adams and Cook [Disability and Rehabilitation: Assistive Technology, 2014;9(4):286-298].

Method: Three students with cerebral palsy used the robot to measure objects using non-standard units, such as straws, and then compared and ordered the objects using the resulting measurement. Their performance was assessed, and the manipulation and communication events were observed. Teachers and education assistants were interviewed regarding robot use.

Results: Similar benefits to the previous study were found in this study. Gaps in student procedural knowledge were identified such as knowing to place measurement units tip-to-tip, and students' reporting revealed gaps in conceptual understanding. However, performance improved with repeated practice. Stakeholders identified that some robot tasks took too long or were too difficult to perform.

Conclusions: Having access to both their SGD and a robot gave the students multiple ways to show their understanding of the measurement concepts. Though they could participate actively in the new mathematics activities, robot use is most appropriate in short tasks requiring reasonable operational skill.

Introduction

Students who have motor disabilities and/or complex communication needs (CCN) are at risk in the development of mathematics skills. Some students have found that limited skills in mathematics have led to restrictions in their daily living activities and employment opportunities [1,2].

Students with disabilities participate in math less often than their non-disabled peers [3], at least, in part due to limited access - physical and linguistic - to the learning materials and strategies associated with mathematics instruction. Hands-on problem solving and reflecting about concepts for the development of mathematical thinking is well supported in educational literature [4]. Current mathematics pedagogy recommends that young students both participate interactively with objects to learn concepts and communicate about the concepts they have learned [5,6]. However, students with motor limitations may not be able to touch or grasp the objects used in hands-on activities. Students with CCN may not be understood when using their own voice to communicate, and may use augmentative and alternative communication (AAC) methods. However, limited vocabulary choices related to math can inhibit students with CCN from using AAC devices to communicate about mathematics in the classroom.

Students with motor impairments have used assistive robots to manipulate objects used in science classes, including bringing items closer for sensory inspection [7,8], putting a glass over a burning candle to extinguish it [9], mixing solutions, planting seeds, and plugging in electrical wires to make a radio [10]. Recent studies have used low-cost Lego Mindstorms robots (The Lego Group, Billund, Denmark) in academic activities such as programming in science [11], and counting and geometry in mathematics as well as acting out stories in social studies [12]. Students with disabilities could use these low-cost Lego robots to manipulate objects in various mathematics early learning activities.

Being able to communicate while performing math is important so students can 'verbalize to internalize' [13, pg. 145], ask for help, or talk aloud so teachers can ascertain their level of understanding [4]. Students with CCN have used speech generating devices (SGDs) to direct mathematics activities, such as choosing what object to measure [14,15]. If students control a robot from their AAC device, they can 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 disabilities can therefore use an integrated access method (e.g., switches connected to their SGDs) to control both the robot for hands-on activities and the SGD to communicate.

In a study of Level 1 mathematics measurement concepts students used a Lego robot controlled by an SGD to compare the length of objects to a pencil referent, sort objects into 'shorter than', 'same as' and 'longer than' bins, and ordered objects according to length [16]. Having access to a robot enabled the students to perform the manipulative tasks and allowed the teacher to assess their procedural knowledge. The use of the robot revealed gaps in their knowledge, such as the requirement to line up the ends of objects in order to compare their lengths. Students also had difficulty generalizing concepts (e.g., comparing concrete objects versus comparing lengths of string that represent objects). Because the participants also had access to their SGD they could report and reflect on the mathematical concepts. Vocabulary and use of language varied among the students and that affected how effectively they commented on the math tasks, but their comments allowed the teacher to assess conceptual understanding. In general, each student's reporting of the answer was strong (e.g., 'the red is shortest'), but their reasoning about concepts was weak, often requiring prompting through yes or no questions. Having access to both their SGD and a robot gave participants multiple ways to demonstrate understanding of concepts. They could demonstrate understanding by manipulating the mathematical objects using the robot or they could talk about the concept using their SGD. The students' conceptual and procedural knowledge improved as they practiced with the concepts. A major outcome was that the direct manipulation actively involved students in the learning task.

Despite the practice required to successfully manipulate the robot and the limitations of the robot in stopping exactly where intended, the students preferred to use the robot over watching the teacher demonstrate the concept. The social validity of the study, examined by interviews with the teachers and parents, indicated that the goal of involving the students in the Level 1 activities was important and the robot would promote engagement and collaborative learning in the

classroom. Teachers and parents thought that the cost of the robot was reasonable, and that building the robot and programming the SGD by them would be doable.
Follow-up studies are important to examine if the same results can be seen under different conditions [17]. The study presented in this paper was performed to determine if the same benefits in the study above [16] could be found when the students performed Level 2 mathematics measurement lessons. A low-cost robot system controlled via SGDs was used by students with physical and communication limitations to work with Level 2 mathematics measurement concepts involving measurement with non-standard objects (e.g., paperclips, straws). The research questions addressed were the following:

(1) How does using an SGD-controlled Lego robot contribute to how students with severe physical and communication limitations perform hands-on and communicative mathematics measurement activities?

(2) Do the stakeholders consider robot use in these activities to be important and feasible?

Methods

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. Approval to perform the study was obtained through the relevant university ethics board.

Participants

The same non-random convenience sample of three children with cerebral palsy from the Level 1 study [16] participated in this 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. None had visual impairments (as reported by their mothers), except for Doug who wore glasses. The participants' classroom experience, SGD features, and mathematics measurement experience are shown in table 1. For more detail refer to [16].
---- Insert table 1 about here ----
At the end of the study, the mother and the EA (or teacher, in the case of Emily) of each participant were interview participants. In addition, the students' common assistive technology (AT) team were interview participants. The AT team consisted of an occupational therapist, a speech language pathologist, and two teachers.

Materials

The Level 2 Math Makes Sense curriculum resource [18] was used for this study. Students performed three lessons in Level 2. The concept focus for Level 2 is measuring objects using non-standard units (e.g., objects such as straws, toothpicks, etc.) and then comparing and ordering the objects using the resulting length measurement. Table 2 summarizes the focal concept, the problem to solve, and suggested materials for each lesson performed.

---- Insert table 2 about here ----
A task analysis of the manipulative portions of the lessons resulted in 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 requirement for the robot was a gripper, a pen attachment (figure 1), and some programs to make the robot move forward by a unit length. The key feature of the environment was to mount the unit objects on small 4 centimetre foam blocks, so that the blocks could be grasped by the robot gripper. Magnetic rods were used as one of the non-standard units. The rods snapped together and made it easier to line up the units tip to tip (these were only used after the participant showed he/she knew the concept of not overlapping units or leaving gaps).
---- Insert figure 1 about here ----
The participants used their own SGDs to control the robot via the infrared output of the SGD. Emily had the robot commands on the top row of her SGD communication display, Doug and Jane used a separate page with robot commands (see [16] for details of SGD layouts). The participants recorded the results of their measurements into worksheets on a tablet computer. Their SGDs were connected to the tablet computer via a USB cable.

Setting

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

Procedure

Several measures were made prior to the Level 1 study to establish the skills and abilities of the participant: a test of the speed and accuracy of scanning by the participants on their SGDs; an evaluation of participant's receptive language using the Peabody Picture Vocabulary Test, Fourth edition (PPVT-4) [19]; and an assessment of the general level of communicative competence of each participant using a narrative re-tell task [20]. Also, each participant received training in the control of the robot. The methods and results for the pre-session measures and robot training are reported in [16].
The Level 2 measurement lessons were taught by the same special education teacher as in the Level 1 study [16]. Lessons 3, 4, and 5 from the Math Makes Sense Teacher Guide [18] were used in this study, and they are called Lessons 1, 2 and 3, respectively, here. The lesson plans were revised to include a reduced amount of guided discussion by the teacher. 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. Session length and number of sessions depended on time available and the length of time to finish the lessons (Emily had seven

sessions, Doug had three, and Jane had five). Sometimes a lesson carried over to the next session.

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?’; ‘The gingerbread man is <how many> straws tall, and you are <how many> tall?’, and ‘Who is tallest?’; 'Is 8 bigger than 9?'). 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 [21,22], so specific math words were not added to the SGDs of the participant. A Word Wall board (3' × 4') was available during the session to show the symbol pathways to the core math vocabulary (e.g., 'measure', 'how long' instead of 'length', and 'thing' instead of 'unit'). 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 author 1 in a high to low level hierarchy (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. After seeing artefacts, videos and performance assessments from the sessions, 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.

Data collection

As in the Level 1 paper [16], 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 a video of the session immediately after the session was over. 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 using the same rubric by a second special education teacher (referred to as the external teacher in the results). 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 a research assistant who was not involved in the intervention. This coding was based on a framework advocated by Clarke and Kirton [23]. Communication events were coded by the communication mode (SGD output or non-verbal gesture) and a qualitative note was attached to each event to describe the utterance spoken (cross-checking with the logfile output) along with 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 by a second research assistant 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 pre-session measures established the pre-existing skills and abilities of the participants. Doug and Jane were fast and accurate at using their SGD, so it was expected that if they had problems performing the manipulation or communication tasks, it was because the task demand was high. Emily was not as accurate, so it was expected that she would sometimes make unintended manipulation or communication errors. All participants had a minimum receptive language level of grade 2 on the PPVT receptive vocabulary test so it was assumed that the language level in the Level 2 math lessons was appropriate for the participants. The narrative re-tell task 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. Based on that performance, it was expected that Doug and Jane would be able to articulate their ideas about the math concepts. However, it was expected that Emily would have problems expressing her thoughts. Robot training results showed that the participants were able to manipulate the robot and objects adequately [24].

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 ‘Adequate’ ‘Not Yet 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 (Excellent, Proficient, Adequate, and Not yet adequate) was 63%. The percentage agreement of ratings within one level of each other was 95%.

Emily required three practice activities in addition to Lesson 1. She did not attempt Lessons 2 or 3. The practice activities repeated the concept of focus for Lesson 1, but with different objects to compare: in Practice 1 and 2 she measured, compared and ordered items 3, 2 and 1 rods in length, and in Practice 3 she measured, compared and ordered jump lengths. Emily did a 'jump' by running a program to make the robot go forward for a few seconds. The teacher cut a string the same length as the 'jump' and Emily measured it to be 8 rods long. Her Education Assistant and author 1 did physical jumps, and Emily measured those to be 8 and 7 rods long, respectively.

The teacher also did a jump (12 rods long) so that there would be a clear longest jump. She made statements about her measurements, but was not given the opportunity to order them in Lesson 3.

Doug performed all three lessons as planned, except he chose not to measure the straight or wavy snake with multiple copies of a unit in Lesson 3. He said it would be 'too hard', and he had already demonstrated that he knew that measuring length using single copies of a unit and multiple copies of a unit would give the same value. An example of his measurements using multiple copies of a straw unit in Lesson 1 is shown in figure 2.

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

Jane did all three lessons, but with some modifications. Since all the measurements were the same in Lesson 1 when using straw units, Lesson 2 was performed using smaller units. The teacher explained that smaller units would give more accurate measurements. Since a choice of units was not offered in Lesson 2, Jane did a practice activity measuring different body parts on a drawing of a giraffe, i.e., the total height (requiring large units) and the face (requiring small units). She was not asked to order these measurements. The concept of knowing to not overlap or leave a gap between units was not assessed in all lessons because after proving that the students knew the concept, magnet rod units which snapped together were used instead of straws.

---- 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. For 'Place unit lined up with baseline' (where baseline is the imaginary line at the end of the object), Emily drove the robot along the full length of the gingerbread man instead of stopping at the baseline for the first measurement in Lesson 1. Jane required repeated prompting for her first and second measurements in Lesson 1 and in Lesson 2, requiring a demonstration of where to stop the robot so that the end of the unit was lined up with the end of the object.

For 'Place next unit tip to tip with previous unit' Emily left gaps between the units and at first the teacher compensated by putting the straw where it should go. For the last time, the teacher placed the straw exactly where the robot stopped, and if there was a gap or overlap, Emily moved the robot backwards or forwards, and the teacher moved the straw accordingly. Doug did well with this concept, except for measuring the wavy snake (pipe cleaner) using single copies of a unit, Doug sometimes used the robot program to move ahead and then turned, which caused his marks to be closer together than one unit. He opted not to measure the snake with the multiple copies of a unit, because he said it would be 'too hard'. Jane required repeated prompting for placing units tip to tip in all lessons. For her first measurement in Lesson 1 she began by placing her second straw beside the first straw. On her second measurement, she left gaps between units and did not understand where the second straw should be placed. In Lesson 2 she overlapped the second straw with the first on a couple of measurements, but that was probably due to holding the robot forward button too long. She corrected the placement by backing up the robot. Jane needed heavy prompting to use the unit program to measure the snakes with single copies of a unit, she tended to use the little forward movements which resulted in some pen marks being closer than one unit apart and some farther. Eventually she learned a good strategy (make a mark, make a small turn, adjust with little movements so pen was over top of the mark, make a mark to see if the marks lined up, if they were lined up, move ahead using the unit program).

Jane also needed a lot of teacher support in order to place the multiple units tip to tip to measure the snakes. She chose to drive the robot to the pile of units herself instead of letting the teacher pick up the robot and put it in the start position with a new unit. Emily drove directly toward the pipe cleaner and placed the units at right angles to it then looked at the teacher to request that the unit be turned to make it tip to tip.

For 'Place last (integral) unit mark at baseline' all participants had some trouble at first with rounding up or down when counting multiple units in order to obtain an integer, but they quickly got the concept. One example was Jane's first measurement where she placed an eighth straw when the string was only slightly longer than seven straws. Jane also had trouble placing the last mark at the baseline when measuring with a single copy of a unit by using the robot program. She put the last mark exactly at the end of the pipe cleaner for the straight snake, and she did this again for the wavy snake, in spite of being prompted about the correct procedure after the straight snake.

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

Communicative events

Table 5 shows the duration of the 'talking' portions ('Introduction', 'Suggesting potential strategies', and 'Reporting results') and the 'doing' portions ('Manipulating with robot') of the main lessons and the rate in events/minute of each communication mode used in these portions. The modes were SGD, non-verbal communication, and robot (the research assistants coding the communication events indicated a couple of events where they felt the participants were using the robot to communicate a message).

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

In the introduction portion of the lesson, participants reviewed concepts and vocabulary from prior lessons. Only Jane suggested a potential way to solve a problem. In Lesson 3 Jane suggested using a pen if the teacher only had one unit to measure with, however she needed a hint about how to use it to measure. Primarily the participants agreed with the strategies eventually suggested by the teacher.

Examples of SGD output made by the participants during the reporting portion of the lessons are shown in tables 6 and 7. Reporting on order was primarily done by listing the numbers from shortest to longest. All of the participants gave limited responses for their reasoning for their answers. Emily's practice sessions are not shown in table 6, but after practicing with objects only 1, 2 or 3 rods in length, she began to demonstrate understanding of the concept of ordering using the length measurements. She reported which object was shortest and longest correctly and stated that she knew why the scissors were shortest, i.e., 'scissors 1'. After the teacher asked, 'Why was the shovel longest?', Emily responded '3'.

---- Insert table 6 about here ----

---- Insert table 7 about here ----

The events that the research assistants coded as using the robot to communicate a message were as follows: Emily backed up the robot to indicate where the straw should be placed in response to the question, 'Is this where you want it?'; Doug made the robot beep when he pressed the robot Stop command, which seemed to indicate a response to 'are you done?'; and Jane put the robot pen beyond it's limits to demonstrate the situation that she was worried about (since the teacher and her mom did not understand her non-verbal communication attempts to explain it).

Social validity

The social validity comments that were additional to those about Level 1 [16] primarily involved the length of time that it took to accomplish the lessons in this level. The stakeholders felt that the amount of time it took to do things with the robot was not always practical in the classroom, due to time constraints and the energy level of the participants. Some of the lessons had to be completed over a couple of sessions and this was not ideal since repetition of the same task within one session probably would have helped the participants to retain concepts and to generalize them to other problems. One solution they offered was to measure shorter objects, or reduce the number of objects they had to measure. The EAs noted that the participants retained some of the concepts after the study. Doug's and Jane 's EAs noticed that their understanding of measurement improved when they went back to school that year and the EAs attributed it to the participants being able to use the robot for hands on activities. The EAs had a lot of interest in implementing robot use for standard units of measurement, e.g., pulling a 30 centimetre ruler and metre stick with the robot.

The AT team pointed out the limitation that the robot could only measure objects that were lying down on the table. They would like to be able to measure objects in an upright position. Also, positioning to be able to see was an issue. They would like to see the students be able to move themselves or the objects on the table around because that is how non-disabled children would handle the situation (e.g., standing frames or powered mobility to move or lift themselves to a location where they could see better or from a different angle). The team felt that measuring curvy objects was very difficult for all participants, even for Doug who had excellent robot operational skill. Also, moving the pen up and down to make tick marks was difficult for all of the participants.

Discussion

As in the Level 1 mathematics measurement study [16], using an SGD-controlled Lego robot contributed to how these three students with physical and communication limitations could perform hands-on and communicative mathematics measurement activities. The students used the robot to perform the manipulative tasks, allowing the teacher to observe and assess their procedural knowledge. The manipulation events in table 4 where the participants did not 'get it' right away, correspond with the teacher's assessment of 'Not yet adequate' and 'Adequate'. For example, comments 27 and 29 in table 4 correspond with how Emily required one or two prompts before placing the first unit lined up with the baseline. Comment 31 in table 4 corresponds with how Emily did not perform the task of placing the last unit mark at the baseline, even after prompting. Though table 4 indicates instances when the participants did not 'get' placing units tip to tip, the teacher did not penalize the students for this error in the assessment, perhaps because she felt the errors were due to the inaccuracies of the robot, or troubles controlling the robot.

Some gaps in procedural knowledge were identified, particularly for Emily and Jane, who did not immediately demonstrate that one should place the first measurement unit lined up with the end of the object being measured. They also did not immediately demonstrate that one needs to place units tip to tip along an object in order to measure it. As in the Level 1 study, the EAs attributed these gaps to the EAs doing the procedures for the students, but not explaining what exactly they were doing. In level 1 the participants had trouble generalizing the concept of baseline (lining up the ends of objects) when the objects changed from concrete objects to strings that represented the length of objects. It appears that changing from lining up concrete objects/strings in Level 1 to lining up measurement units along the baseline of objects in Level 2 was also problematic. In addition, when changing from Lesson 1 to Lesson 2, Jane seemed to have trouble knowing that she could use the same procedure of placing units tip to tip no matter what the object was. Jane's problems with overlapping units when measuring with single units in Lesson 3 could be because it was her first time using programs stored in the robot and replayed from the SGD. Doug had fewer problems measuring with single units in Lesson 3 (only the wavy snake gave him problems), but he had used programs for Giant and Baby steps in Lesson 2. Jane's problem rounding up to the nearest integral number of units in Lesson 3 when measuring with single units is interesting. She performed better with this concept with multiple units than with single units and it could have something to do with environmental cues. When measuring with multiple units, the units fill the space along the snake and it is clear that there is no more room for another unit at the end of the snake. When measuring with single units, the participant only sees pen marks along the snake, and since Jane had access to all commands, the small forward command could just as easily be selected as the program command.

The students used their SGD to report and reflect on their measurements. In general, the amount of SGD communication decreased compared to the Level 1 activities, partly due to the lesson requirements. In Level 1, the students were expected to answer in sentences, in Level 2, they were asked to report by entering the measurements into worksheets on a tablet computer and then answer reflection questions. Although using the tablet was sometimes time consuming or awkward during the lesson, it was reinforced by the AT Team that filling in the worksheets was a beneficial activity because that is what the classmates would do. In general, all participants answered questions from the teacher with short answers (Emily once said a 4-word sentence, with prompting, in her third practice, and Doug and Jane generated some sentences, but there were fewer and shorter sentences than in Level 1). The teacher frequently had to ascertain participant understanding of concepts from their responses to yes and no questions.

The participants were not as strong at explaining their reasoning as they were at reporting. Emily needed prompting and questions to be broken into yes or no responses in both Level 1 and Level 2. Doug explained his reasoning fairly well in Level 1, however, he sometimes needed prompting (in the form of yes no questions) in Level 2. Jane did not offer strong reasoning in Level 1, did fairly well in her first lesson in Level 2, but needed prompting in the later lessons. Doug and Jane performed well in the pre-session story re-tell so they should have been capable of explaining themselves, and the core vocabulary on their SGD's should have been sufficient to answer the questions, so their lack of responses in Level 2 probably means that they did not have explanations of their reasoning about math concepts or problems.

Performing these lessons themselves with the robot, gave the students a chance to practice and apply the concepts in multiple activities and their SGD output and non-verbal communication allowed the teacher to assess their understanding of several measurement concepts:

> **Comparing and ordering**: In Level 1, comparing was done by moving objects side by side to look for differences in length. In Level 2, comparing and ordering was done by comparing numbers representing the length of items measured in non-standard units. Emily had trouble with this concept and needed three practice lessons. Even with practice, she basically compared lengths rather than ordering them, (e.g., 'block taller foot'). She only referred to the measurement values when prompted, and rather than ordering, identified the biggest number. Emily's teacher reported that ordering numbers was still a problem for her in the school year after the study and was part of her Individualized Program Planning goals.

Estimation: All of the participants' first estimates of height, before making any measurements, were very high (between 3 and 10 times too high - see comments 4, 14, and 21 in table 3) despite both Doug and Emily having previously done some estimating in school. After more estimating and using the robot to measure and confirm their estimates, their estimates improved. Emily's estimation accuracy decreased in Lesson 3, but accurate estimates in that lesson were dependent on understanding multiple concepts, which she did not understand (i.e., the same object, whether straight or curvy, will have the same measurement, and measuring an object with single and multiple units will give the same measurement). Doug became very accurate at estimating and sometimes estimated the exact number of units required. Doug's EA attributed his improvement in estimation over the course of the study to being able to do the hands on activities with the robot. Jane's EA supported this idea, but also commented that Jane's estimates 'start out a little bit wild, but then once we've worked on the concept a bit, then it gets down to a more realistic estimate.' So, perhaps Jane's estimates would have become better even if she was just observing someone do the measurements.

Changing orientation: Emily's teacher and Doug and Jane's EAs reported that none of the participants had much prior experience with the concept that changing the orientation of objects does not change their length. At first, all participants thought the measurement would change when the orientation changed (see comments 6 and 24 in table 3). Lessons 1 and 3 gave the students practice with this concept in multiple ways. Lesson 1 presented the concept as an object lying down versus standing up. Lesson 3 presented the concept as straight versus wavy snakes. Lesson 3 also involved understanding the concept that the snakes should be the same length regardless if they were measured with multiple or single units. Only Doug understood these concepts. Jane appeared to understand the concept that multiple and single units would give the same number when she measured the straight snake, but when the orientation was changed to a wavy snake, she did not retain understanding of the multiple and single units concept. Due to multiple concepts being covered at once and the added demand of using the robot to measure with single units (the manipulation required the use of the robot and pen was rated as 'hard' by the participants), the high cognitive load could have prevented Jane from remembering the concept, and generalizing it to the wavy snake.

Choice of appropriate unit and choice affects number: Both Doug and Jane chose appropriate units and gave reasons (table 6), but at first they did not understand the concept that the length of objects which were measured with different units could not be directly compared to each other. Doug got the concept quickly, but Jane did not. The AT team teachers commented that this is a difficult concept for students, but it is important because it relates to life skills such as dealing with units of time (converting minutes and hours to the same unit). Jane's EA commented how she continued to have problems with units of time.

As in Level 1, the fact that the participants had access to both the robot and SGD was very important. They were able to perform the measurement procedures themselves, and then almost immediately, report on their findings (rather than having to move their switches from controlling the robot to controlling the SGD). The robot was used as another communication mode, as if to say, 'no, this is what want'. In addition, the robot manipulation and SGD communication augmented each other. One example is when Emily used the SGD output to clarify what she was doing with the robot. When she was attempting to lay down her first straw to measure the gingerbread man, she was not on the baseline yet. This was possibly because the participant was far away from the straw and foot of the gingerbread man, and they possibly looked lined up due to parallax. The teacher asked her to clarify where she was aiming with the robot, and because Emily had her SGD available, she replied 'foot'.

The stakeholders considered robot use in these Level 2 measurement activities to be important, saying that they helped to reinforce concepts that the students used in subsequent school years. However, the feasibility of using the robot for all of the activities came into question. The length of time to complete the activities was not practical in the classroom, and having to continue a lesson in a subsequent session was detrimental to students retaining the concepts and applying them in new activities. Doug felt that he would rather watch the teacher measure the long items. That opinion and Doug's choice not to measure the snakes using multiple copies of a unit because it would be 'too hard' speak to how he is very pragmatic. Emily and Jane preferred to use the robot over watching the teacher demonstrate the concept for all performed activities. But, they were older than Doug and perhaps more interested in being independent. Regardless, accepting the advice of the stakeholders and ensuring that the items to measure are a reasonable length, and/or reduce the number of items to measure would be prudent. In addition, expecting the students to be able to measure the curvy objects with single and multiple copies of a unit was unreasonable. Even Doug, with his excellent operational skills, had difficulty with these tasks. Lifting the pen up and down and moving forward using a program required great coordination to select the appropriate robot commands, in the correct order. Perhaps leaving the pen down the whole time would be sufficient. This way each time the robot stops between programmed unit movements a tick mark will occur from the marker ink seeping into the paper. This could be an option for measuring straight objects with a single unit.

This study had the same inherent limitations as the Level 1 study. There was no experimental control, so the effect of the robot is not clear. Also, the lessons were tailored to each participant, rather than implemented exactly the same for all three participants, so treatment integrity could be called into question. However, the benefit of following the socially valid method of tailoring to the varied levels of abilities of students in the classroom outweighed that limitation. Finally, there was low inter-rater reliability between the teacher and the external teacher on the assessments of conceptual understanding, procedural knowledge and communication about concepts. As in the Level 1 study, they sometimes interchanged conceptual understanding and procedural knowledge. Also, the external teacher sometimes penalized the participant's procedural knowledge, but the research teacher realized that it was the robot's fault. Conversely, the research teacher sometimes penalized the participants on their communication because she needed to prompt them. The external teacher reflected that the differences could be because the research teacher was more familiar with the participants and the context. This low inter-rater reliability may not cause a concern for a classroom situation where a student is compared to own his/her prior performance over time by the same teacher. However, the low inter-rater reliability does indicate that further work should be done to make the assessments more reliable [25].

Future studies should examine different mathematical areas (e.g., measurement with standard units such as centimetres, addition, and subtraction) and the benefits and limitations of robot use should be compared to other methods of manipulating objects, such as observing teaching staff do it, or using a program on the computer.

Conclusion

This follow up study involving new mathematics procedures and concepts revealed similar benefits to the earlier study [16]. Having access to the robot gave students the opportunity to participate interactively with objects to learn the measurement procedures and to communicate about the concepts. The gaps in their procedural knowledge, i.e., putting measurement units tip-to-tip and generalizing procedures to multiple objects, were remedied with repeated practice. Inadequate understanding of concepts was identified when the students communicated with the teacher. The EA and AT team thought that the improvements in conceptual understanding occurred because the students could do their own hands-on 'experiments', rather than observing someone else's. Using both the robot and SGD together complemented each other: SGD output could help clarify intentions with the robot, and the robot could be used as another mode of communication. However, a robot should not be used for all tasks, as indicated by the stakeholder opinions about measuring long or curved objects, but this study shows that it is a flexible tool that is easily adapted to new activities. With extended use, a robot may help students who have motor disabilities and/or CCN to learn and develop mathematics skills.

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Declaration of Interest

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References

[1] 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. Charlottesville, VA.2008.

[2] 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. Augmentative and Alternative Communication 2007;23(2):126 – 139.

[3] Eriksson L, Welander J, Granlund M. Participation in everyday school activities for children with and without disabilities. Journal of Developmental and Physical Disabilities 2007;19:485–502.

[4] 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.

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

[6] Western Canadian Protocol for Collaboration in Basic Education. The common curriculum framework for k–9 mathematics. 2006.Cited 2008 March 21 <http://www.wncp.ca/math/ccfkto9.pdf>.

[7] Howell R, Hay K. Software-based access and control of robotic manipulators for severely physically disabled students. Journal of Artificial Intelligence in Education 1989;1(1):53-72.

[8] Howell R, Martz S, Stanger CA. Classroom applications of educational robots for inclusive teams of students with and without disabilities. Technology and Disability 1996;5:139-150.

[9] 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.

[10] Eberhart SP, Osborne J, Rahman T. Classroom evaluation of the arlyn arm robotic workstation. Assistive Technology 2000;12:132-143.

[11] Adams K, Cook A. Programming and controlling robots using scanning on a speech generating communication device: A case study. Technology and Disability 2013;25:275–286.

[12] Adams K, Cook A. Use of robots in 'hands-on' academic activities: A case study examining the skills required to use a speech generating device to control a robot. Disability and Rehabilitation: Assistive Technology 2014(Dec 11):1-11.

[13] 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.

[14] 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. Augmentative and Alternative Communication 2002;18:20-35.

[15] 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. Journal of Special Education Technology 2000;15(1):31-44.

[16] Adams K, Cook A. Access to hands-on mathematics measurement activities using robots controlled via speech generating devices: Three case studies. Disability and Rehabilitation: Assistive Technology 2014;9(4):286-298.

[17] Schmidt S. Shall we really do it again?: The powerful concept of replication is neglected in the social sciences. Review of General Psychology 2009;13(2):90-100.

[18] Pearson Education Canada. Math makes sense 2. Toronto, Ontario Pearson Education Canada; 2008.

[19] Dunn L, Dunn L. Peabody picture vocabulary test. 1997

[20] 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) Conference. Barcelona, Spain2010.

[21] Baker B, Hill K, Devylder R. Core vocabulary is the same across environments. Technology and Persons with Disabilities Conference. Northridge, CA2000.

[22] 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. Perspectives on Augmentative and Alternative Communication 2012;21:99-104.

[23] Clarke M, Kirton A. Patterns of interaction between children with physical disabilities using augmentative and alternative communication systems and their peers. Child Language Teaching and Therapy 2003;19:135-151.

[24] 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. Maastricht, The Netherlands2011.

[25] Loshny K, Adams K, Carbonero M. Assessment tool for elementary student with physical disabilities in mathematics. 33rd Annual Closing The Gap Conference Minneapolis, MN 2015.

Tables

Table 1: Participant information including classroom experience, SGD features, mathematics measurement and pre-existing language skills

		Emily	Doug	Jane
Classroom experience	**Grade in school**	8	4	6
	Classroom setting	Self-contained	Integrated regular-stream classroom	Integrated regular-stream classroom
	Assistance	One EA shared with another student	Dedicated EA, for >5years	Dedicated EA, for >5years
SGD	**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
	Year of experience	2 years	5 years	5 years
Measurement experience?		None. Understood counting up to 20. Working on addition.	Had done measurement within 2 years	Had done measurement within 2 years
Pre-existing language skill	**Social opener on re-tell task**	"Alice [a] you (?. That's interesting tell me more.) Listens."	"I'm going to tell you a story."	"I tell you a story."

[a] Alice is a pseudonym for Emily's EA

Statements by participant are in "quotes"

Mistakes that were not corrected are in (brackets)

Table 2: Description of the focus, materials, and the problem to solve from Math Makes Sense 2 (Pearson Education Canada, 2008), the environment or robot adaptations needed, and what the participant was expected to do with the robot

	Lesson 1	Lesson 2		Lesson 3
Concept of Focus	Measure with multiple copies of a non-standard unit, compare and order lengths	Estimate, select appropriate non-standard units, measure with multiple copies of a non-standard unit, compare lengths, and relate the size of unit used to the number of units needed		Estimate, measure using a single copy of a non-standard unit, compare straight and non-straight items
Materials	Picture of a gingerbread man about the height of the students, string, scissors, tape, craft sticks, and straws	None	Straws, rods, toothpicks	A pipe cleaner to be a straight snake and a wavy snake [Make sure the student can see the teacher when she bends the pipe cleaner], some toothpicks and a pencil
The problem to solve	How do you find out who is tallest, the gingerbread man, you, or a friend? Is the gingerbread man the same height laying down as he is standing up (orientation)?	Start at one end of the room and take 3 giant steps, 2 bunny hops, or 1 baby step. The first to reach the other end of the room wins.	Estimate and measure the giant and baby steps. In your group, who has the longest giant step?	How long is the snake when it is straight and when it is wavy? Part 1: Estimate, then measure using one unit. Part 2: Compare the length to that obtained with multiple units.
Environment or robot adaptation	- Straw units affixed to the top of 1.5" square blocks. - Robot gripper	- Three robot programs created which go forward different distances (a giant, medium, or baby step)	- Toothpick and magnetic rod units affixed to the top of blocks. - Robot gripper - Teacher, and investigator also took baby and giant steps. - Teacher cut lengths of string as long as each step taken (i.e., the robot baby and giant steps).	Part 1: - A pen attached to the front of the robot which could be raised/lowered (on side of robot so participant could see the pen marks as they drew them) - A robot program to move ahead one toothpick length Part 2: Toothpick units affixed to the top of blocks
What the participant was expected to do with the robot	- Grasp a straw unit with the robot gripper - **Place unit lined up with end of the picture** (or string representing length) - **Place next unit tip-to-tip** with the previous unit (repeat) - **Place last (integral) unit as close as possible to the end of picture** (string)	- Start robot at one end of the table - Select between the three different robot programs and try to finish as close as possible to the other end of the table	- Grasp a toothpick/rod unit with the robot gripper - **Place unit lined up with end of the string** - **Place next unit tip-to-tip** with the previous unit (repeat) - **End lined up at integral unit** as close as possible with the end of string	Part 1: - **Place unit mark lined up with end of the pipe cleaner** (Drive robot so the pen tip is lined up at the end of the pipe cleaner, move the pen down and up to make a pen mark) - Run the program to move ahead one toothpick length and then **place next unit mark** (repeat) - **Place last (integral) unit mark as close as possible to the end of the pipe cleaner** Part 2: Measure with multiple copies of toothpick unit as in Lessons 1 and 2

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

		Participant	Emily				Doug			Jane			
		Lesson	1				1	2	3	1	2		3
		Activity	M	P1	P2	P3	M	M	M	M	M	P	M
Conceptual understanding	Compare Order	Excellent				x			x				
		Proficient						x		x			
		Adequate	x [1]		x [3]		x [13]				x [18]	x [19]	
		Not yet adequate		x [2]									x [20]
	Overlap/ Gap (tip to tip)	Excellent		Used Magnetic rods			x	Rods			Rods	x	x
		Proficient	x							x			
		Adequate											
		Not yet adequate											
	Estimation	Excellent						x	x				
		Proficient											
		Adequate				x [5]	x [14]					x [22]	
		Not yet adequate	x [4]							x [21]			x [23]
	Orientation	Excellent							x				
		Proficient					x						
		Adequate	x [6]										
		Not yet adequate								x [24]			x [25]
	Appropriate Choice of unit	Excellent						x			Choice not given	x	
		Proficient											
		Adequate											
		Not yet adequate											
	Choice of unit affects #	Excellent						x					
		Proficient										x	
		Adequate											
		Not yet adequate									x [26]		
ral Knowle	Compares Measurements	Excellent	x	x	x			x	x	x			
		Proficient				x						x	x
		Adequate					x [15]				x [27]		
		Not yet adequate											

Order	Excellent						x		All same			
	Proficient											
	Adequate					x[16]				x[28]		
	Not yet adequate	x[7]	x[8]									
Multiple Units	Excellent	x	x	x		x	x	Chose not to do			x	
	Proficient				x					x		
	Adequate								x[29]			x[30]
	Not yet adequate											
Single Units	Excellent							x				
	Proficient											
	Adequate											x[31]
	Not yet adequate											
Commun-ication	Excellent											
	Proficient						x	x	x	x	x	
	Adequate	x[9]		x[11]	x[12]	x[17]						x[32]
	Not yet adequate		x[10]									

Comments on 'Not Yet Adequate" and 'Adequate' ratings

1) Does not understand that she is using non-standard units to measure, not concrete items (like strings)
2) Does not connect that the number represents length.
3) Could do concept, but needed support
4) Estimated gingerbread man drawing would be 100 straws tall
5) Estimate OK (9 when actual was 12) but couldn't explain reasoning.
6)After measuring the gingerbread man lying down (9 straws), she said standing the gingerbread man would be 100 straws long
7) Did not know if 8 or 9 was bigger (until looked at a numbers line)
8) Struggled to order them, but knows 3 greater than 2
9) Said EA was tallest because she's an adult (did not use the numbers)
10) Said "longer fork foot" when asked how do you know, she said she was guessing
11) Struggles to communicate her reasoning
12) Struggles to communicate her reasoning, but can answer Y/N questions

13) His attempt to use fractions may have confused him
14) First time he Estimated 40 (actual 7) but became good at estimating after this.
15) He needed concrete visuals to fully understand concept
16) He needed concrete visuals to fully understand concept
17) Required prompting

18) Needed reminder about how to measure
19) Forgot that numbers must use same unit
20) Did not understand that single and multiple copies give the same number
21) Estimated 30 (actual 9) in sticks. Then Estimated 10 in straws when it should be < 9.
22) The toothpicks are much shorter than the rods, therefore the estimate should be higher. She said 12 but the actual value was 18
23) Did not get concepts of straight = wavy and single = multiple therefore estimates off
24) Said 10 (actual 7), it took 3 demonstrations to understand concept
25) Did not understand that straight = curvy measurements
26) Said numbers measured in rods and straws could be compared
27) Did not put first rod at the end of the string
28) Needed prompting to use data to answer
29) Did not put unit at end of string
30) Errors probably due to robot control
31) Last dot at end of pipe cleaner not end of unit.
32) Gave 1-word answers, needed prompting

Shaded areas were not applicable in those lessons.

Table 4: Tasks in each lesson 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 performed

		Lesson 1			**Lesson 2**	**Lesson 3, Part 1**		**Lesson, Part 2**	
Manipulative Task	**Participant**	Ginger-bread man	Student	Friend		Single copies - straight snake	Single copies - wavy snake	Multiple copies - straight snake	Multiple copies - wavy snake
Place unit lined up with baseline	Emily	o	+	+					
	Doug	+	+	+	+	+	+		
	Jane	o	o	+	o	+	+	+	+
Place next unit tip to tip with previous unit	Emily	o	o	o					
	Doug	+	+	+	NA	+	o		
	Jane	o	o	+	o	o	o	+	-
Place last (integral) unit mark at baseline	Emily	+	+	+					
	Doug	+	+	+	+	+	+		
	Jane	o	+	+	+	-	-	+	+

Table 5. Duration of time and rate of communication in the ‘‘Introduction’’, ‘‘Suggesting strategies’’, ‘‘Manipulating with robot’’ and ‘‘Reporting’’ portions of the lesson.

		Introduction			Suggesting strategies			Manipulating with robot			Reporting		
		Lesson 1	Less on 2	Lesso n 3	Lesso n 1	Lesso n 2	Lesso n 3	Lesso n 1	Lesso n 2	Lesso n 3	Lesso n 1	Lesso n 2	Lesso n 3
Emily	Duration (h:mm)	0:14						0:48			0:21		
(events / min)	SGD	0.6						0.1			0.4		
	Non-verb.	0.2						0.1			0.7		
	Robot							0.1					
Doug	Duration (h:mm)	0:25	0:03	0:15			0:01	0:27	0:33	0:09	0:18	0:18	
(events / min)	SGD	0.5	0.3	0.5					0.1		0.1	0.1	
	Non-verb.	1.1	2.3	1.1			2.0	0.4	0.3	0.2	0.7	1.2	
	Robot									0.1			
Jane	Duration (h:mm)	0:03		0:07			0:02	0:43		0:57	0:10		0:23
(events / min)	SGD						0.5			0.1	0.8		0.7
	Non-verb.			0.1				0.1		0.4			0.4
	Robot							0.1					

Communication rate is given in events/min, for SGDs (event = utterance), non-verbal communication (event = gesture), and robot (event = robot movement that was perceived as a communicative message)

Table 6: Participant reporting and reasoning given in Lesson 1 and Lesson 2. Descriptions of the teacher's prompting, or participant's non verbal interactions are given in square brackets, and participant SGD output is given in quotes.

Lesson	Questions Asked	Emily	Doug	Jane
1	**Can you order your measurements?**	[Needed support to order. The values were 8, 8, and 9.]	"**6, 5 ½, 7, 7 ¼**" [After teacher drew a picture (Figure 2), he understood that 5 ½ was less than 6.]	"**We are all the same**." [The values were 7, 7, and 7. The activity was repeated with smaller units resulting in 13, 14 and 14 rod units.]
	Who is tallest? Shortest?	Tallest: Gazed at EA	Tallest: Gazed to adult friend Shortest: Gazed to young friend	"Same G[ingerbread man] and me", "Mom is the shortest"
	How do you know?	**"Adult"** [It is something to do with numbers. Which is the bigger number?] **"Nine"** [Answered yes and no questions about the shortest, but incorrectly.]	**"I looked."** [He's tallest because he's an adult?] Nodded head	"Mom 13" and "2 14s".
2	**Can you order the giant steps?**	Lesson not performed	[Answered yes and no questions appropriately]	[In Lesson 2 Practice ordering was not required]
	Can you order the baby steps?		**"1 1 2"**	
	Why did you choose that unit?		**"Straws are longer than the rod."**	**"straws longer"**
	Can you compare measurements made with different units?		Shook head **"Straws are longer than the rod."**	[Answered yes and no questions correctly, but did not give a reason.]

Table 7: Participant reporting for Lesson 3

		Doug			Jane		
	Number of units	**Order performed**	**Estimate (toothpicks)**	**Measurements (toothpicks)**	**Order**	**Estimate (toothpicks)**	**Measurements (toothpicks)**
Straight Snake	**One**	2nd	"7" "6"	"6"	1st	"6"	"7"
	More than one	1st	Not performed	"5" [This was a demonstration by the teacher, and was incorrect]	2nd	"7"	"7"
Wavy Snake	**One**	3rd	"6"	"6"	4th	"9"	"7"
	More than one	4th	"6"	[Chose not to do this but he indicated that it would be the same number as the others] "6"	3rd	"10"	"7"

Figures

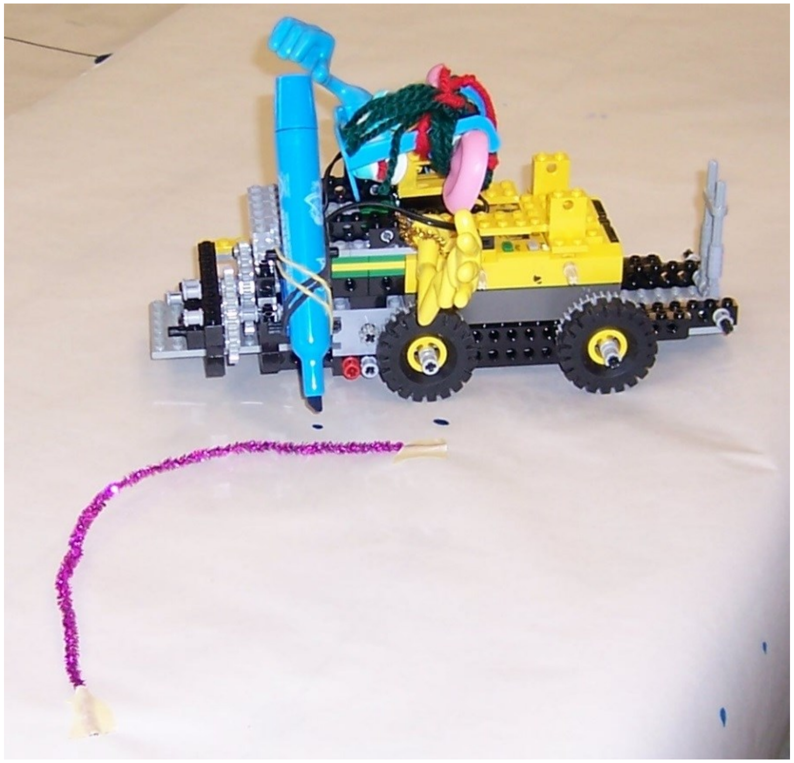

Figure 1: Robot with pen attachment. A pipe cleaner, representing a wavy snake, is taped to the table using masking tape. The figure shows a unit mark placed lined up with end of the pipe cleaner, and then the next unit mark is one toothpick length from the first one.

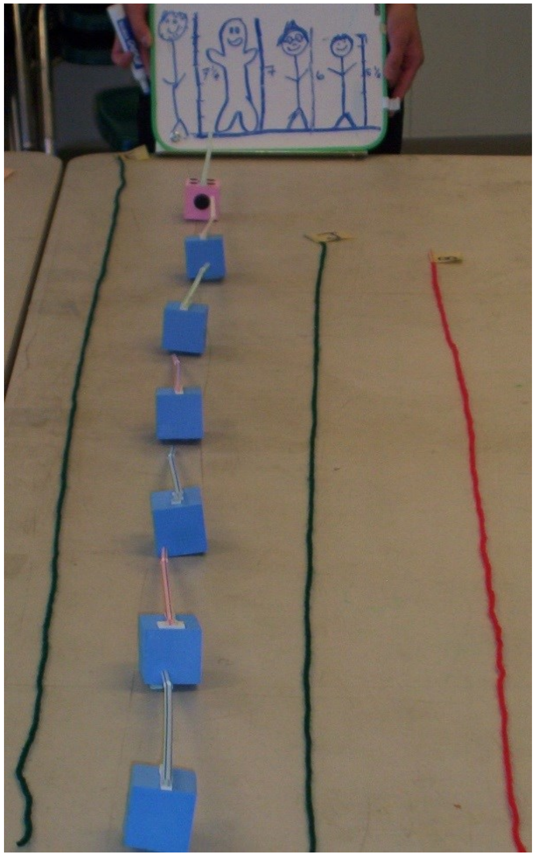

Figure 2: Doug's results when measuring heights with multiple straw units in Lesson 1. The strings represent the height of the participant and two friends. The teacher is holding a picture she drew to help Doug understand that 5 1/2 was less than 6.