I hear and I forget

I see and I remember

I do and I understand

- Chinese Proverb

University of Alberta

Access to Math Activities for Children with Disabilities by Controlling Lego Robots via Augmentative and Alternative Communication Devices

by

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DEDICATION

To my parents, Caroline and Ken,
for their love and support in this and other endeavors

ABSTRACT

Children who have complex communication needs often use Augmentative and Alternative Communication (AAC) devices and strategies to address their communication requirements. If they have concurrent physical impairments, they may have difficulty accessing educational materials, especially when manipulation of items is used to enhance learning. This study consisted of three case studies with children who used their own speech generating device (SGD) to control a Lego robot to do math measurement lessons. System use was examined by measuring participant performance in math measurement lessons, describing the process of using the system, and contrasting system use with other methods of accomplishing math measurement activities. The study informed the underlying theories driving the study: that being able to do hands-on activities in learning is beneficial, that integration of AAC and manipulation in educational activities is important, and that assistive robots can bridge the functional gap between participant abilities and activity requirements.

The teacher measured participants' procedural knowledge based on how they manipulated items using the robot. She measured participants' conceptual understanding, use of appropriate language, and explanation of reasoning based on their communication. The participants used SGD output, non-verbal communication and the robot to communicate. The study showed that manipulation and communication can be interrelated and that having access to both enhanced the participants' message. Using the robot as a tool in these math lessons had some limitations, but they were easily compensated for by the teacher.

The efficiency of using the robot to accomplish tasks was lower than observing the teacher, but there were benefits in terms of effectiveness and participant satisfaction. Stakeholders felt that using the robot was a more effective way for participants to "show what they know" than observing the teacher and guiding her based on her questions. Using the robot also had some perceived benefits in terms of effectiveness as a learning tool with regards to motivation, engagement, and hands-on experience. In general, participants were more satisfied using the robot than watching the teacher do the math activities. However, improving robot task efficiency would further improve user satisfaction and this challenge will be addressed in future studies.

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LIST OF ABBREVIATIONS

AAC	Alternative and Augmentative Communication
AT	Assistive Technology
CP	Cerebral Palsy
EA	Educational Assistant
HAAT	Human, Activity, Assistive Technology
hh:mm	Hour Minute (time format)
HTI	Human Technology Interface
IR	Infrared
L1L1, L2L2	Level 1 Lesson 1, Level 2 Lesson 2, etc.
LAM	Language Activity Monitor
NA	Not Applicable
OT	Occupational Therapist
PPVT	Peabody Picture Vocabulary Test
QRC	Quarter-Row-Column (scanning)
RC	Row-Column (scanning)
SGD	Speech Generating Device
SLP	Speech Language Pathologist
TM	Trademark
USB	Universal Serial Bus

1 INTRODUCTION

Typically developing children learn physical, cognitive, social, and linguistic skills through active engagement in play and educational activities. However, children who have severe physical and communication limitations often cannot engage in activities like their able-bodied peers. In play, physical disabilities may prevent them from independently manipulating objects and communication impairments may prevent them from exploring language and interacting with others (Musselwhite, 1986). As students, it can be difficult for them to be actively involved in learning activities, especially when hands-on activities are used to enhance learning and demands on verbal and written communication increase (Eriksson, Welander, & Granlund, 2007; Schlosser et al., 2000).

Conceptual frameworks for effective learning show the relative advantage of being able to actively participate, by doing hands-on activities and communicating about them, in direct purposeful experiences as opposed to demonstrations, e.g., the "Cone of Experience" developed by Dale (1946) and its many derivations over the years. Therefore increasing the active component of the learning experience for children with disabilities by providing access to manipulation and communication should have a large impact on a child's education.

1.1 Access to Learning for Children with Disabilities

There is assistive technology (AT) such as Alternative and Augmentative Communication (AAC) devices and strategies to address the communication needs of people who have complex communication needs (Cook & Polgar, 2008).

AAC ranges from no-tech gestures and vocalizations, to low-tech communication boards with symbols and/or letters, to high-tech speech generating devices (SGDs) with color displays and speech synthesis. For children with severe physical limitations who cannot point to items on a keyboard or display, AAC devices can be accessed with one or two switches to do scanning. With scanning, choices are sequentially presented to the user and the user selects an item by pressing their switch. Children build language and social skills while they direct play activities and make comments using AAC (e.g., "green dress", "beautiful"). There are many clinical tools to support using AAC in play activities (e.g., Burkhart, 2006; Rush, 2006). However, there is evidence that obtaining educational gains for children who use AAC has been problematic. Kent-Walsh and Light (2003) interviewed 11 teachers in the United States who had children who used augmentative communication devices in their classrooms and found that teachers had "concern regarding the lack of academic gains for their students" and "although they felt that students using AAC developed some scholastic, speech and AAC system operational skills, they were uncertain about whether or not these students were being academically well-served, overall" (p. 118). Researchers have indicated that participation in educational activities of children who use AAC is low (Olsson, 2010; Schlosser et al., 2000).

Having good academic skills is an important factor when students finish school and go into the workforce. McNaughton, Light and Arnold (2002) interviewed eight people who have cerebral palsy (CP) and use AAC and the participants felt that their education was critical to success in employment and many were critical of the special education services that they had received (i.e., expectations were not high enough). Researchers have indicated that a barrier to employment for people who use AAC was poor academic skills, including literacy and math (Bryen, Potts, & Carey, 2007; Meyer & Loncke, 2008). Development of literacy skills for students who use AAC has been an area of focus for several years (Erickson, Hatch, & Clendon, 2010; Koppenhaver, Hendrix, & Williams, 2007; Light, McNaughton, Weyer, & Karg, 2008), but math skills have not yet been addressed. There have been no comprehensive studies investigating the development of mathematical ability in children with severe disabilities (Jenks et al., 2007).

There is evidence that children with physical and language impairments have difficulties with math. For example, Jenks et al. (2007) and Arp and Fagard (2005) identified difficulties for children who have CP, and (Donlan, 2003) has identified difficulties for children who have language impairments. The difficulties could stem from cognitive impairments resulting from the disability, or the difficulties could stem from environmental factors such as limited time spent learning math or not being able to physically access learning materials. Children with disabilities were observed to participate less than their peers in structured activities such as math and science (Eriksson et al., 2007). They may also have less time for math instruction than their peers due to the time it takes for toileting, eating, and therapy (Jenks et al., 2007; Light & Lindsay, 1991). This is problematic because "the amount of schooling can have a strong effect on young children's accuracy on arithmetic" (Bisanz, Sherman, Rasmussen, & Ho, 2005, p

152). In exploring the literature on the development of mathematical thinking in typical children (Bisanz et al., 2005; Ginsburg, Klein, & Starkey, 1997), one is struck by the importance of being able to physically manipulate items to learn math concepts. Children with physical limitations may miss this important "hands-on" aspect of learning math.

Research in developmental psychology and education support that physically manipulating items for learning is an important step in attaining early math concepts. For example, Ginsberg et al. (1998) presented Bruner's (1966) formulation that "mathematics learning involves a progression in forms of representation, from enactive, to iconic, and then to symbolic" (p. 408) and added that "child's learning often involves the manipulation of objects, and is always active, self-regulated, and particularly sensitive to disequilibrium between the current cognitive state and the immediate demands of the environment" (p. 408). He goes on to discuss effective educational materials where "the intention is to show the child (and the teacher) that one can learn about number by performing 'experiments' on physical objects, that even fingers are an acceptable tool for conducting such investigations and for promoting mathematical thinking" (p. 439). Children with physical disabilities cannot perform experiments on objects, or fingers, so providing a means for manipulating objects may be of ultimate importance.

1.2 Access to Manipulation and Communication for Learning

There is assistive technology for children to manipulate objects in their environment, but it is limited. For example, AT such as a switch mounted near a child's head and a battery interrupter can enable him to activate an electrical toy for play. Or, in school, a child can activate electric scissors so another student can cut items for a collage. Once school activities become more sophisticated, children with physical disabilities may have to observe while their classmates or an educational assistant perform activities involving manipulation of items. Children can use their AAC to participate in an activity by telling a classmate or an educational assistant (EA) which objects to use or how to perform an activity (Schlosser et al., 2000). However, directing an assistant using an AAC device can be slow for scanning users. The rate of communication for a speaking person is 150-200 words per minute, whereas the rate of output using alternative access methods can be as low as 1 to 8 words per minute (Koester, 2004).

Research has shown that children with severe disabilities can use robots as a tool to exert control over activities and robots are more motivating than single switch toys or computer programs (Cook, Bentz, Harbottle, Lynch, & Miller, 2005; Howell, Martz, & Stanger, 1996; Plaisant et al., 2000). Recent studies have utilized low cost robots. For example, Cook's assistive robotics research program showed that children had similar positive gains while using educational Lego[1] robots as in previous robot studies (Cook, Adams, Volden, Harbottle, & Harbottle, 2010). Since teachers, therapists and parents can easily replicate the Lego robots, it follows that children may engage in a greater variety of activities, on more occasions, for longer periods of time, thus maximizing the likelihood that robotic play will influence development of physical, cognitive and social skills.

It was at the point when Cook began using Lego robots that the author

[1] The LEGO Group, www.Lego.com

joined the research team. Two results in the Lego robot studies were noted by the author that indicated the need to integrate robotic manipulation with augmentative communication. The first result was that children who were emerging communicators made an increased number of vocalizations during and after robotic play activities (Cook, Adams et al., 2010). Providing AAC during this motivating activity could enhance early communicative skills. Second, if a child had a communication device, it had to be removed so the participant's switches could be used to access the robot controller, resulting in missed communication opportunities. For example, a participant accessing robotic control instead of her speech generating communication device (SGD) strayed from the pre-planned robot play activity, ignoring prompts from investigators (Cook, Adams, & Harbottle, 2007). Luckily, the participant's mother interpreted the child’s non-verbal intentional behavior for the investigators. If the mother had not been present, the investigators would have missed the participant’s communicative bid for innovative play.

The previous example demonstrates a known problem when using SGDs, that children have to turn away from play items in order to communicate and vice-versa (Light & Drager, 2002). There is a call for combining AAC and play. Light and Drager (2002) challenged the AAC industry to "investigate the impact of greater integration of functions so that children can engage in life activities such as play and communication seamlessly rather than be forced to choose between them" (p. 20). Five years later they repeated the challenge and noted that "to date, there are no controlled research studies that have investigated the effects of integrating AAC with play and other daily activities" (Light & Drager, 2007, p. 207). Another push for integration comes from the assistive robotics field, "to provide true independence, it will also be necessary to integrate the robotic technology with other assistive technology including control of the power wheelchair, environmental control unit, computer access, and so on" (Stanger & Cawley, 1996, p.135). Since most SGDs are equipped with infrared (IR) output they can send commands to IR controlled Lego robots. In this way, children can participate in activities in an integrated way without having to disengage from manipulating with the robot in order to communicate with their SGD, and vice versa.

In addition to being able to manipulate, being able to communicate while performing math is important so children can "verbalize to internalize" (Bley & Thornton, 1994, p 145), ask for help, or talk aloud so teachers can ascertain their level of understanding (Ginsburg et al., 1998).

Present math instruction paradigms emphasize the integration of problem solving, procedures, concepts and communication to build math literacy. Schools in Alberta follow the "The Common Curriculum Framework for K-9 Mathematics" (Western Canadian Protocol for Collaboration in Basic Education, May 2006) which is based on the National Council of Teachers of Mathematics Standards (NCTM, 1989). These standards provide a framework for looking at mathematics learning and "have clearly been influenced by psychological research" p. 431 (Ginsburg et al., 1998). For instance, the Math Makes Sense curriculum resource presents their four key components to build mathematical literacy: 1) **Problem Solving:** Each lesson introduces new concepts by presenting a problem to solve, 2) **Understanding concepts:** A variety of activities allows students to bring their own experiences to new concepts and employ different tools and strategies, 3) **Application of Procedures:** Gives purposeful practice for students to apply, clarify and extend the learning, and 4) **Communication:** Guides student to represent their thinking in pictures, numbers, or words (Pearson Education Canada, 2007).

With an integrated communication and robotic manipulation system children can be better prepared for the integrated paradigm of math instruction, and the learning strategies employed by typical children described by Ginsburg (1997): "work with objects to construct ideas of number, devise your own problems, think about what you are doing, and express what you have learned" (p. 440). There is evidence that children with disabilities attain mathematical thinking. Bley and Thornton's (1994) instructions to teachers indicate that most students with physical disabilities (e.g., musculoskeletal conditions, congenital defects, neurological impairments such as cerebral palsy) will achieve the same level as their peers, although they may be slower or require AT. AT can potentially allow children to "work with" objects (using a Lego robot) and "express" themselves (using an SGD). Perhaps then they can "devise their own problems" and develop mathematical thinking. For purposes of this study, the math activity area was limited to the measurement of length since it could be performed adequately using a Lego robot car, the robot used in previous studies.

It was necessary to restrict the activities in order to address them in detail, but many other math activity areas could be addressed.

1.3 AT Frameworks used in the Study

As reported by Fuhrer (Fuhrer, 2001) "published studies of assistive technology outcomes tend to be atheoretical in character. That may be attributable partly to the fact that assistive devices have a tangible character that encourages common sense, largely implicit consideration of how they result in benefits for their users", p. 534. The field has not yet developed treatment theories that provide explanations for how AT interventions are related to outcomes. However, there are several models and frameworks which are widely used, and which were applied in this study.

1.3.1 The HAAT Model

Measuring the contribution of assistive technology to outcomes in activities is complex due to interacting factors. A model used frequently to consider the multiple factors contributing to the AT system is the HAAT model (**H**uman, **A**ctivity, **AT**, and context) as shown in Figure 1-1 (Cook & Polgar, 2008). In prescribing assistive technology, one begins by considering the **Activity** that the human wishes to perform. The activity is composed of tasks and sub-tasks, each having a required set of skills and abilities. Next, one evaluates the **Human,** to determine their physical, sensory, and cognitive skills and abilities as well as their preferences. The **Context** in which the human will perform the activity must be considered. For example environmental, social, cultural, or institutional factors could influence system functioning. Finally, **AT** which takes the contextual factors into account is prescribed to bridge the gap between the human's skills and abilities and the activity requirements. The AT consists of the Human Technology Interface (HTI) (in this study, the switches and scanning access method) and has activity outputs (in this study, manipulation via the robot and communication via the SGD). The HAAT model was used in this study to consider all elements which may affect the use of the robot in the math activities.

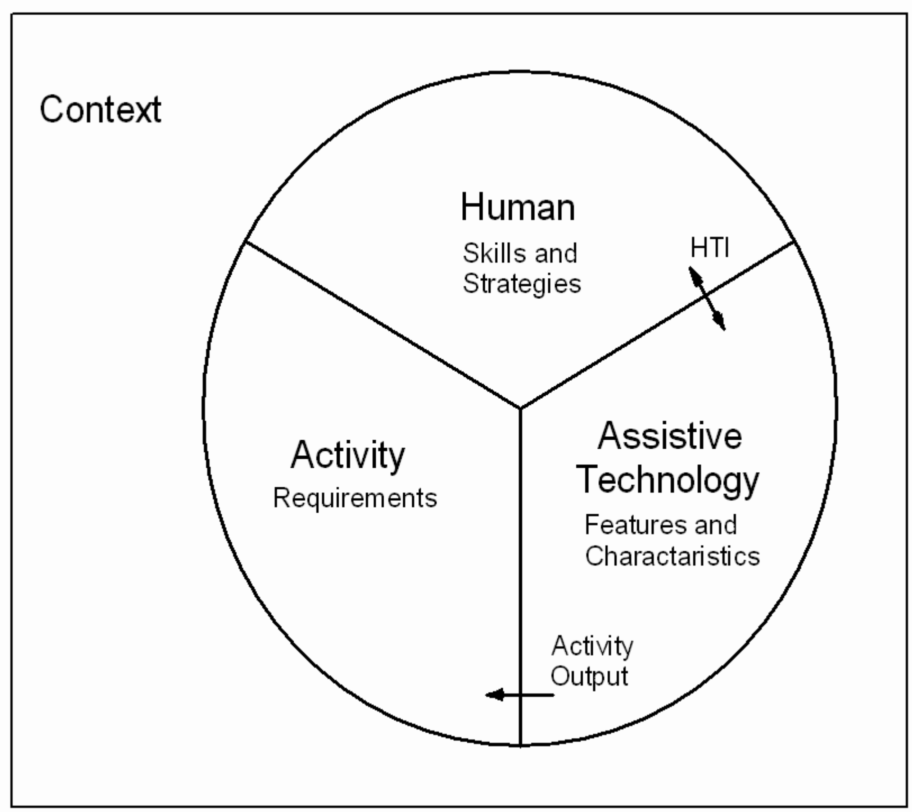

Figure 1-1: HAAT Model of an AT system, adapted from Cook & Polgar (2008) with permission.

1.3.2 The Dynamic Support Triangle Framework

A person generally needs more than just assistive technology to accomplish functional activities, they also need strategies and sometimes additional personal assistance. The amount contributed by each component changes depending on the activity and context. This dynamic relationship is captured in Enders' Dynamic Support Triangle Framework (Enders, 1999). In the framework, a Functional Ability triangle (specific to someone who has a disability) is embedded in a larger Human Accomplishment triangle (general for all individuals) (See Figure 1-2). The sides of the Functional Ability triangle represent AT, Personal Assistance Services (PAS), and Adaptive Strategies (AS). The sides of the Human Accomplishment triangle represent Generic Tools, Cooperation, and Strategies. All sides of the triangles are dynamic depending on the person's participatory role and context. The Dynamic Support Triangle framework was used in this study with the understanding that the participants would not be able to accomplish all portions of the measurement activities using only the robot.

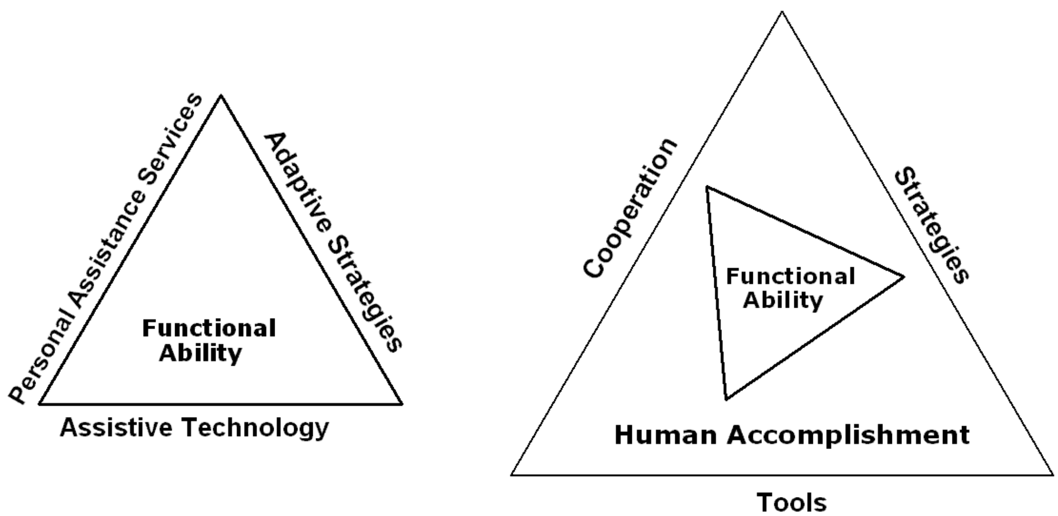

Figure 1-2: Dynamic Support Triangle Framework (Enders, 1999), included with permission. The Functional Ability triangle consisting of Assistive Technology, Personal Assistance, and Adaptive Strategies (specific to someone who has a disability) is embedded in a larger Human Accomplishment triangle.

1.3.3 Communicative Competency Domains

The competency of a user of AAC can be described with Light's (2003) AAC competency domains: 1) linguistic competence is understanding and using symbols "to communicate their ideas, thoughts and feelings" (p.11); 2) operational competence is operating the device accurately and efficiently; 3) social competence is using the tool effectively to communicate with others (discourse strategies, communicative functions, social relations); and 4) strategic competence is using strategies to minimize the limitations in the other domains. This framework was used to measure the participant's AAC competence prior to performing the math lessons.

1.3.4 Human Factors Principles

A human factors approach was utilized in a study using AAC where the dependent measures were classified as task **performance** measures (e.g., the listener's narrative comprehension test score) and **process** measures (e.g., number of words produced, words per minute) (Higginbotham, Bisantz, Sunm, Adams, & Yik, 2009). The performance measure used in this study was a curriculum based rubric and multiple qualitative measures were used to assess the process.

Arthanat et al. (2007) state that usability of AT is critical to increased functioning in activities and utilize the definition of device usability from human factors engineering: "the **effectiveness, efficiency and satisfaction** with which specified users achieve specified goals in particular environments" (International Standards Organization (ISO), 1994). These usability measures are defined as follows (Green & Jordan, 1999):

Effectiveness: the extent to which a goal, or task, is achieved

Efficiency: the amount of effort required to accomplish a goal

Satisfaction: how acceptable the product is as a means of achieving the goal

Arthanat et al. stress that usability is not a function of the AT device alone, but must be considered holistically, considering the entire AT system (i.e., using a holistic model such as the HAAT model). Research has shown that client satisfaction with AT is a strong predictor of whether it will be used (Riemer-Reiss & Wacker, 2000; Wielandt, Mckenna, Tooth, & Strong, 2006).

To increase the usability of devices, human factors engineers (Green & Klein, 1999) and AAC users (Blackstone, Williams, & Joyce, 2002) encourage the involvement of end users and other stakeholders in the stages of device development: i.e., 1) requirements gathering, 2) iterative development of device concepts, and 3) testing the usability of devices. Although there are examples of involving adults with disabilities and children without disabilities in these design stages (Bekker, Beusmans, Keyson, & Lloyd, 2003; Light, Page, Curran, & Pitkin, 2007; Plaisant et al., 2000; Waller, Balandin, O'Mara, & Judson, 2005), involving children with disabilities is not well studied. In this study, participants were involved in their SGD interface design and observing the participants while using the robot was used to obtain real-time usability information which fed into iterative robotic and environment design improvements.

1.4 Purpose of the Study

The purpose of this study was to design and implement a low-cost integrated communication and robot system to be used by students with severe physical and communication limitations to do the hands-on tasks in math measurement lessons. Additionally, system use was examined by measuring participant performance in math measurement lessons, describing the process of using the system, and contrasting system use with other methods of accomplishing math measurement activities.

1.5 Research Questions

The research questions guiding this study were:

1. Can students with physical and communication limitations demonstrate and explain their understanding of math measurement concepts using an integrated communication and robot control system in math measurement activities?
2. What are the key features and characteristics of the student, activity, integrated communication and robot control system, and context that limit system usability?
3. What differences are there in terms of usability (effectiveness, efficiency, and satisfaction) between using the integrated communication and robotic control system to do the manipulative tasks and other modes that students may use such as observation of the teacher, responding to questions, or directing the teacher?

1.6 Significance of the Study

This study contributes to the theoretical body of knowledge for children with severe physical and communicative limitations that performing "hands-on" learning activities is beneficial, that integration of manipulation and communication is important in math learning experiences, and that assistive robotic technology can be used to compensate for manipulative limitations in math activities.

This study contributes to the practical issues of providing methods to address math literacy for children who use AAC, finding appropriate applications for assistive robotics in mathematics, and implementing integration of AAC devices with manipulation in education and play.

The population who may benefit most from this study is children who have severe Cerebral Palsy (CP). Cerebral palsy is a nonprogressive motor impairment due to a lesion or anomalies of the brain arising in the early stages of its development (Mutch, Alberman, Hagberg, Kodama, & Perat, 1992). Children may also have associated impairments in language, cognition, vision, and hearing and there is evidence that children with CP have difficulties in math (Arp & Fagard, 2005; Jenks et al., 2007). Prevalence of CP in children born between 1985 and 1988 in Alberta was 2.57 per 1000 which is consistent with rates reported in other developed countries (Robertson, Svenson, & Joffres, 1998). Incidence rates are not generally reported. Children who have other disorders resulting in little function in their upper extremities such as muscular dystrophy, poliomyelitis, arthritis, osteomyelitis, congenital heart defects, absence of arms or legs, hemophilia, diabetes and spina bifida may benefit from the robot intervention in this study (Howell & Hay, 1989; Stanger & Cawley, 1996) and some of these may also involve speech limitations.

2 LITERATURE REVIEW

2.1 Assistive Technology for Learning Math

There are very few research studies regarding the use of assistive technology to involve children with severe physical and/or communication limitations in math activities. The approach has been to use augmentative and alternative communication (AAC) methods to direct others to handle manipulatives in math activities or to use specialized math software. The physical abilities of the children in the studies, when reported, were generally higher than the population of interest in this study. They were generally able to use their hands to some degree to use physical manipulatives or they could use direct access methods (keyboard, mouse, head-pointer) to access math software . Note that the more general term, AAC, will be used in this section rather than the more specific term speech generating device (SGD).

The studies using AAC show that the topic of math measurement has already been an area identified where an increase in participation of students who use AAC is desirable. The focus in two AAC studies was to evaluate if training teachers and support staff how to involve students who use AAC devices in curriculum activities would increase the participation of students. In the first study, the effect of a training intervention was investigated which showed teachers and support staff how to include a 10 year old boy who used an AAC device in literacy and math activities (Schlosser et al., 2000). A math measurement activity was done in groups of four. The boy directed group-mates by telling them with his AAC device what should be measured and reported if it was longer or shorter than a meter. The other students did the physical measuring and recording. The child also did a numeracy activity with an education assistant (EA). Before being trained on how to include the boy, he watched the EA handle the manipulatives used in the activity, but after intervention the participant was given an abacus to do addition problems. In the second study, Hunt et al. (2002) trained staff to involve three students who used AAC devices to work on various math topics. The first participant was in grade 5 and used the head-pointing access method to work on math activities on a computer. The second participant was in Kindergarten and used his hands to work with physical manipulatives to create repeating patterns with a classmate. The third participant was in grade 1 and used his hands to work with physical manipulatives, workbooks, and computer programs to recognize the numbers 1 through 5. In both studies, there was increased participation as a result of the training intervention.

Another study investigated using writing software along with math measurement manipulatives. Symington and Stanger (2000) described one teacher's experience using Intellitalk[2] software (a module for writing which is accessible for children with physical disabilities) in her classroom with a mixed group of children, some of whom used AAC. The teacher used a third-party product called "Measure It!"(TM), a kit of manipulatives for determining lengths, weight, and volume of items, and the children wrote about their math discoveries by using the auditory and graphics features of IntelliTalk. The level of physical abilities was not described, but the authors state that the children who did not use AAC devices showed improvements in expressive language skills, vocabulary and richness of measurement concept usage. The children who used AAC devices did

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[2] IntelliTools, http://www.intellitools.com/

not have as many gains, but did learn vocabulary such as "more", "less", and "weigh". The authors noted that they felt all of the children's self perception improved.

2.2 Access to Manipulatives for Learning Math

There is ample evidence that using physical manipulatives can contribute to improved outcomes for children with difficulties learning math. For example, grade three students used Cuisenaire rods[3] (colored cubes which can connect into lengths of 10) for solving word problems (Marsh & Cooke, 1996) and first graders used TouchMath[4] (cards with numbers composed of raised dots) to overcome math difficulties (Dev, Doyle, & Valente, 2002; Wisniewski & Smith, 2002). However, since children with physical disabilities cannot access physical manipulatives, using virtual manipulatives on the computer may be suggested as an option. For example, third graders had improvement in conceptual and procedural knowledge about using fractions after using software with virtual manipulatives (Reimer & Moyer, 2005). However, these programs, including the plethora of on-line manipulatives for learning math concepts (e.g., National Library of Virtual Manipulatives at http://nlvm.usu.edu/), generally require good skill at using the computer mouse.

There are computer programs for performing math designed for people with physical disabilities, for example, IntelliMathics[5] and MathPad[6]. Only one study was found where IntelliMathics was used with children who had disabilities, and none were found for MathPad. Stanger et al. (2000) performed a

[3] ETA/Cuisenaire, http://www.etacuisenaire.com/
[4] Innovative Learning Concepts Inc., http://www.touchmath.com/
[5] IntelliTools, http://www.intellitools.com/
[6] Spectronics, http://www.spectronicsinoz.com

case study with four children using IntelliMathics "Number Concepts 2". The children had differing physical, cognitive and math skill levels, and they used either an enlarged keyboard or a mouse to access the software. The times that each participant used the software during a four month time span ranged from 3 ½ to 15 hours. Children's scores from the pre-test to the post-test increased in every activity except for one where the participant was not testable in that activity. Teachers were able to use the software to track student progress, whereas previously they were "challenged by assessing when [a student] has learned something " (p. 66).

Accessing software for children who are scanning users requires them to either access it through their AAC device operating in mouse or keyboard emulation mode or remove the AAC device in order to use the switches to control scanning on the computer. If the AAC device is removed, it forces them to choose between communicating or doing math. With either method, some customization of the interface is necessary to make scanning less onerous (e.g., remove non-essential items so the scan sequence is a manageable length). With the introduction of recent AAC systems which are computer-based, there is an opportunity to perform integrated communication and math activities, however, the systems are new and not yet wide-spread.

2.3 Participation in Integrated Activities

There are a few projects where AAC and play have been integrated. In one project, communication symbol cards were integrated into the play environment (reported in Light & Drager, 2002). This system is appropriate for children who have the physical abilities to manipulate the play items and cards. A recent AAC, device, the Dynavox V, has games built into it, and these are accessible for children with limited physical abilities because they can use their own access method to access the AAC device. Likewise for computer-based AAC devices, games can be played and accessed by any access method. Anderson (2002) presented instructions on controlling infrared toys from AAC devices and stated that it offers "highly motivating activities for use in the development of language" (p. 7) i.e. "come" "go", "in" "out", "my turn" "your turn". No published studies were found on these projects.

These integration projects for children with severe physical disabilities may have limitations. For instance, although games and communication can be integrated on recent AAC devices, the games are predetermined, and many shared play opportunities will be "outside the [AAC] box". Although using AAC devices to control infrared toys provides physical manipulation of real objects in the environment, a toy will always perform the same pre-programmed function. Robots have a potential learning advantage over infrared toys since robots can be reprogrammed to keep the interest of the child and to present increased challenges. Previous robot studies have shown robot activities to be more motivational than computer games (Cook, Howery, Gu, & Meng, 2000; 2003; Plaisant et al., 2000).

2.4 Assistive Robots for Doing Activities

The term assistive robot has been used to encompass a range of robotic assistance to humans: therapeutic robots assist people with performing exercises (e.g., Lathan et al., 2001), social robots assist the elderly with loneliness or health safety (e.g., Ezer, Fisk, & Rogers, 2009) or they assist children who have autism to build social skills (e.g., Michaud, Duquett, & Nadeau, 2003), and guidance robots assist people with physical or visual disabilities to move about in the environment (e.g., Davenport, 2005). For the purposes of this study, assistive robot is defined as robots that "enhance ability to manipulate objects and to function independently" (Cook & Polgar, 2008, p. 483). Assistive robots can be workstation based, mounted on a wheelchair, or mounted on a mobile base. This literature review is limited to assistive robots for children with physical disabilities.

Research in assistive robots for children (also known as robot assisted play, robotic aided education) began with a push to develop robots to be used in educational and play activities in the late 1980's and consisted mostly of user trials. The educational activities involved pick and place or drawing tasks in the areas of art and science and the play activities were varied. "A lack of substantive, consistent exposure to a stable robotic device has led to interventions that are called 'clinical trials'... too brief in duration and too few subjects to be able to achieve any level of generalizability" (Howell, 2005, p. 858). It appears that children and teachers have been pleased with the robotic interventions, but the access method has been a common limitation, especially for children who are scanning users. Another limitation was high cost (from $12,000 to $30,000), the requirement for structured environments, and safe for use around children (Lees & LePage, 1994).

2.4.1 Robots to Assist With Manipulation in Education

Most studies reported on the development of the robot or were trials examining the feasibility of using the robot in tasks and trialing the user interface. Howell and Hay (1989) developed a robot arm workstation for access to science lab activities and performed trials with seven students aged 9 to 11 years who had physical disabilities. Investigators made observations and did a pre-test post-test measure of motor control skill (results not reported). Children accessed the device with a 5 slot switch and a scanning display for selecting the robot mode (pre-stored locations mode or direct control mode). Investigators found that children needed two phases, first to learn the robot functions, and then to use it for educational activities. Limitations were that the access method was inflexible, and that the rate of robot movement was slow.

The activity of drawing was targeted in trials with the Handy ARTbox workstation with children with CP (Smith & Topping, 1996). The project aim was for children to complete educational worksheets (for practice in joining lines, word and picture matching, mazes, and basic sums). Children used a scanning interface that cycled through embedded lights in a pen pallet, four lights under the paper for directions, and three additional lights for up, down, and new pen. Three children were assessed to see if they had the skills to use the robot, and one child was selected for a longer trial. They reported that the teacher and user were satisfied with the system. Problems identified were that the scanning speed was too fast resulting in mis-selections and it was difficult for the child to see the drawing. Authors speculated that this activity would be good for spatial three dimensional skills, and commented that the user made fewer directional errors as he became familiar with the system.

Kwee and Quaedackers (1999) adapted an assistive robot arm designed for adults (called MANUS) to be used by children with CP (called POCUS). The robot workstation was used for various pick and place academic activities, such as putting a glass over a burning candle to extinguish it. Investigators used an iterative development design with qualitative observations with six participants, 7 to 29 years old, all of whom had CP. The children accessed the robot using a scanning interface with three push button switches. One limitation investigators found was that the students required high cognitive skill to understand the interface.

A multi-purpose workstation called the ArlynArm was trialed by five students, aged 10 to 18 years, who had arthrogryposis, muscular dystrophy, and CP (Eberhart, Osborne, & Rahman, 2000). Two participants used the Arm for an art project (pasting items onto a collage) and three participants used it for three science projects (plugging in electrical wires to make a radio, mixing solutions, and planting seeds). The system was designed for children with good fine motor control, and required the user to manipulate one joystick for three-dimensional position and another joystick to change modes. System feedback was given through a display. Investigators used video recordings to measure time to complete sub-tasks and the number of times the investigator had to intervene. There was a substantial variation in sub-task time for the users and one child with CP had considerable problems with the interface.

There were two studies where educational outcome measures were taken. Howell, Martz and Stanger (1996) used the robot discussed above (Howell and

Hay (Howell & Hay, 1989) to determine if robot mediated instruction affected acquisition of curriculum concepts (about the five senses) and transfer of skills in science experiments (to compare the weight of objects on a balance scale). Three physically disabled students were each paired with three non-disabled students, all in grade three or four, and performed five experiments about human senses using a scientific inquiry process. Children worked together for five sessions, once a week for 45 minutes each. The robot was used to bring items closer for sensory inspection (items were placed in a box with a handle so the robot could pick them up). The students came into the study already having knowledge about senses so there was no room for improvement in the curriculum concept, and they performed the scientific inquiry process actively. Questionnaires to students and teachers regarding social validity showed that the students enjoyed using the robot and felt they learned a lot. However, the teacher was concerned that using robots in the classroom would require more training for teachers.

In an educational study with a Lego robot, a nine year old girl used a car-like Lego robot to work with phonemes (Cook, Schneider, Stokes, & Lockhart, 2008). Twelve phonological awareness tasks were tested using a standardized test and three weak areas were targeted for practice activities using the robot. The girl used four single switches to drive the robot car towards the appropriate phoneme. Improvements were detected in two out of three targeted tasks. The education assistant noted that the student's reading abilities improved following the study.

2.4.2 Robots to Assist With Manipulation in Play

Like the assistive robots for education above, most studies for robots for play reported on the development of the robot or were trials to examine the feasibility of using the robot in tasks and trialing the user interface. Harwin, Ginige, and Jackson (1988) described a workstation consisting of a robot, a visioning system and sensors. Children could perform three tasks at the workstation (stacking and knocking over blocks, sorting items, and the Tower of Hanoi task with 3 discs) and since the interface was computer-based, they could use any standard computer access method (e.g. switches, expanded keyboard). The system reduced the physical and cognitive burden on the user by using a visioning system, sensors and built-in intelligence to accomplish parts of tasks. For example, the system used vision and sensors to stop at locations and would not allow the user to make incorrect moves. Investigators stated that the first trial uncovered many technical issues, but the children still enjoyed using the robot.

Karlan et al. (1988) reported on a preliminary clinical evaluation of a prototype interactive robotic device (IRD-1). The robot workstation was used by two groups of children all having moderate to severe physical impairments. Four children were in pre-school (2 to 4 years old) and five who also had cognitive delays were in elementary school (5 to 9 years old). Children chose toys and actions from pictures on a membrane keyboard. The number of times they picked up a toy and the number of actions performed on it were tracked. The pre-school children were attentive, and chose toys 7 to 32 times and performed actions on them 4 to 27 times. The elementary school children had more cognitive problems so they did not understand the interface, but two out of five of them were at least able to demonstrate an understanding of cause and effect.

Tsotsos' (1998) long term development project, the PlayBot, consisted of an integrated wheelchair, a robot arm and a visioning system to allow children with physical disabilities to play with toys. With this system, the child defined the target by pointing to items on a control panel and the visual system guided the robot to the goal. The interface was described as a concept similar to the BLISS[7] symbolic language (where symbols are combined to generate meaning). For the interface, the child used his or her finger to press a picture of a toy and then one or more actions, also represented by pictures. No user trials were reported. Recently, the system, consisting of an autonomous wheelchair with a vision system and the MANUS robotic manipulator, was used to find and open doors (Andreopoulos & Tsotsos, 2007).

A sequential dig and dump task in a macaroni "sand" box was performed in two studies: four children with CP aged 6 and 7 (Cook et al., 2000) and 12 children aged from 6 to 14 (Cook et al., 2005). Children accessed the robots using one to three single switches, and goal attainment scaling was used to measure progress in three areas (operation of the robot, turn taking etc., and carry over into classroom activities). In subsequent studies using car-like Lego robots, participants performed various pick and place tasks using a robot car (where an assistant placed and removed objects on top of the robot) and a robot arm (Cook, Adams et al., 2010; Schulmeister, Wiberg, Adams, Harbottle, & Cook, 2006). The children accessed the robot using one to four single switches. Children demonstrated skills at using the robot at differing levels, from basic skills to innovative play.

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[7] Blissymbolics Communication International (BCI), www.blissymbolics.org

The PlayRob system was built specifically for manipulation of Lego bricks and was trialed with three children without disabilities, and then three children (9-11 years old) with multiple disabilities, quadriplegia, and spinal cord syndrome (Kronreif, Kornfeld et al., 2005; Kronreif, Prazak et al., 2005; Prazak, Kronreif, Hochgatterer, & Fürst, 2004). The aim was to evaluate acceptance and intuitiveness of the user interface. With this system, children chose a Lego brick, guided it to position and placed it using a dedicated input device (5 slot switch, single switch, or a mouse). The investigators found that the children enjoyed the activity, but that mapping the required input movement to the desired robot movement was difficult for the mouse user and the scanning user. They proposed that the robot may need to do more of the task for the scanning user. After making modifications to the robot, the investigators began a larger scale trial in a school (Kronreif, Prazak et al., 2005). At the time of writing they were working with 10 to 15 children with varying physical, mental and communication abilities. They were tracking duration of play, number of bricks used, time to place brick, and use of play area. Preliminary results were positive, indicating that placement time and accuracy was improving, more of the play area was being used, the trajectory from picking up a brick to placing it was being reduced, and the items being built were getting more complex.

A consortium of European investigators (IROMEC) have been doing recent research with children with autism spectrum disorder, intellectual disabilities and severe motor impairment to see how robotic toys can become social mediators and provide opportunities for learning and enjoyment. For their first user trials with children with motor impairment they worked with groups of two to eight boys and girls, aged 3 to 15 who used three robots: AIBO (a puppy from Sony), a two wheeled prototype developed by Profactor (one of the consortium partners), and the first IROMEC prototype, a flexible modular mobile robot which accommodates multiple users and play scenarios (Besio, 2009). In the trials with children with disabilities, they used four play scenarios in the trials: turn taking, imitation game, make it move (by making sounds), and catch me if you can. They found that the children had a preference for the AIBO puppy, and that the other robots did not sustain their attention. Limitations pointed out by the investigators were that the robots were slow and too heavy to be handled by the children. Although access methods were not specifically discussed, except for making sounds, it is assumed that the children had some gross motor abilities if they were handling the robots. In another study, the consortium identified three off the shelf toy robots (Mr. Personality from WowWee group Limited, I-Sobot from TOMY Company Ltd, and Wall-E from Thinkway Toys) that they will use in future play interventions in the turn taking, imitation and make it move scenarios (Caprino, Laudanna, Potenza, & Scebba, 2009). Since these robots are IR controlled they intend for them to be controlled via switches, computer software, or adapted environmental control units (such as a big button learning remote controller for the TV).

The Trik Project uses a bluetooth Lego robot which draws geometric shapes and is controlled via a touch screen (Ljunglof et al., 2010). Their purpose is to help children to "learn language, language use and cooperation". For example, the child selects the triangle shape on the computer and it says "Draw a triangle", a speaker on the robot responds, "how big?", and the child chooses the "large" symbol on the computer. They tested the system with 2 children with CP and 1 with Autism who used it once per week for 2 months. They found that accessing the computer via the touch screen was hard for the kids with CP.

2.5 Integration Of Communication And Robotic Manipulation

To the author's knowledge, there have been no studies on the integration of augmentative communication and robotic manipulation except for two pilot projects undertaken by the author. One project investigated appropriate aspects of the human technology interface and the other explored appropriate educational activity areas for robot use. Both studies utilized low-cost Lego robots.

In the first study, a testing platform was developed along with several sample integrated communication and robotic play interfaces (Corrigan, Adams, & Cook, 2007). The testing platform consisted of prototype AT Creator[8] software on a tablet computer with a RedRat[9] for infrared output. The sample interfaces underwent usability testing by five expert users with relevant backgrounds and then were modified iteratively after input from each user. The experts were: a rehabilitation engineer, a speech language pathologist, a human factors psychologist, a pediatric psychologist, and an adult with complex communication needs who uses an AAC device. All users accessed the interfaces with direct selection by pressing their finger on the tablet computer touch screen. They performed various structured play activities using a car-like robot and a robotic

[8] Madentec Limited, http://www.madentec.com/
[9] RedRat Ltd., http://www.redrat.co.uk/

arm. Subsequently, one interface underwent testing by six children without disabilities (two each at ages 3, 5 and 7) and then three children with mild physical but severe communication limitations (all aged 5). The participants with disabilities accessed the interface using a keyguard. They performed pick and place activities (feeding and watering animals) in a zoo scenario. AAC navigation system and robot control mode conditions were tested to examine how they influence rate of communicative output. The navigation systems tested were when vocabulary and robot commands were all-in-one page or on linked pages (vocabulary on one and robot commands on another). The control methods tested were if the robot played back pre-programmed movements with one button press or if it was under direct-control by pressing forward, back, left and right commands. In addition, preference for controlling the robot or having an assistant accomplish the tasks was tested and all participants chose to control the robot more frequently.

Results showed that the control mode of robot playback resulted in increased verbal output (probably because children were focusing on maneuvering the robot in the direct control condition). Having the vocabulary and robot commands all-in-one page was beneficial for the children with disabilities and the younger children without disabilities. The older children actually had more vocabulary output in the Linked condition with robot playback mode.

The second study investigated the feasibility of using a Lego robot controlled by the infrared capability of a speech generating device (SGD) in educational activities (Adams, Yantha, & Cook, 2008a; Adams, Yantha, & Cook, 2008b). A 12 year old girl who has cerebral palsy with severe physical limitations and complex communication needs participated in the case study and used a Vanguard(TM) II communication device with Unity(TM) 45 Full language system. Goal attainment scaling was used to evaluate her performance in numeracy in math (doing board games, making puzzles, drawing connect-the-numbered dot pictures), writing in social studies (creating a play about a Greek myth), and robot programming in science (using her SGD in mouse emulation mode to control the mouse position on the computer screen). Robot operational accuracy and mean length of utterance were also examined. There were problems with establishing meaningful goals (too many goals, overlapping goals, inaccurate initial assessment of the participant's level). These problems are consistent with pitfalls of GAS use described by other researchers (summarized in Schlosser, 2004). However, feasibility of using the system was demonstrated in other ways. The participant was able to functionally manipulate the items used in the numeracy activities and used math related vocabulary when prompted. Acting out the Greek myth provided a salient learning experience with high participant engagement and she provided the script vocabulary. The participant achieved improvement in robot programming which was validated by her teacher and classmates. However, it took her considerable time to accomplish the programming tasks, and she was not able to do them without investigator assistance. As in previous robot studies, the teacher perceived the student as more capable after working with the robots (Cook et al., 2005; Cook et al., 2000). A speech pathology student working on the project recommended that providing robot commands alongside the participant's core vocabulary may have encouraged higher vocabulary output.

These two pilot projects informed the present study in the following ways:

- Using the Lego robot was very motivational to the participants and classmates.
- It may be beneficial to have vocabulary alongside robot commands.
- Full access to direct robot commands can be understood by children 5 years and older, but their amount of vocabulary output may decrease.
- Controlling the Lego robots via a commercial SGD is feasible, and the Vanguard II device supports robot control such as repeated commands for moving long distances.
- The teacher was most interested in giving the student access to math activities.

2.6 Summary

Researchers in the area of AAC have indicated that improving participation of children who use AAC in learning activities, particularly math is important. In the studies cited, children used manipulatives or computers which can be difficult to access for children who have severe disabilities who require the scanning access method. Accessing communication and manipulation at the same time is compromised with some technology solutions. The literature supports that combining AAC and play is a desirable and motivating learning scenario but the area of integrating AAC and physical manipulation in educational activities has not been explored. Though it has been shown that AAC devices can control infrared toys, robots could have a learning advantage since they can be reprogrammed to perform various functions to better match the child's increasing abilities and various topics of study.

The research in assistive robotics shows emerging evidence that assistive robots are capable of providing access to manipulation of the environment for play and educational activities. However, the area of robotic assistance with math activities has not yet been explored. One limitation in previous studies was that many systems could not be used by switch users. The studies which did provide robotic control via switches reported problems. Either the cognitive demand was high for the participants, mapping of symbol to robot function was a problem, or there was a limit in the number of robot functions that could be provided to the user. The purpose of this study was to examine the use of an integrated communication and robotic manipulation system to perform math measurement activities where children use their own SGD and scanning access method. The integration of the AAC device and robot control overcomes many previous limitations.

The high price of early robotic systems made them unaffordable for most people. For that reason, recent researchers have gone towards using inexpensive, mainstream robots. The Lego robots proposed for use in this study are inexpensive, safe and flexible. There is some criticism of "forcing cheap robots to barely meet [children's] needs rather than developing robotic systems that are truly well suited for educational purposes" (Lees & LePage, 1994, p. 298). In 2005, Howell (2005) predicted that it will take years to develop an easy-to-use, cost-effective, and reliable assistive robot for classroom use, and once developed, it will take more time to develop appropriate educational activities. The need is still present, as there have been recent calls to develop appropriate robots for children (Cook, Encarnação, & Adams, 2010). Lego robots are already being used in mainstream education (Cooper, Keating, Harwin, & Dautenhahn, 1999; Karna-Lin, Pihlainen-Bednarik, Sutinen, & Virnes, 2006). Since Lego robots can be made accessible to children with disabilities, they provide an opportunity to develop educational activities today, while more robust technology is being developed. This study examined the use of the inexpensive robotic system in math activities and identified limitations in their usability.

This review showed that there are various means that someone with severe physical and communication limitations can accomplish manipulative learning activities: observing others and participating in reporting, directing others to perform portions of the activity, using math software, or using robots. This study investigated the differences in using the robot versus participating by observing or directing others. Comparisons with utilization of math software is beyond the scope of this study.

3 METHODS

This study consists of three case studies with children who used their own speech generating device (SGD) to control a Lego robot to do Level 1 and 2 math measurement lessons. Case study methodology was used in order to focus on the individual since the AT system must be tailored for individual skills and abilities and because of the exploratory stage of this area of research. The research was designed with multiple methods of data collection: math performance measures; observational data providing a rich description of the process of using the AT system, including system usability and how the system was used for manipulation and communication; and interviews and surveys with participants and stakeholders. The multiple methods of data collection provided converging evidence for the findings.

The study was composed of the following main parts, in sequence, and will be described in more detail in the section indicated:

- Obtaining ethical and operational approvals (Section 3.1).
- Development of the integrated communication and robotic control system (Section 3.4.1):
    - Design and development of a Lego robot to perform the tasks required in math length measurement activities.
    - Development of individualized SGD interfaces for each participant to control the robot.
- Establishment of participant's existing competencies related to speech generating device (SGD) use (Section 3.5.1).

- Training of participants on robot control while tracking performance and making robot, environment, and SGD system adjustments to optimize functioning (Section 3.5.2).
- Participant use of the integrated communication and robotic control system to perform length measurement activities (Section 3.5.3). The following data were gathered:
  - Assessment of student performance, and
  - Observational data regarding the process of using the system.
- Interviews with participants and stakeholders regarding participant performance and system usability (Section 3.5.4 and 3.5.5).

3.1 Ethical Approval

Ethical approval was obtained through the University of Alberta's Health Research Ethics Board. The required consent documents and operational approval to perform research at the Glenrose Rehabilitation Hospital and city educational system were also obtained.

3.2 Population Sample

A non-random, purposive sample of three participants (called M01, M02, and M03 here) participated in the study. All three participants were diagnosed with spastic athetoid quadriparetic cerebral palsy and had their own Vanguard(TM) II SGDs mounted to their manual wheelchairs, which they activated using two Spec(TM) switches, located on either side of their wheelchair headrests, to step scan through their vocabulary arrays. Relevant participant and SGD characteristics are shown in Table 3-1. Participants had no reported visual impairments, except for M02 who wore glasses. The mother and Education

Assistant (EA) of each participant participated in an interview at the end of the study.

Table 3-1: Participant sex, age, grade, educational setting, scanning method and SGD language system

Participant	**M01**	**M02**	**M03**
Sex	Female	Male	Female
Age (years)	14	10	12
Grade	8	4	6
Educational setting	Self contained classroom, life skills program	Integrated classroom	Integrated classroom
Scanning method	Row-Column (R-C)	R-C	Quarter-Row-Column (Q-R-C)
Language system and grid size	Unity™ 45 Full	Unity 45 Full	Unity 84 Sequenced

An **Evaluation Team** participated in interviews relating to each participant and system usability. The team consisted of:

- A speech language pathologist (Evaluation SLP)
- Two special education teachers (Evaluation Teacher1 and Evaluation Teacher2)
- Two occupational therapists (Evaluation OT1 and Evaluation OT2), and
- An adult who uses a speech generating device and other means of augmentative and alternative communication (Adult user of AAC). She was 30 years old and had been using AAC since she was 6 years old. She reported that she did not take math classes as a child because the teachers did not know how to involve her in the hands-on activities that her classmates were doing.

The investigator participated in the training and math lessons and led the interviews. Since investigator involvement in case studies can affect the case, a short description of the investigator's experience is included here. The investigator has an educational background in electrical engineering and 20 years of experience in various aspects of the field of assistive technology including service delivery, research, and teaching. The investigator's area of technology expertise lies mainly in alternative computer access with experience in team assessment and recommendation of augmentative and alternative communication systems.

3.3 Setting

M01's sessions took place at her school in a large room which was occasionally shared with other students using computers. The other side of the room was used as a classroom and was frequently occupied during the sessions, however, the participant did not appear to be distracted by the sounds. The parents of M02 and M03 were reluctant to add additional time requirements to the participants during the school year, but desired for the children to be involved in some stimulating activity during the summer break so the sessions were framed as a "robot and math camp" during July and August. M02 was seen at a day care and sessions took place in a large foyer area. The space was quiet for the first part of the study and then became somewhat noisy as teachers from an adjoining school began working in the last part of the summer. However, the participant did not appear to be distracted by the sounds. Participant M03 was seen at various locations (e.g., laboratory space at the University of Alberta, laboratory space at the Glenrose Rehabilitation Hospital, or her home) according to the convenience of her mother, and all locations were quiet.

3.4 Materials

The Math Makes Sense curriculum resource (Pearson Education Canada, 2007, 2008) was used for this study which adheres to the "The Common Curriculum Framework for K-9 Mathematics" (Western Canadian Protocol for Collaboration in Basic Education, May 2006). The resource includes three lessons on length measurement in Level 1 (plus an introductory math measurement unit launch) and three lessons in Level 2. The integrated communication and robotic control system was developed to accomplish the communicative and manipulative tasks in those lessons and is described here. The materials used in the math lessons are described below.

3.4.1 The Integrated Communication and Robotic Control System

The integrated communication and robot control system was operationalized by using the participant's own SGD and a car-like Lego robot, built from the Lego Mindstorms for Schools[10] kit. A task analysis of the physical "doing" requirements of typical children in the Math Makes Sense Level 1 and Level 2 length measurement lessons was performed in order to establish specific robot and environment design requirements (Appendix A). The goal was for the participant to be able to perform as much of each lesson as independently as possible, but some tasks required teacher facilitation. This allocation of tasks between AT, strategies and assistant was described in the Dynamic Support Triangle Framework presented in Chapter 1. The full task analysis (in Appendix A) contains:

[10] Lego Group, http://www.lego.com/

- a short description of the materials and problem to solve in each Math Makes Sense lesson
- the derived list of manipulative tasks to be performed for each lesson
- the corresponding robot environment and teacher facilitation requirements, and
- pictures of each design feature implemented.

A summary of the resulting robot and environment features is presented below. Each participant's SGD interface was modified to give them access to the Lego robot control commands. A Lego infrared (IR) remote control unit was used to train the SGD to send the required IR command to the robot. The participants were involved in the design of their own SGD interface and the resulting SGD interface designs are described below. Results of the design process have been accepted for presentation (Adams, Accepted for 2011).

3.4.1.1 Lego robot and environment design

The main design requirements for the robot, which were in addition to the car-like capability of the robot used in previous studies, were: 1) a low robot body with a flat surface, 2) a location to attach referents and non-standard units to the top of the robot, 3) a gripper, 4) a mechanism for moving a pen up and down, and 5) a spool to hold string (see Figures in Appendix A). The main design requirement in the environment was to affix items and non-standard units to the top of blocks so that they could be grasped by the robot gripper (see Figure in Appendix A). The robot was controlled by direct commands to two motors for forward, backward, left or right movements or by programs to go forward by the length of a non-standard unit (one toothpick, rod, or straw). An additional motor was used for the detachable gripper or pen. Lego Robolab[11] programming software was used to program the robots. In order to send subsequent programs to the robot, a Stop command (available on the Lego IR remote control) was inserted after each program command.

The robot was personalized by creating a different robot head for each participant by using Mr. Potato Head(TM) parts and other craft supplies. Each participant named their robot: M01 called hers "Mac" (from "Macaroni and cheese"), M02 called his "Truck", and M03 called hers "Lavonie" (after a character in her favorite cooking show). Colored arms from the Mr. Potato Head(TM) game were also added to the robot (yellow on the left, and blue on the right). This was expected to facilitate deciding how to turn left (toward the yellow arm) and right (toward the blue arm) when the participant's frame of reference was not the same as the robot's (e.g., when the robot was coming towards the participant). The SGD interface symbols for the turn commands required corresponding color coding.

3.4.1.2 The SGD Interface for robot control

Initial SGD characteristics were documented and then tracked during the training and math sessions. The participant's initial SGD grid size, language system, and scan type was used for the duration of the study (Table 3-1) with the exception of M03 who changed language systems to Unity 84 during the math sessions. The SGD auto repeat feature was set to 0.7 seconds for all participants. This allowed

[11] Lego Group, http://www.lego.com/

them to press and hold a selection to obtain repeated robot movements (e.g., forward movement to go a long distance).

The SGD navigation system (e.g., using a separate page for robot commands or having commands on the main page) and symbols for mapping robot movements were negotiated with each participant and modified during training sessions according to the participant's skills and preferences in order to obtain better system usability. In a previous pilot study, it was recommended that robot commands be made available alongside the core communication symbols in order to facilitate access to vocabulary items (Adams et al., 2008b). Hence, all participants were encouraged to start with this layout. In the Unity language system that the participants were using this is accomplished with an activity row. The top row of the grid array stays constant with the robot activity symbols (e.g., robot commands) until a new activity is selected. The commands which were programmed into the SGD are shown in Table 3-2 and are indicated as required or optional.

Table 3-2: The required and optional robot commands to be programmed into the SGD

Optional or Required	Robot command	Description
Required	movement commands	forward and backward (approximately 10 cm. in length)
		left and right (approximately 15 degrees in angle)*
Optional	small movement commands	forward and backward (approximately 2 cm. in length)
		left and right (approximately 5 degrees in angle)*
Required	gripper commands	open and close
Required	pen commands	up and down
Required	Programs for Level 2 Lessons 3, 4 and 5	to move forward by one unit length (e.g., one toothpick, rod, or straw)
Required	Programs for Level 2 Lesson 4	to move the robot one giant step and one baby step forward (the program to move one toothpick was used for the baby step).

* optional yellow and blue color coding for left and right turn symbols corresponding to the arms on the robot could be added if desired

Initial symbols and locations were suggested by the investigator and approved by the participant. Note that M02 created his own SGD page, assigned commands to cells, and labeled them with words. The following figures show each participant's interface at the start of the study, after robot training and after the math sessions (Figure 3-1 to 3-3). Major interface changes which influenced system effectiveness are listed in the results section (Section 4.4.4, HAAT Elements).

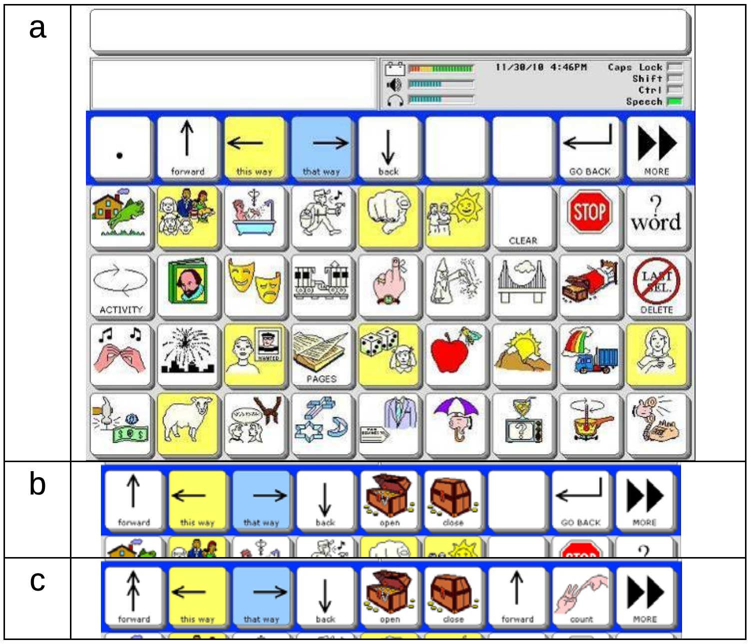

Figure 3-1: M01's SGD interfaces: (a) initially, (b) after training, and (c) after the math sessions.
Screen captures created using Vantage-Vanguard PASS(TM) software.

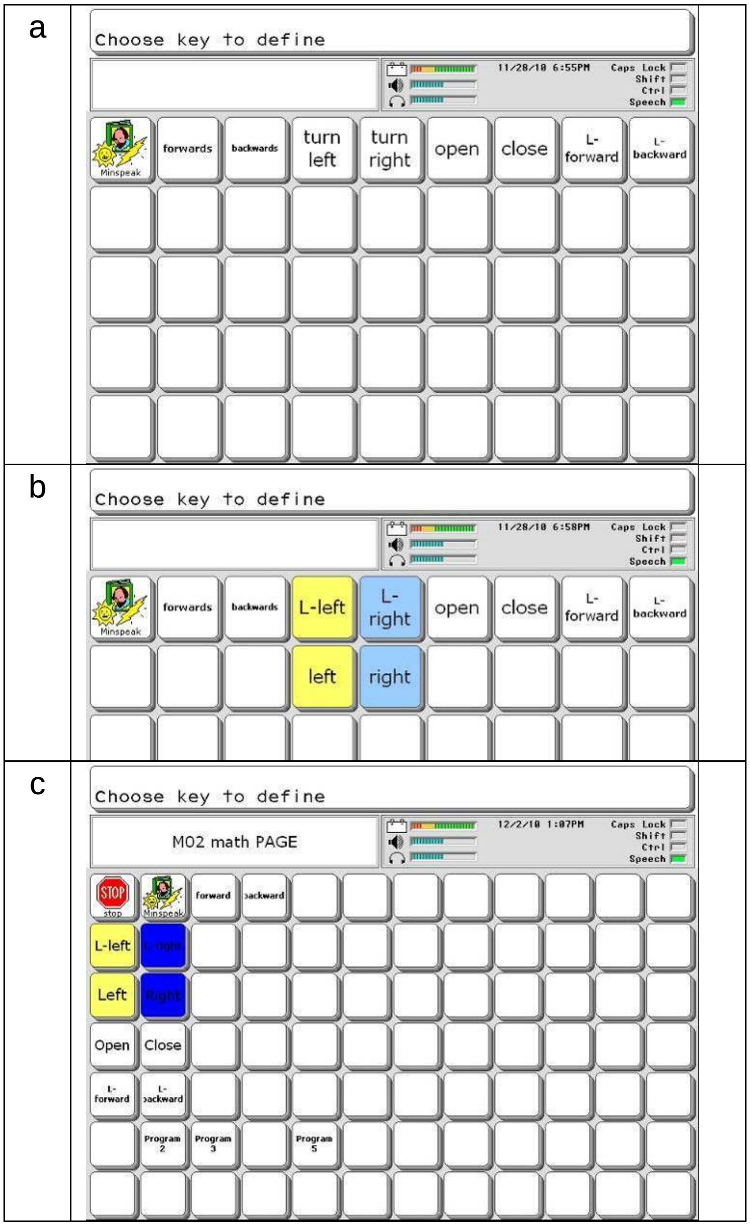

Figure 3-2: M02's SGD interfaces: (a) initially, (b) after training, and (c) after the math sessions.
The word labels in the dark cells in (c) are "L-right" and "Right". Screen captures created using Vantage-Vanguard PASS(TM) software.

Figure 3-3: M03's SGD interfaces: (a) initially, (b) after training, and (c) after the math sessions.
Screen captures created using Vantage-Vanguard PASS(TM) software.

M01 accessed the program commands from her SGD page from the previous pilot study (Adams et al., 2008b). An additional SGD page was created for M01 to facilitate the counting of units. With the count page, M01 could select the unit (e.g., straws, rods, or toothpicks), and then the robot moved ahead one unit length and the SGD spoke aloud the number increasing one at a time with each selection of the count symbol (Figure 3-4). The page also had some vocabulary items, a TAB to facilitate tabbing through worksheets on the tablet, and links to the Numbers and Math pages.

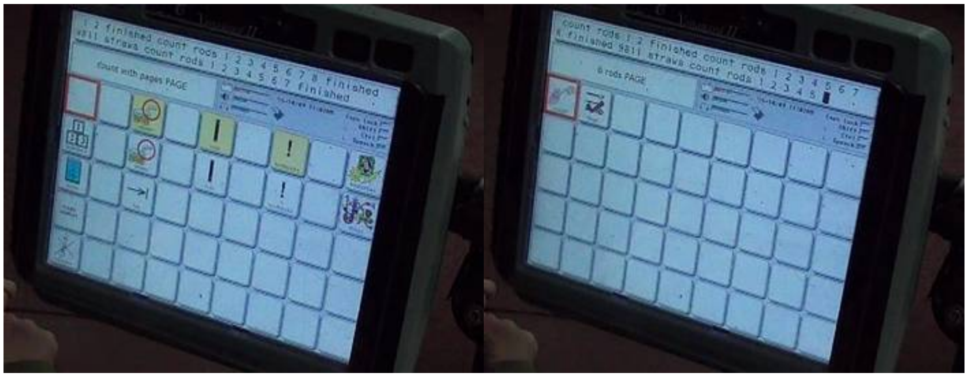

Figure 3-4: M01's count pages: (left) select the unit (e.g., straws, rods, or toothpicks) to count and (right) select the count symbol for the robot to move ahead one unit length and for the SGD to say the number aloud

3.4.2 Math Lesson Materials

A brief description of the required materials are provided in this section and more details are provided in the math session procedures below and also in Appendix B, Revised Lesson Plans. Materials needed for the lessons were typical items that are found in a classroom, for example, supplies like tape, scissors, string, and toys like blocks and cars.

Large sheets of paper (2' x 3') were created indicating the math vocabulary from Level 1 and Level 2 and also the SGD symbol pathway representing each vocabulary item (word wall words). In Level One, the math word wall words were, “long, longer, longest, short, shorter, shortest, far, farther, farthest, same, compare, length, baseline”. Some of the words required substitutions in order to be able to use the SGD core vocabulary, e.g., “compare = is it different”, “length = how long”, “baseline = match up or match ends”. In Level Two, the additional word wall words were "measure, height, unit, order” and the substitutions were "height = how tall", "unit = thing", and “order = from shortest to longest”. The Revised Lesson Plans, Appendix B, show the complete list of math word wall words corresponding to each lesson. A tablet computer with Vantage-Vanguard PASS(TM) software was also used by the teacher to look up symbol pathways during the lessons.

Participants entered their measurements into electronic worksheets (forms created in Microsoft Word(TM)) by output to the table computer via a USB cable from their SGD computer.

3.5 Procedure

Each participant progressed through the steps of measurement of pre-existing competencies, training in controlling the robot and then performance of math measurement lessons. The participants were seen over the course of 5 to 8 weeks according to the schedule in Table 3-3. Pre-existing competencies were established before commencing the training.

Table 3-3: Schedule of observations, training sessions, and level 1 and 2 lessons

	Week:	1	2	3	4	6	7	8	9...	13	14	15	16	17	18	19	20
M01	Observe	1	1	1													
	Training			4													
	Level 1				0,1,2	2,3											
	Level 2						3	3	3								
M02	Training									2	2						
	Level 1												0,1	2,3	3		
	Level 2															3,4	4,5
M03	Training											1	2				
	Level 1												0,1	2	3		
	Level 2														3,4	4,5	

Legend:

For the observation and training entries: the number represents the number of sessions that week

For the level entries: the number represents the lesson number performed that week

M01's holiday occurred during week 5, M02's holiday is shaded in grey

After the last session of the study, participants M02 and M03 trialed some Level 3 math measurement activities which involved using a 30 centimetre ruler and a metre stick attached to the robot.

3.5.1 Establishment of Pre-Existing Competencies

Several measures were made prior to the robotic intervention to establish existing skills and abilities of the participants.

3.5.1.1 Background information

Background information regarding the participant's SGD and other assistive technology (AT) was obtained at an initial meeting with the participant, parent and/or EA. In addition to the information presented in Section 3.2, Population Sample, information obtained included: amount of time since acquiring the SGD, previous experience with robots or other infrared controlled items, and motivating activities.

The participant's education assistant (EA) was interviewed to determine if the participant had previous math measurement experience and how they performed the manipulative tasks. Where possible, the participant was observed doing math activities using their typical methods with their EA.

The Peabody Picture Vocabulary Test, Fourth edition (PPVT-4) was used to assess receptive language (Dunn & Dunn, 1997). It was administered by a Speech Language Pathologist (SLP) who accommodated administration of the test by using partner scanning, i.e., pointing to the potential answers sequentially (without looking at the answers) and watching for the participant to indicate his or her choice with a reliable and repeatable verbal sound or physical movement.

3.5.1.2 Communicative Competence using SGD

The same SLP also evaluated the participants to ascertain their general level of communicative competence. Since there was no standardized measure for this, a protocol was developed with another SLP (Adams, Helmbold, & Lucky, 2010). The InterAACT Framework Dynamic AAC Goal Grid (the InterAACT Grid) was used as a systematic way to evaluate the level of AAC skills (Clarke & Schneider, 2008). The InterAACT Grid is a matrix checklist of a hierarchy of skills under each communicative ability level (emergent, context dependent, and independent) (Dowden & Cook, 2002) and across each AAC competence domain (linguistic, operational, social and strategic) (Light, 2003). Approximately twenty percent of the InterAACT Grid items which were applicable to the study were chosen for examination. Items were chosen in both the context dependent and independent levels to accommodate the estimated level of the participants (M01 context dependent, M02 and M03 independent). The participants re-told a story to their familiar conversation partners, who served as naïve “listeners.” Using familiar partners provided the best-case scenario for the participants to be understood in the re-tell task and allowed investigators opportunities to observe typical user communication strategies. M01's Education Assistant (EA), with whom she had worked for one school year, served as her listener. M02's EA, with whom he had worked for five years, served as his listener. M03's mother served as her listener.

The Renfrew Bus Story was used to obtain a language sample (Glasgow & Cowley, 1994). This narrative recall screening tool, designed for children ranging from 3:6 to 7 years of age, utilizes a wordless picture booklet. Unbeknownst to the listener waiting outside the room, the SLP read the bus story script twice and showed the story pictures to the participant. The SLP instructed the participant that when the listener returned, the participant should (1) tell the listener what was going to happen and then (2) re-tell the story. During the re-tell, the participant had access to story illustrations--but not the textual script--as plot reminders. The listener was permitted to ask the participant questions and use whatever communication strategies they would normally use. The participant was allowed to ask the SLP for assistance. To assess communication effectiveness and "listener" comprehension, the listener was then asked to repeat back the events of the story. The SLP interviewed the listeners to obtain additional information/examples that demonstrated participants’ competencies for the designated InterAACT Grid items.

The automatic data logging feature of the SGD captured and time-stamped message output from the story re-tell and these logfiles were retrieved for analysis. Two videos were taken, one framing the interaction between participant, listener and SLP, the other framing the SGD dynamic display. Events where the participant demonstrated InterAACT Grid competency skills were coded by the SLP who administrated the test, another SLP and the investigator by analyzing the logfile while watching the videos. Evidence of competency skills from logfile and video analysis were documented on the InterAACT Grid, along with reported examples from interviews. Agreement of evidence of skills was determined by consensus building. The SLP documented the amount and nature of cueing provided by herself and/or the listener and summarized the participants' story content, sentence length, and linguistic complexity.

3.5.1.3 Operational Competence of using the access method with the SGD

Operational competence using the access method on the SGD (i.e. accuracy and speed of selecting target items) was probed before beginning the study, after robot training, and after math measurement activities. It was tested before the study to ensure that the participants had sufficient accuracy in selecting target items and it was tested during the course of the study in order to track if motor learning occurred. Since there was no standardized measure for this, a protocol was developed (Adams & Cook, 2010) which was based on the "Trace Green Dot Test" (Smith & Vanderheiden, 1992). The Green Dot Test is typically used to measure speed and accuracy when typing on keyboards (standard or alternative sizes). The test removes the cognitive aspect of recognition and understanding of letters or symbols by using "dots" as targets instead. In the Green Dot Test, a number of dot stickers are placed on target keys (the standard test recommends twelve) making sure to include the extremities and the user presses the keys in a predetermined order as quickly and accurately as possible.

Two sets of 12 SGD target cell locations were determined by consensus between three augmentative communication specialists, one for the 45 cell grid, and one for the 84. Targets were chosen in each scanning area, with emphasis on the first scan position since it requires the fastest reaction time. Target locations remained constant for all tests.

An SGD page was created with all cells left blank (i.e., no symbol or label). The cells were programmed to send the row-column location of all selections to the logfile and to perform audio and visual feedback for correct selections (i.e., speak and display "Got it" in the message window). With the Unity Language system, the command <LAM-MARKER>(row,column)" sends the row-column location to the logfile, but not the message window contents.

Selection order for targets was determined by randomly drawing the target locations from an envelope prior to each test. The total "distance" travelled to attain all 12 targets was constant from one test to the next since the cursor jumped back to an initial scan position after a cell was selected.

During the test, the participant was told that both accuracy and speed were important in these tests and that they were not allowed to correct errors. The investigator manually placed an adhesive dot on a target cell (making sure to press hard enough to activate the cell), waited for the participant to make their selection, and then removed the dot (again activating the cell). SGD activity was captured and time stamped using the Language Activity Monitor (LAM) logfiling feature and a video that framed the SGD screen. The logfile showed three entries per target, the first and third entries were those of the investigator and the middle one was the participant's selection. Selections were marked as errors if the participant's row-column location was not the same as the investigator's. The video was used to provide supplemental information on what happened when a participant missed a target cell.

Total time to complete the test was measured with a stop watch by the research assistant during the test. Values were verified later by the investigator from the logfile by taking the time when the participant selected the last target minus the time when the investigator placed the first target. Accuracy was calculated as number of targets selected correctly divided by the total number of targets presented.

3.5.2 Training In Controlling the Robot via the SGD

It was known that the participants had varying levels of experience controlling IR devices (including Lego robots), so a training protocol was performed in order to bring the participants to a sufficient competency level before performing the math activities. The robot training protocol was designed so that participants could learn skills that would be required to perform the subsequent math activities with the robot (e.g., maneuvering in two dimensions, manipulating items, and switching between robot and communication modes), but no math instruction was given during training. Domains were introduced one at a time: first robot control only; then robotic control with manipulation of items; and then robotic control with manipulation of items and communication. The protocol consisted of a familiarization session, trials doing a slalom course, and then a final operational accuracy test. Participants had three to four sessions of 30 to 60 minutes each, and all sessions were video recorded.

3.5.2.1 Familiarization session

The participant spent one session learning robotic control by progressing through learning each robot command one at a time (e.g. forward, reverse, left, right) in a task protocol used in a previous robot study (Poletz, Encarnação, Adams, & Cook, 2010). The first task (Task 1 - causality) required the participant to move the robot forward until it knocked over a stack of blocks. The participants could press and hold their forward command selection to move the robot forward and then release the switch to stop. In the second task (Task 2 -negation) the participant was asked to help build the stack of blocks. They were required to stop the robot beside a pile of blocks to allow the investigator to load them onto the robot and then they were required to stop at the original stacked blocks location where the investigator unloaded the blocks. Participants were allowed to use the backward command if they went past the stop location. The third task involved two stacks of blocks located to the left and right of the original stack with the robot placed between them facing away from the participant. The participant was asked to choose a pile (by indicating with eyegaze) and then knock it down. To accomplish that, the participant had to use the appropriate left or right turn command (Task 3A - binary logic), and then use the forward command to drive the robot to knock over the blocks (Task 3B - sequencing of two actions). The participants did each task 3 times and their success or failure at accomplishing the task of knocking over the blocks was recorded.

3.5.2.2 Slalom course with robot control, manipulation and communication components

In the slalom course trials participants drove the robot through a course 1.15 m long. The course was on a large sheet of paper and a marker was attached to the back of the robot so accuracy measures could be made afterwards from the pen-trace. Small 5 cm^3 blocks were used as obstacles and two toy ships were used as the sides of a goal at the finish line. The trials increased in complexity (by adding obstacles) and progressed through performing robot control only, robot control with manipulation, and robot control with manipulation and communication. Table 3-4 shows the protocol and the corresponding math lesson where the skills learned in the training sessions would be used.

Table 3-4: Robot training protocol and corresponding math lesson where the skills would be used

Comp-onent	Number of obstacles in slalom course and concurrent activity	Corresponding math lesson
Robot only	1 obstacle, then 2 obstacles, then 3 obstacles including **stopping on a finish line**	All lessons (stopping on a baseline) Level 1 Lesson 1 (maneuvering between items)
Robot & Manipulation	2 obstacles while: • un-winding a **string** behind the robot and requesting the teacher to tape it down	Level 1 Lessons 2 Level 1 Lessons 3
Robot & Manipulation	2 obstacles while: • gripping a **block** at the start position and releasing it at the end position, then • gripping a second block at the start position and releasing it lined up **tip-to-tip** with the first block	Level 2 Lessons 3 Level 2 Lessons 4
Robot & Manipulation	1 obstacle while: • gripping a **block with a straw** mounted on it at the start position and releasing it at the end position, then • gripping a second block at the start position and releasing it lined up **tip-to-tip** with the first straw.	Level 2 Lessons 3 Level 2 Lessons 4
Robot & Manipulation	2 obstacles while: • lifting the pen up and down to make a dotted line	Level 2 Lesson 5
Robot & Manipulation & Communication	2 obstacles while: • raising and lowering the pen whenever passing the obstacles (i.e., twice), and • switching to communication mode to say a randomly chosen word (pulled from an envelope by a research assistant) once every 2 minutes (notified by a timer set by the investigator)	All lessons (switching between robot control and communication modes)

The participant was told that accuracy was more important than time in these trails. After each set of trials the participant was asked how difficult they felt it was using the following rating scale: really easy, easy, so-so, hard and really hard.

Accuracy was measured as the area enclosed between the participant's pen-traced pathway and the mid-line from the start to finish locations (i.e., the smaller the area, the better the accuracy). To determine the area, a photo of the pathway was taken, each pathway and mid-line was digitized using ImageJ[12], and ImageJ calculated the area. Time to complete each pathway was measured by a research assistant with a stop watch and the values were verified by the investigator from the video of the session at a later date.

3.5.2.3 Robot operational accuracy

Operational accuracy and efficiency using the SGD to control the robot was tested after robot training. Like the operational competence test for scanning on the SGD described earlier (Section 3.5.1.3), this test was also patterned after the "Green Dot Test" (Smith & Vanderheiden, 1992). In this test, the investigator drew targets (circles of 10cm diameter) on a large piece of paper. The random order for 8 target locations was determined prior to the test. The first target was drawn quickly on the paper, and the participant drove the robot to it with a marker attached to the back of the robot (so accuracy measures could be made afterwards from the pen-traces). When the robot reached the circle the robot was picked up and placed back to the start position (at the centre of the paper). Then the procedure was repeated for the remaining targets.

Accuracy was measured as the ratio of the length of the actual trajectory

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[12] ImageJ is available from the National Institutes of Health, http://rsbweb.nih.gov/ij/

taken by the participant divided by the ideal trajectory (i.e., the closer to 1.0, the better the accuracy). The ideal trajectory was chosen as if the participant spun the robot around in a circle until the robot faced the target dot, and then traveled directly forward to reach it, which was the basic pathway taken by all of the participants. To determine the ratio, a photo of the pathway was taken, the trajectories were digitized using ImageJ, and ImageJ calculated the length of each trajectory. Total time for the test was measured by the research assistant with a stop watch and then verified later by watching a video of the test.

3.5.3 Math Sessions

Each math session lasted 30 to 90 minutes and was video recorded. Participants performed the length measurement lessons from the Math Makes Sense resource guide (Pearson Education Canada, 2007, 2008) (a lesson launch and three lessons in each of Level 1 and Level 2). The lessons were taught by a teacher with a minor in Special Education who recently graduated. If the teacher assessed that a participant did not demonstrate knowledge of the concepts from a main lesson, then the participant performed practice activities which were either a repeat of the main lesson with different items to measure or an additional activity from the Math Makes Sense Activity Bank (Pearson Education Canada, 2007). The main lessons and number of practice activities completed by each participant are shown in Table 3-5. All participants completed all of the lessons except M01, who only completed the first lesson of Level 2. M01 and M03 both performed some practice activities.

Table 3-5: Summary of lessons completed by each participant (indicated with ✓) and, if applicable, the number of practice activities done per lesson. Shaded cells are lessons which were selected for inter-rater reliability assessments.

Level	**1**				**2**		
Lesson	**0**	**1**	**2**	**3**	**3**	**4**	**5**
M01	✓	✓ 1 Practice	✓ 2 Practices	✓	✓ 3 Practices	NA	NA
M02	✓	✓	✓	✓	✓	✓	✓
M03	✓	✓	✓	✓	✓	✓Adapted* 1 Practice	✓

* M03 adapted L2L4: Since M03's measurements with straws in L2L3 did not yield values that she could order, the activity was redone in L2L4 by using smaller units so more accurate measurements could be compared.

Each math session followed revised lesson plans created by the teacher (Appendix B) which were based on the Math Makes Sense Teacher guide (Pearson Education Canada, 2007, 2008). The lessons were revised to include a reduced number of questions and manipulative activities. For example, the original Level 1 Lesson Launch had 11 suggested questions for the students, whereas the revised lesson plan had five. Likewise, the original launch had the children compare several items, whereas in the revised lesson plan they were to compare three maximum. The revised lesson plans (Appendix B) contain full session details for each lesson regarding:

- the math vocabulary
- the concept focus and problem to solve
- the materials (with the adaptations required as determined from the task analysis in Appendix A)
- the statements and questions that the teacher said to the student during the introduction, activity and closing

- a description of how the participant was expected to perform the manipulative tasks with the robot and any assistance required from the teacher (as determined from the task analysis in Appendix A).
- an indication of any minor modifications to the procedure between participants
- pictures of how the robot was used in the activities

A brief summary of Level 1 and 2 lesson focus, materials, problem to solve and expected manipulation with the robot are shown in Table 3-6 and Table 3-7. Figure 3-5 shows the layout for the Snake measurement activity. A brief summary of the practice activity materials, activity and expected manipulation with the robot is shown in Table 3-8. A more detailed description of the practice activities can be found in Appendix C. The short names used in the tables will be used to refer to the lessons in the subsequent methods, results and discussion sections.

Table 3-6: Level 1 brief description of the focus, materials, problem to solve, and what the participant was expected to do with the robot for each lesson

Focus, materials and problem to solve from Math Makes Sense 1 (Pearson Education Canada, 2007).

Changes from the original activities in order to accomplish them with the robot are noted and described below the table.

Level	**1**				
Lesson	Launch	1	2	3	
Short Name	L1L0 Compare	L1L1 Bins	L1L2 Ramp and Cars	L1L3 Pathways	L1L3 Draw your own path
Focus	Demonstrate prior knowledge of measurement	Compare objects to one common referent	Order objects according to length	Challenge: apply concepts from earlier lessons	Extension Activity
The materials	collection of objects	unsharpened pencil	ramp, string, tape, pens and three toy cars	a picture of tracks of three animals in the snow	paper and a pencil
The problem to solve	Choose 2 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 the three toy cars travels the farthest past the ramp.	how to can you find out who went the farthest.	create your own "Which one went the farthest?" problem using curves they draw. Have someone else solve your problem.
What the participant was expected to do with the robot	• one item was placed on top of the robot and the other item affixed to the top of a block. • use the robot to place the items side by side, parallel, and line up the ends of the items.	• one item was placed on top of the robot and the other item affixed to the top of a block. • use the robot to place the items side by side, parallel, and line up the ends of the items. • then, grasp the second item with the grippers and put it in the appropriate bin (the bins were hanging off the edge of the table).	• use the gripper to grasp and then release the car at the top of the ramp. • then, drive the robot (with a spool of string on a spindle at the back of the robot) from the bottom of the ramp to the car location (indicated with a piece of tape) while un-winding the string. • then, use the robot to pull the strings side by side, parallel, and line up the ends of the strings.	• drive the robot (with a spool of string on a spindle at the back of the robot) along each pathway while un-winding the string and asking the teacher to tape down the string. • then, use the robot to pull the strings side by side, and parallel (the strings were taped to the start position, so it was not necessary for the participant to line up the ends of the strings).	• drive the robot to the desired start position • put the pen down and drive the robot along their desired pathway design • lift the pen up when finished

* instead, find objects around a table

Table 3-7: Level 2 brief description of the focus, materials, problem to solve, and what the participant was expected to do with the robot for each lesson

Focus, materials and problem to solve from Math Makes Sense 2 (Pearson Education Canada, 2008).

Changes from the original activities in order to accomplish them with the robot are noted and described below the table.

Level	2			
Lesson	3	4		5
Short name	L2L3 Heights	L2L4 Game	L2L4 Giant/Baby Steps	L2L5 Snakes
Focus	Measure, compare and order with multiple copies of a non-standard unit	Estimate, measure, and compare lengths, select appropriate non-standard units, 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
The materials	picture of a gingerbread man (the height of the student), string, scissors, tape, craft sticks, and straws		straws, rods, toothpicks	pipe cleaner (to be a snake) and some toothpicks and a pen
The problem to solve	How do you find out who is tallest, the gingerbread man, you, or a friend?	Start at one end of the room and take 3 giant steps, 2 bunny hops, or 1 heel-to-toe **step***. The first to reach the other end of the room wins.	Estimate and measure the baby step and giant step. In your group, who has the longest giant step?	How long is the snake when it is straight and wavy? [bend the pipe cleaner in front of student]. Estimate, then measure, using one unit. Compare the length to that obtained with multiple units (see Figure 3-5)
What the participant was expected to do with the robot	• Grasp the straw unit with the gripper (unit mounted on a block so it can be held by the robot gripper) • place unit lined up with end of the picture (or string) • place next unit tip-to-tip with the previous unit (repeat) • end lined up as close as possible with the end of string (Or, Method 2 described below**)	• start at one end of a table • select between three different robot programs to move the robot forward different distances • finish at the other end of the table	Same as L2L3 with rod and toothpick units mounted on blocks	• Drive the robot so the pen tip is lined up at the end of the pipe cleaner and move the pen down and up to make a pen mark • Select a program to move the robot ahead by one toothpick length and make another pen mark (repeat) (curvy snake strategy below***) • Place last unit's pen mark at an integral unit's distance but lined up as close as possible with the end of the pipe cleaner

* instead, use robot programs to go forward different distances on a table

** Method 2 was to store a bundle of straws on the top of the robot and the participant was expected to place the straw unit by requesting for the straw to be taken "off" when it was lined up with the end of the string. Then they were expected to move ahead so the back of the unit was tip to tip with the previous unit (repeat unit end of string).

*** Make a small turn prior to selecting toothpick unit program

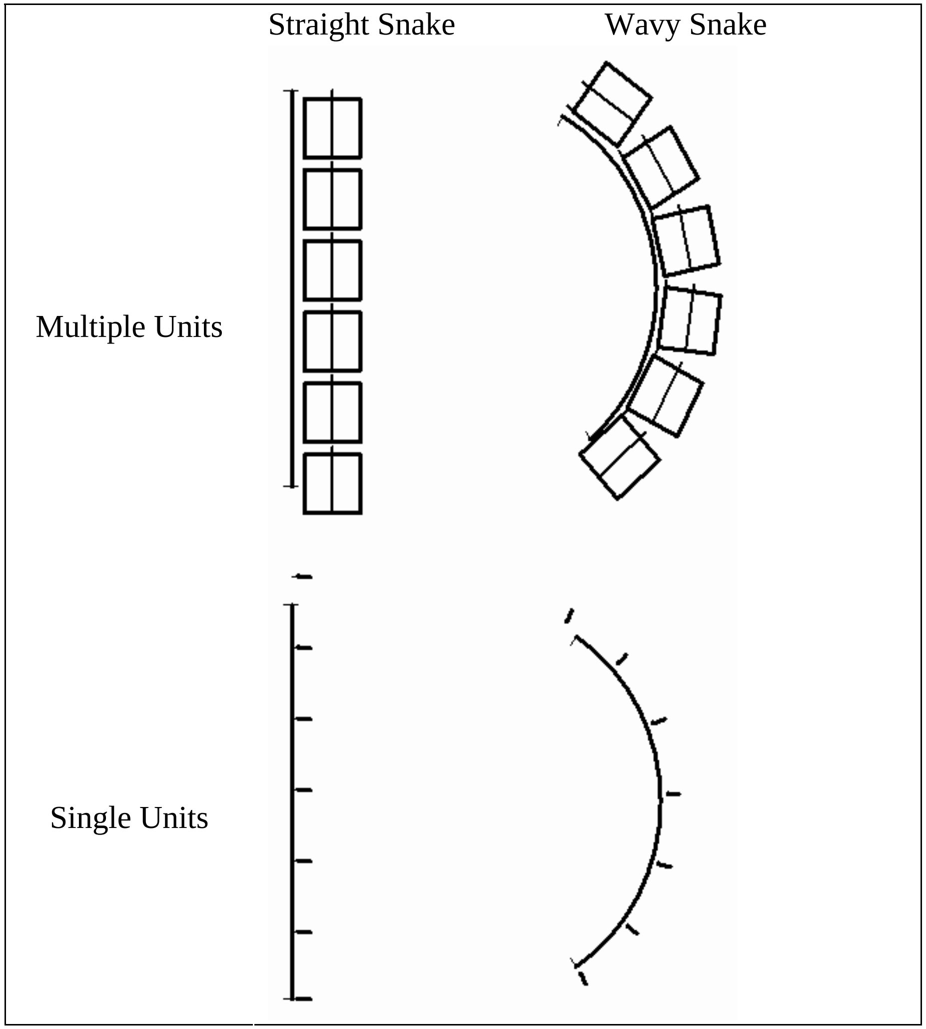


Figure 3-5: Straight and wavy snakes measured in multiple and single units.
For the multiple units, a toothpick placed on top of a block was used as the measurement unit. For single units, the participant advanced the robot a unit interval and then placed a pen mark.

Table 3-8: Practice activities performed by M01 and M03
Included in the table is whether the activity was a repeat of the lesson or if it was from the Math Makes Sense Activity Bank, the materials and problem to solve (from Pearson Education Canada, 2007), and what the participant was expected to do with the robot. Changes from the original activities to accomplish them with the robot are noted and described below the table.

Participant	M01				M03
Level & Lesson	L1L1 Practice	L1L2 Practice 1	L1L2 Practice 2	L2L3 Practice 1,2,3	L2L4 Practice
Short name	Draw lines	Ramp and Cars	Order 4 straws	Heights	Giraffe
Repeat or new	Activity	Repeat	Activity	Repeat	Activity
The materials	a referent and **modeling clay***	Strings from a fake car race	a handful of **crayons**** and the **edge**** of a piece of paper as a baseline	Practice 1: rake, foot, blocks (3, 2, 1 rod units long) Practice 2: shovel, scissors, tree (3, 2, 1 rod units long) Practice 3: jumps of friend & teacher & robot program (12, 8,8,7 rod units long)	a selection of non-standard units and **three objects provided by the teacher*****
The activity	Draw lines that are about as a long as, shorter than, and longer than a referent.		Order the straws by length, from shortest to longest along the baseline.		Estimate, choose the appropriate unit and measure parts of the picture
What the participant was expected to do with the robot	• drive robot so pen tip is at end of referent • put pen down and draw line • stop robot at appropriate location and lift pen	Same as L1L2 above, except releasing car and un-winding strings was omitted.	• Grasp a straw (mounted on a block) with the robot gripper • place unit lined up on baseline (& in proper order) • repeat	Same as L2L3 above, except in Practice 3 she measured using the pen on the robot and moved the robot ahead one rod length using a program (resulting in a line with marks where the ink seeped in to the paper between movements).	Same tasks as L2 L4 above.

* instead of making modeling clay worms, draw lines with a pen
** instead of crayons on the edge of a paper, order straws of differing lengths along a line drawn for the baseline
*** instead of objects, measure different body parts on a large picture of a giraffe

In general, each lesson consisted of some or all of the portions of the lessons shown in Table 3-9, roughly in that order. The lessons sometimes spanned over two sessions and portions were sometimes shortened due to lack of time. The investigator was present in the sessions to facilitate use of the robot. M03's mother was present for all of M03's sessions and she helped to interpret M03's communication attempts if the teacher or investigator did not understand.

Table 3-9: Description of each portion of the lesson

Portion of lesson	**Description**
Introduction	A review of the previous lesson and/or vocabulary and introduction of the problem to solve
Instructions	The teacher gave instructions regarding the activity or how the robot could be used
Ask strategies	The teacher asked the participant for strategies to solve the problem.
Main activity - done using one or more manipulation modes:	**Directing** the teacher so she could manipulate the items
	Observing the teacher **demonstrate** the manipulative task
	Observing the teacher and **guiding** her to do the manipulative task (via teacher-directed questions)
	Using the **robot** to do the manipulative task
Counting (in Level 2 lessons)	The participants counted silently while watching the teacher point to the units, one at a time. The participant then spoke aloud the final number and entered the value into a worksheet on the tablet computer (via a USB connection). M01 sometimes used an SGD page for counting with the robot (described in Section 3.4.1 SGD Interface Design) or the teacher placed numbered cards next to the units.
Reporting	The participants answered questions about their measurements.
Wrap up	The teacher summarized and gave a preview of the next activity.

Prompts during the math session were provided as necessary by the teacher, and followed the hierarchy in Table 3-10.

Table 3-10: Hierarchy of questions asked to participant

Prompt level	**Examples**
High level	What can you tell me about your measurements?
More specific	Which string is longest?
Fill in the blank or one word answers	The yellow string is ____.
Yes or no questions	Is the yellow string longest?

Prompts regarding finding symbol pathways for vocabulary on the SGD were provided by the teacher either using the Word Wall Word Board or by looking up symbol pathways on the Vantage-Vanguard PASS software on a tablet computer. Prompts regarding robot control were provided by the teacher or investigator.

3.5.3.1 Measurement of performance in math activities

The participant's performance was assessed by the teacher immediately after each lesson while watching a video of the session. A rubric from the Math Makes Sense Teacher Resources was used where students are rated from not yet adequate to excellent in four knowledge/skill areas. The knowledge/skill areas and rating levels are shown in Table 3-11 and the full rubric for Level 1 and Level 2 are in Appendix D.

Table 3-11: The assessed knowledge/skills areas and rating levels based on the Math Makes Sense rubric (Pearson Education Canada, 2007).

Knowledge/skills	• **Conceptual understanding** (shows understanding by explaining and/or demonstrating) • **Procedural knowledge** (accurately compares and orders) • **Problem solving skills** (uses appropriate strategies to solve measurement problems) • **Communication** (uses appropriate language and explains reasoning and procedures clearly)
Rating levels	• **Not yet adequate** (needs knowledge/skill re-explained with no achievement) • **Adequate** (needs knowledge/skill re-explained and has partial achievement) • **Proficient** (needs prompts, verbal cues & reminders but achieves knowledge/skill) • **Excellent** (achieves knowledge/skill independently)

The concepts assessed in Level 1 and Level 2 are shown in Table 3-12. The procedures assessed in Level 1 were accurately comparing, sorting, and ordering items and in Level 2, accurately measuring length using multiple or single copies of a non-standard unit and comparing and ordering length measured in non-standard units. Problem solving was not rated with the rubric since the strategies available to the participants were limited by the robot and environment design. Instead, participants were asked for strategies in some problems and the teacher made notes on participant responses.

Table 3-12 : Concepts assessed in (a) Level 1 and (b) Level 2 and the items that were used to assess the concept.
NA = Not Applicable

a)

Concept	**L1L0 Compare**	**L1L1 Bins**	**L1L2 Ramp and Cars**	**L1L3 Pathways**
Compare	Compare two items (one mounted on the robot and the comparison item mounted on a block)		Compare strings representing:	
			distances that the cars travelled	length of the curvy pathways
Sort	NA	Sort the items on blocks into shorter, same and longer than bins	NA	NA
Order	NA	NA	Order the lengths of the strings verbally by looking at them after they are pulled parallel, and lined up at the ends	

b)

Concept	**L2L3 Heights**	**L2L4 Giant/Baby steps**	**L2L5 Snakes**
Comparing and ordering using non-standard units	Heights of gingerbread man, self, and friend	Steps of self (using robot program), friend1, and friend2	Straight and wavy snakes measured with single and multiple copies
How overlapping or leaving gaps affects accuracy	Using multiple copies of non-standard units		Using a single copy of a non-standard unit
Estimation strategies	Height of gingerbread man	Length of steps	Length of snake
How changing orientation of object does not alter measurements	Gingerbread man lying down versus standing up	NA	Straight snake versus wavy snake (made from same pipe cleaner)
Choice of an appropriate unit (i.e., smaller units for smaller items)	NA - participant given straw units	Choose between straws, rods or toothpicks to measure giant and baby steps	NA - participant given toothpick units
How choice of unit affects number needed (i.e., smaller units give larger numbers for measurements)	NA	Understand that cannot compare measurements made with different units	NA

Twenty percent of the math sessions were assessed by a retired special education teacher (External Teacher) using the same rubric to establish the reliability of the teacher's assessment. The sample included one video of each lesson, featuring all participants (selected lessons are shown as shaded cells in Table 3-5). Percentage agreement over the total number of ratings was calculated.

3.5.3.2 Observation of the process of using the integrated communication and robotic control system

Observations of the AT system training and intervention sessions allowed examination of the *process* of using the system. Picture in picture videos were created with a view of the SGD screen within a broad view of the participant and the activity. All session videos were observed to determine the amount of time spent in each portion of the lesson and also:

- the type of manipulation events and amount of prompting needed,
- the number and mode of communicative events,
- HAAT elements (human, activity, assistive technology, and context) which limited the effectiveness of using the robotic system in the tasks.

The HAAT elements and manipulation events were coded by the investigator using NVivo™. NVivo is qualitative analysis software which allows user defined coding of multiple types of documents (e.g., videos and text). Communicative events were tracked using two methods. First, by the built-in SGD automated data logging feature which gives a record all of the words spoken and buttons pressed. This feature was turned on at the beginning of each session, and turned off at the end. The logfile gave a quick indication of the words spoken using the SGD in the session. Second, the SGD and non-verbal modes of communication were coded by two research assistants who were not involved in the intervention. Coding was based on a framework by Clarke and Kirton (2003). Communication events were first coded as an Initiation or a Response and then the mode utilized was coded (SGD output, eye gaze, head nod/shake, or verbalization). A qualitative note was attached to each code to describe the situation or question which resulted in the Initiation or Response and the type of question (e.g., Yes or No, multiple-choice, fill in the blank, or open ended). The number and mode of communication events (as well as time in each portion of the lesson) were measured using Morae(TM) usability software. Videos of the sessions were imported into Morae and then coded for the aforementioned events.

Twenty percent of the communicative event data in the main lessons was reviewed to establish reliability of coding. Percentage agreement over total codes was calculated.

3.5.4 Evaluation of Effectiveness, Efficiency, and Satisfaction

Differences in effectiveness, efficiency and participant satisfaction of using various modes of manipulation were explored. To explore effectiveness and efficiency, video clips were created where the participant performed the same task within a lesson with both the robot and one other manipulation method (e.g., directing the teacher or guiding the teacher with teacher-directed questions). The video clips were from the same lessons selected for the External Teacher assessment inter-rater reliability (shown in Table 3-5). Table 3-13 lists the manipulation mode used in each clip and a short description of the task being performed in the clip. M01's L1L3 was not observed because there were no instances of the teacher doing a part of the main activity.

Table 3-13: Description of each video clip shown to the evaluation team

Lesson & participant	**Manip. Mode**	**Description of video clips**
L1L0 M02	Direct	Teacher asked the participant to tell her "what to do to make sure they are both the same". The participant directed her teacher using his SGD.
L1 L1 M02	Observe	Part 1: The investigator placed item #9 on the baseline and M02 looked towards the "shorter than" bin, the one that he felt the item should be placed in.
	Robot	Part 2: M02 drove the robot beside item #10, moved the robot closer to the object and then gripped the object and placed it in the "same as" bin.
L1 L2 M03	Robot	Part 1: M03 pulled the third string which was attached to the back of the robot and placed it beside the first two strings. The string was parallel to the strings, but the ends were not lined up.
	Observe	Part 2: Teacher moved two of the strings closer to M03 and turned them 90 degrees so M03 could better see the end of the strings
L2 L3 M01	Observe	Part 1: Teacher laid craft sticks down on the gingerbread man picture and sabotaged as she went (e.g., put sticks crooked, with gaps between them)
	Robot	Part 2: M01 drove the robot to put straws down on the gingerbread man picture. She drove the robot to the location that she wanted to have a straw and then said "off" to Teacher to request it be laid down.
L2 L4 M02	Observe	Part 1: Teacher placed straws to measure two different giant steps, the first time with no sabotage (4 straws), and the second time with some sabotage (4 straws).
	Robot	Part 2: M02 placed toothpicks with the robot to measure three baby steps. He entered the results into a worksheet on the tablet computer between measurements.
L2L5 M03	Observe	Part 1: Teacher drew tick marks beside an item as she measured it using a single copy of a unit.
	Robot	Part 2: M03 placed multiple copies of a unit along the straight snake by using the robot and gripper.

Effectiveness was described by the Evaluation Team in an interview while watching the video clips. The following question was posed to the team: "These are video clips of participants doing math tasks using three modes, by directing the teacher to do it, by watching the teacher do it and guiding her based on teacher questions, and by doing it with the robot. Please watch the videos and then comment on effectiveness, i.e., how well the participant can portray what they know about the concept being discussed." In addition, the Adult user of AAC observed a video of each complete lesson and then made comments via email in response to the question, "In your opinion, what do you feel worked and what do you feel did not work when using the robot in the math lessons". The evaluation team responded to her comments via eMail. **Efficiency** was described as the time to perform the task in each manipulation mode. **Participant satisfaction** was measured in all lessons by asking each participant for their preference of manipulation mode to accomplish the math tasks (when they used more than one mode in the lesson).

3.5.5 Post Intervention Interviews

A survey was given to the participants immediately after the last math session based on an "attitude survey" given to third graders after they used computer-based virtual manipulatives for a module to learn about fractions (Reimer & Moyer, 2005). The survey used the technique described by Hanna et al. (1999) for administering surveys with children. The technique asks children to respond to statements on a Likert scale as to whether the statements were: a lot true for me, a bit true for me, sort of true, not really true for me, not at all true for me.

They found that children respond more reliably to pictorial representation of meaningful anchors (smiling and sad faces) and concepts of more and less are better facilitated on a vertical scale rather than a horizontal scale so a five point scale with smiling and sad faces was created on an eye gaze board so the participants could gaze at their response. The statements used in this study were as follows:

1) I liked using the robot to work on measurement
2) The robot helped me understand measurement
3) The robot was easy to use
4) I would like to use the robot to learn other math concepts
5) I like using the robot to do measurement more than I liked telling my EA what to do, and
6) The robot helped me answer the questions on the test

The participants were also asked to rank all of the math lessons in order of preference by directing the investigator in sorting photos of each of the activities into three groups: did not really like it, liked it so-so, and liked it a lot.

After the teacher assessment data was summarized there were two sets of follow-up interviews:

- The participant, EA, teacher and parent: The interviews had an informal structure consisting of describing the lessons, going over the teacher assessment data and focusing the conversation on items where the participant had difficulty. Also, they were asked for any other comments. The participant was asked to confirm that the investigator's summary of their preferences was accurate.

- The Evaluation Team: The interviews had an informal structure which focused on discussion of interesting "events" which occurred during the sessions (e.g., when a participant seemed to have a concept in one instance, but then did not demonstrate the same concept subsequently).

4 RESULTS

4.1 Pre-Existing Competencies

4.1.1 Background Information

As seen in Table 4-1, all of the participants had a number of years of experience using their speech generating devices (SGD), varying experience controlling devices using infrared (IR) from their SGD, and varying interests. M03 also used a letterboard on her wheelchair lap tray by pointing at letters using a closed fist. M01 was a participant in a pilot study where Lego robots were controlled from her SGD to perform math, social studies and science activities two years previously (Adams et al., 2008a) and M03 was a participant in two Lego robot studies performing play activities by controlling the robots using a switch adapted IR controller (with 2 head switches and 2 switches on her lap tray) two years previously (Cook et al., 2007; Cook et al., 2008).

Table 4-1: Participant experience using his/her SGD, experience controlling devices via infrared, and motivating activities

	Experience using SGD	**Experience controlling devices from their SGD**	**Motivating activities**
M01	2 ½ years	Lego robots	using the computer
M02	5 years	IR toys, television and DVD player	driving his power wheelchair, riding on his bike, and playing video games
M03	6 years*	television and DVD player	music, and playing a DVD game for designing clothes

* M03 had changed language systems three months prior to the study

M01's teacher reported that M01 had not worked on math measurement because their focus was on math skills for dealing with money such as addition,

subtraction and the numbers up to 30. She reported that there were four numbers that M01 did not know up to 30 and that "numbers are difficult for her." M02's EA reported that he had experience doing math measurement lessons and she held the items for him while he made comparisons. They also worked with standard units, but his EA expressed that "he was having huge issues handling, centimeters, meters, and millimeters". M03's EA reported that they covered some measurement in the year before the study and described how she manipulated the items (e.g., the ruler) with M03 directing her to do the activity (e.g., "start at the zero"). Evaluation Teacher1 had experience working with M03 and stated that "the number part of math has been a weakness for her for a long time."
M03 expressed that she would like to do math activities involving addition, subtraction, multiplication and division. Hence, addition and division were incorporated into her math lessons.

M01 was the only participant who could be observed in her regular math class. She was observed on three occasions, while she did personalized activities with her EA. One activity was to sort stars and hearts which were on her wheelchair lap tray into separate piles by hand. Another activity was to put puzzle pieces (e.g., "3 + 2" being one piece and "= 5" being the other) together by hand. She and her EA also did an activity with number and money flash cards (e.g., "show me the quarter (or 17)"). These appeared to be difficult activities for the participant to perform since her motor skills were not sufficient to successfully manipulate the items. She became distracted from the activity, and began to chat with her EA. Her EA reported that M01 chatted a lot during classes.

The results of each participant's PPVT receptive language test are shown in Table 4-2.

Table 4-2: PPVT results for each participant

	M01	M02	M03
Raw Score	128	135	145
Standard Score	65	86	80
Percentile	1	18	9
Grade Equivalent	2,4	2,9	3:7
Age Equivalent	8,0	8,6	9:4

4.1.2 Communicative Competency Using the SGD

Partial results of the AAC competency assessment were presented previously (Adams et al., 2010). The time for each participant to re-tell the bus story is shown in Table 4-3 along with any social openings or closings that they may have used. A list of each participant's message output contrasted with the original story script is shown in Table 4-4.

Table 4-3: Time to re-tell the bus story and social openings and closings. Legend: [brackets] = Extraneous, self-corrected, retracted words, or description of action.

	M01	M02	M03
Time:	41 min	36 min	35 min
Social opening:	EA you [? . That's interesting tell me more.] Listens	I'm going to tell you a story.	I tell you a story
Social ending:	done	The end.	[No ending]

Table 4-4: List of each participant's message output for the story re-tell along with the Renfrew bus story script (Glasgow & Cowley, 1994)
Legend: [brackets] = Extraneous, self-corrected, retracted words, or description of action.
H-y-p-h-e-n-a-t-e-d = Spelled words

Bus story script associated with each picture	**M01**	**M02**	**M03**
1. Once upon a time there was a very naughty bus.		It is about the not-y bus.	a bad bus
2. While his driver was trying to fix him,	. Bus[drive] driver want fix	The guy was trying to fix him	
3. the bus decided to run away.	. Bus drive	but he drove away.	ran from his driver
4. He ran along the road beside a train. They made funny faces at each other [small portion of original story omitted here]	train mean help	He drove beside the train and he made funny faces.	he made faces at a train
5. But the bus had to go on alone, because the train went into a tunnel.	Bus driver	But the train drove inside the tunnel.	the train drove away
6. He hurried into the city where he met a policeman who blew his whistle and shouted, "Stop, bus."	no police police see	The police guy said "Stop bus, stop".	the police [mades] made a sound with his mouth
7. But the naughty bus paid no attention and ran on into the country. He said, "I'm tired of going on the road".		But the bus kept on going.	the bus drive off
8. So he jumped over a fence.	jump [is going] [van] bus	So the bus jumped across the f-e-nce [word prediction].	he [jumper] jump* over a wood
9. He met a cow who said, "Moo, I can't believe my eyes."	cow see bus[help]	The cow said "I can't believe my eyes."	he saw some cows
10. The bus raced down a hill. As soon as he saw there was water at the bottom, he tried to stop. But he didn't know how to put on his brakes.		He's going to the lake and he can't find [me] the breaks.	
11. So he fell in the pond with a splash and stuck in the mud. When the driver found where the bus was, she telephoned for a tow truck to pull him out...	bus fal[smart period erased the "l"]-l bus water	So he fell into the pond. The guy called the t-o-w truck.	he [fall] [icon tutor to search word] fell into the lake the driver went to get help
12. and put him back on the road again.		So the tow truck [and he set him on the road.] set him back on the road.	the bus is good [icon tutor to search word] now

* tense error due to device

M01 demonstrated emerging narrative abilities. She required verbal and visual cuing to describe the various elements in the story. Many story elements were missing, and some were told out of sequence. M02's narrative of the bus story included all of the story elements (omitting some details), correctly sequenced, with appropriate story grammar elements (e.g., so then, but, and, quote, etc). M03's narrative of the bus story included most of the story elements with information told in correct sequence.

Table 4-5 shows the listener's re-telling of the story giving an indication of how well the participant included all of the elements of the story.

Table 4-5: Each listener's re-telling after the participants re-tell
Legend: Numbers correspond to the line of the story in the previous table, participant answers are in (parentheses), description of actions are in [brackets].

Picture number	**M01**	**M02**	**M03**
1	There was a bus that wasn't working	So there was this naughty bus.	Okay there was a bus who was bad
2	and the driver wanted to fix it? (nod head)	I should have paid more attention. I can't even remember what the beginning was. Note: This listener was not warned by the test administrator that she would have to retell the story	
3			and he took off on his driver
4	I'm not too sure what's happening with the train. There was a train, a mean train? Did it hit the bus at all? (shake head, "**crazy**") A crazy train?		and he made faces and he passed a train
5			
6			[Added afterwards:] There was a policeman that blew the whistle.
7			

8		afterwards.	and then he went over a fence
9	There was a cow that saw the bus		and passed some cows
10			
11	and then it fell in the water.		and then he went into a lake and the driver had to come get help
12			and he's a good bus now.

The InterAACT grid skills for each participant are shown in Table 4-6, Table 4-7, Table 4-8. The tables show the communication competency skills which were evident in the log files and video analysis. If the skill was not observed in the log files or videos, then the example shown in the table was taken from the interviews with the listener.

Table 4-6: M01 InterAACT Grid of skills

Legend: InterAACT grid skill shown in bold, Skills demonstrated during the story re-tell task shown in normal text, Skills reported during interview shown in italics

	Linguistic	Operational	Social	Strategic
Context Dependent	**Able to denote "more than one"** No evidence.	**Asks for assistance when problem arises** M01 consistently looked at the SLP when she required assistance to find a new vocabulary item	**Maintains topic** M01 maintained the topic of story retell, with some verbal prompts to assist with vocabulary selection	**Select from 1 or more messages to prevent commun. breakdown** *M01 uses a combination of vocalization, vocabulary on SGD, to request help*
	Beginning to combine 2-3 word messages E.g., Bus driver, Bus drive, Train mean, Police see bus, Cow see bus		**Requests Information** M01 looked at the SLP when unsure of information in the story	**Select from 2 or more messages to signal a misunderstood message** M01 vocalized if message was not correctly interpreted.
	Uses quick, multifunctional messages to maintain/control *EA reported that M01 uses a number of quick hits(e.g., "What's new?") and some phrase-based vocabulary items (e.g., "I need…")*		**Requests Actions** *M01 reported to use a combination of vocalization, vocabulary on SGD, to request favorite activities/requests for actions*	**After signaling misunderstanding, uses a strategy to repair.** M01 consistently added information to assist listener understanding. However, she requires verbal cuing (choices, sentence cloze) to help her.
	Understands and uses descriptive words to clarify noun (adjectives) M01 used the adjectives 'mean' and 'crazy', as well as the modifier 'no'; and verbs 'help', 'drive', 'want'		**Asks partner focused questions** *M01 is reported to use some conversational starters to initiate/maintain conversation with her partner.*	

Independent	**Uses plural "s" to denote "more than one"** *M01 does not yet use plurals*	**Page navigation** M01 consistently and persistently navigated between pages to find a desired vocabulary item.	**Demonstrates turn-taking** M01 used nonverbal gestures and SGD to appropriately take turns in conversation.	
	Uses existing vocabulary to describe new word not in device *EA reported that M01 used 'silver' to refer to grey using her SGCD*		**Requests Clarification** M01 consistently looked at her conversational partner following her message to check for understanding	
			Changes message to ensure listener understands M01 added the word 'bus' in response to TA's cue "The bus driver wants to fix something?"	
			Initiation of conversation using standard page sets EA_name listen.	

Table 4-7: M02 InterAACT grid of skills
Legend: InterAACT grid skill shown in bold, Skills demonstrated during the story re-tell task shown in normal text, Skills reported during interview shown in italics

	Linguistic	Operational	Social	Strategic
Context Dependent	**Able to denote "more than one"** Example: faces, eyes, breaks.	**Asks for assistance when problem arises** *Asks for help consistently from familiar partners but needs prompting to do so with peers.*	**Maintains topic** M02 easily maintained topic during his story retell task	**Select from 1 or more messages to prevent communication breakdown** M02 uses a range of vocabulary to communicate specific messages
	Beginning to combine 2-3 word messages Sentences ranged from 6 to 11 words, with some compound sentences.		**Requests Information** *This has been an area of growth over this school year. M02 will ask for help if he doesn't understand a question or direction during academic instruction.*	**Select from 2 or more messages to signal a misunderstood message** M02 checked with listener for understanding, signaled if message correctly received, added information as necessary.
	Uses quick, multifunctional messages to maintain/control *Uses quick hits to initiate conversation, provides one more message to maintain..*		**Requests Actions** *M02 was observed to request help from a classmate by looking to the play area that he wanted to go to so that she could push him there.*	**After signaling misunderstanding uses a strategy to repair.** See above.
	Understands and uses descriptive words Example: funny faces.		**Asks partner focused questions** *This is a developing area, will ask about EA's weekend, or how her family is doing.*	
Independent	**Uses plural "s" to denote "more than one"** See examples above.	**Page navigation** M02 navigates through a range of pages/tools on his Vanguard, including programming.	**Demonstrates turn-taking** Consistently looked at his listener after each generated message and waited for confirmation before proceeding.	

	Uses existing vocabulary to describe new word not in device Example: ‘not’ + ‘y’ for naughty Example: breaks for brakes		**Requests Clarification** *EA reports that he will request for a message to be repeated, or indicate that he doesn’t understand with familiar partners (main teacher, TA, family).*	
			Changes message to ensure listener understands M02 used a number of strategies: substituted for novel words; gave additional information; natural gestures, and facial expression.	
			Initiation of conversation using standard page sets "I'm going to tell you a story."	

Table 4-8: M03 InterAACT grid of skills
Legend: InterAACT grid skill shown in bold, Skills demonstrated during the story re-tell task shown in normal text, Skills reported during interview shown in italics

	Linguistic	Operational	Social	Strategic
Context Dependent	**Able to denote "more than one"** E.g.: faces	**Asks for assistance when problem arises** Specifically requested assistance, e.g. requested help spelling a word for the icon tutor and for turning on/fixing equipment.	**Maintains topic** Maintained topic before, during and after administration of the Renfrew Bus Story, including registering disapproval of story, "I am all a (cued:almost) thirteen"	**Select from 1 or more messages to prevent communication breakdown** Used a variety of signals: e.g., looked at listener to ensure message was understood, facial expression to clarify if message was correctly interpreted.
	Beginning to combine 2-3 word messages Messages from 1 – 5 words.		**Requests Information** *Frequently requests information during academic activities, or regarding areas of interest to her*	**Select from 2 or more messages to signal a misunderstood message** Used facial expression, or corrected with her SGD, if not correctly understood.
	Uses quick, multifunctional messages to maintain/control Combination of facial expression, vocalization, quick hits, comments		**Requests Actions** *Frequently requests actions such as headrest adjustments, back rubs, for mother to share stories.*	**After signaling misunderstanding uses a strategy to repair.** Added to message E.g.: What kind of sound? "With his mouth."
	Understands and uses descriptive words to clarify noun E.g.: 'some', 'good', 'bad'; pronouns 'his', 'you'		**Asks partner focused questions** *Uses quick hits with conversation starters/maintainers and participates in conversations*.	

Independent	**Uses plural "s" to denote "more than one"** Independently corrected singular nouns into the plural forms.	**Page navigation** Independently used pages/tools, including quick hits, icon tutor, keyboard, and ‘toolbox’.	**Demonstrates turn-taking** Exchange of 4 or 5 conversational turns when indicating disapproval of story.	
	Uses existing vocabulary to describe new word not in device Example: “sound with his mouth” to describe whistle.		**Requests Clarification** *She asks for an explanation of unfamiliar vocabulary*.	
			Changes message to ensure listener understands *Uses facial expressions, natural gestures, and SGD with family/ EA and SGD with less familiar partners*.	
			Initiation of conversation using standard page sets *E.g.: “I tell you a story.”*	

M01 required the most variety and frequency of cueing on the InterAACT Grid target skills. However, her listener asked few questions and provided few prompts to support her narrative re-tell. Most of the prompts involved requests for clarification. The SLP provided assistance during the re-tell (e.g., suggesting the listener needed more information, finding symbol pathways to words, reminders to clear the message window). M01's core vocabulary layout had been altered from the default so this may have hindered success. M01's device cell for "bus" was programmed without a space after the word. Also, she frequently used the smart period to get back to the core page which resulted in some letters being erased (i.e., the smart period automatically backspaces to erase the space automatically inserted after each word, inserts a period, and then inserts a space).

M02 required only a few cues and demonstrated the most independence in the InterAACT Grid competencies, showing generally strong skills in all four competency areas. His narrative took 36 minutes and included varying sentence structures, correct punctuation, and grammatical conventions. He flexibly substituted any original story vocabulary his device lacked with suitably alternative words (e.g., selecting "not", then backspacing and adding "y"). He was consistently aware of his listener's needs, visually monitoring her understanding before continuing on.

M03 was independent in her story re-tell and competency skills and required few cues from the SLP. Cueing generally related to clearing the message window, reiterating voice output messages, and spelling to look up unknown vocabulary pathways. M03 and her listener showed well-developed conversational strategies, and M03's listener provided a range of supportive prompts including requests for clarification, suggestions for alternative vocabulary, and suggestions for strategies that might assist her (e.g., "Are you using your icon tutor?" "I think you must need another word"). Although M01 and M03 re-told the story in roughly the same time (41 and 35 minutes respectively), the latter used more narrative elements, longer utterances, richer vocabulary, and more sophisticated grammar and syntax.

4.1.3 Operational Competency Using the Access Method

The results in Table 4-9 show the results of the adapted Green Dot Test for each participant in terms of accuracy (% correct selections out of 12 possible targets), the time to perform the test, and average time per selection (total time/12 targets). M02 did not have a test after the math tasks since he switched to a language system with 84 cells during the math sessions (for reasons not related to this study). However, he performed tests with both quarter-row-column (Q-R-C) and row-column (R-C) scanning on the 84 grid to test his assumption that the Q-R-C scanning method suggested by his SLP was not any faster than his old R-C method. Time to manually place and remove the dots was consistent across participants and tests and was a small percentage of the total selection time (6 to 13%).

Table 4-9: Accuracy (percentage of correctly hit targets out of 12), total time, and average time per target for each participant.
QRC = quarter-row-column and RC = row-column scanning.

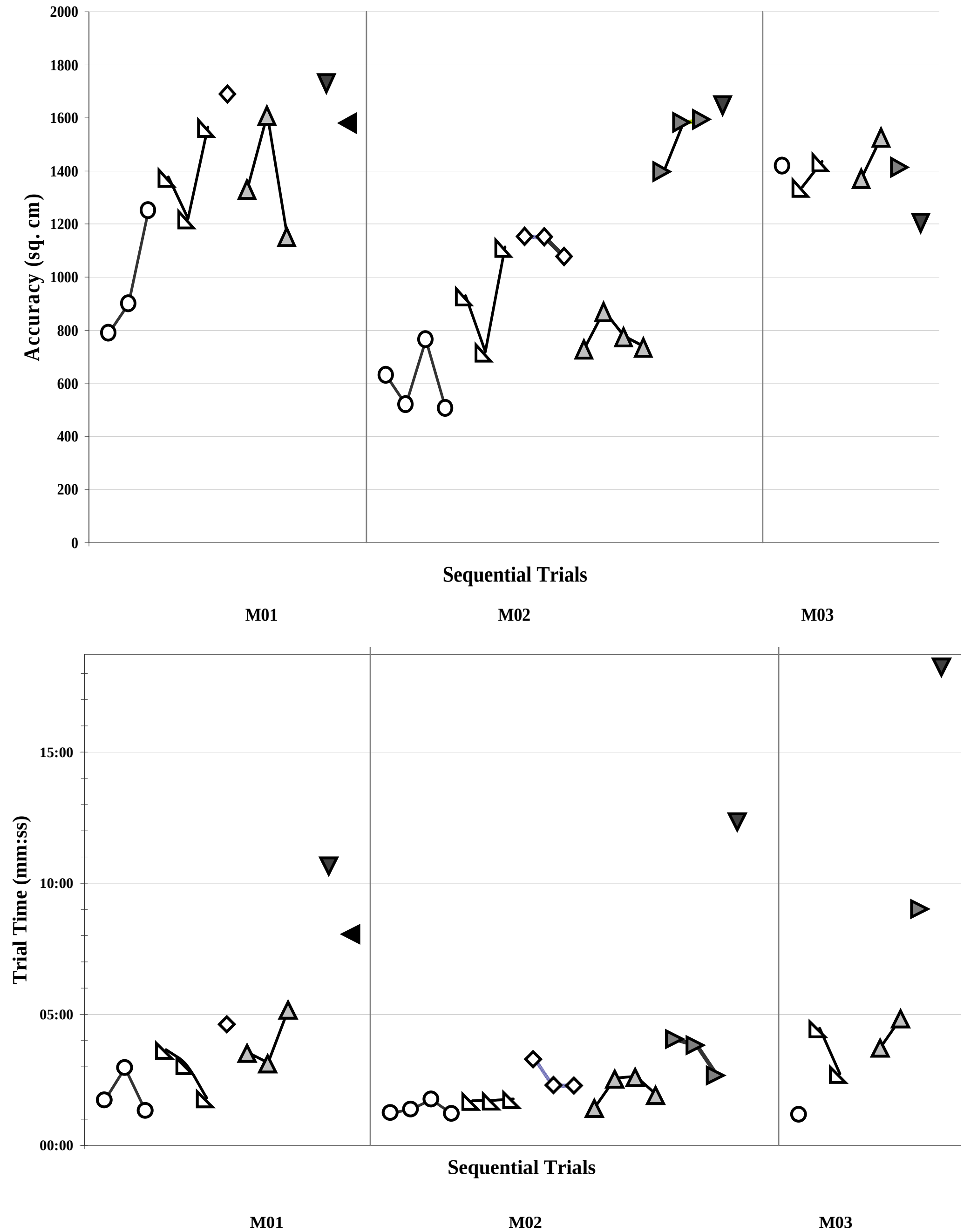
	Trial	Accuracy (%)	Time(mm:ss)	Time/selection (mm:ss)
M01	Initial	83	2:54	0:14
	After training	75	2:33	0:13
	After math tasks	83	3:27	0:17
M02	Initial	100	1:29	0:07
	After training	100	1:32	0:08
	QRC 1	100	1:44	0:09
	RC 1	92	1:48	0:09
	QRC 2	100	1:37	0:08
	RC 2	100	1:40	0:08
M03	Initial	100	2:13	0:11
	After training	100	1:48	0:09
	After math tasks*	100	1:56	0:11

* Calculated with 11 targets.

4.2 Training in Robot Control

All participants accomplished the goal of knocking over the blocks 3 out of 3 times in all tasks in the familiarization session: using forward commands for the cause and effect task, using press and hold forward command for the negation task, choosing the appropriate turn command for the binary task, and performing the turn and then forward commands to knock over the blocks for the sequencing task. All participants completed the slalom course training activities. Figure 4-1 shows each participant's accuracy in terms of area (i.e., the smaller the area, the better the accuracy) and time as each participant progressed through the training activities. Each participant also manipulated straws through a 1-obstacle slalom course, but these data are shown in Table 4-10 since the areas are not comparable to the 2-obstacle slalom trials in Figure 4-1 (the end position was much farther back due to the long straws, see Figure 4-2). The traces from the pen at the back of the robot are also shown in the figure (note the discrete turns of the robot).

M03 did a trial with manipulation of a straw and communication, and her accuracy and time are also shown in Table 4-10. M02 did not do a trial with manipulation and communication, but his skills at changing from robot control to communication mode were demonstrated during a training task where he stopped moving the robot through the slalom course and said, "I can't see". Participant times to un-wind string through the 2 obstacle slalom course (and request to tape it down) were 8:38, 14:32, and 7:01 for M01, M02 and M03, respectively.



Legend: Robot only through course with:
1 Obstacle, 2 Obstacles, 3 Obstacles
Robot through 2-obstacle course with manipulation of:
Blocks, Pen up&down twice, Pen dotted line
Robot through 2-obstacle course with manipulation of:
pen up&down twice and communication

Figure 4-1: Accuracy (top) and Time (bottom) for all participants in training activities.

Table 4-10: Accuracy (in terms of area in cm^2) and time (mm:ss) for the trials with 1-obstacle while manipulating the straws and manipulating the straws with communication

- = Not Applicable for that participant

Measure	Participant	Straw 1	Straw 2 Trial 1	Straw 2 Trial 2	Straw 2 with Communication
Accuracy (cm^2)	M01	570	1413	669	NA
	M02	Not recorded	713	444	NA
	M03	1367	641	NA	1037
Time (mm:ss)	M01	2:54	3:16	2:06	NA
	M02	1:13	1:41	1:34	NA
	M03	5:40	4:53	NA	5:51

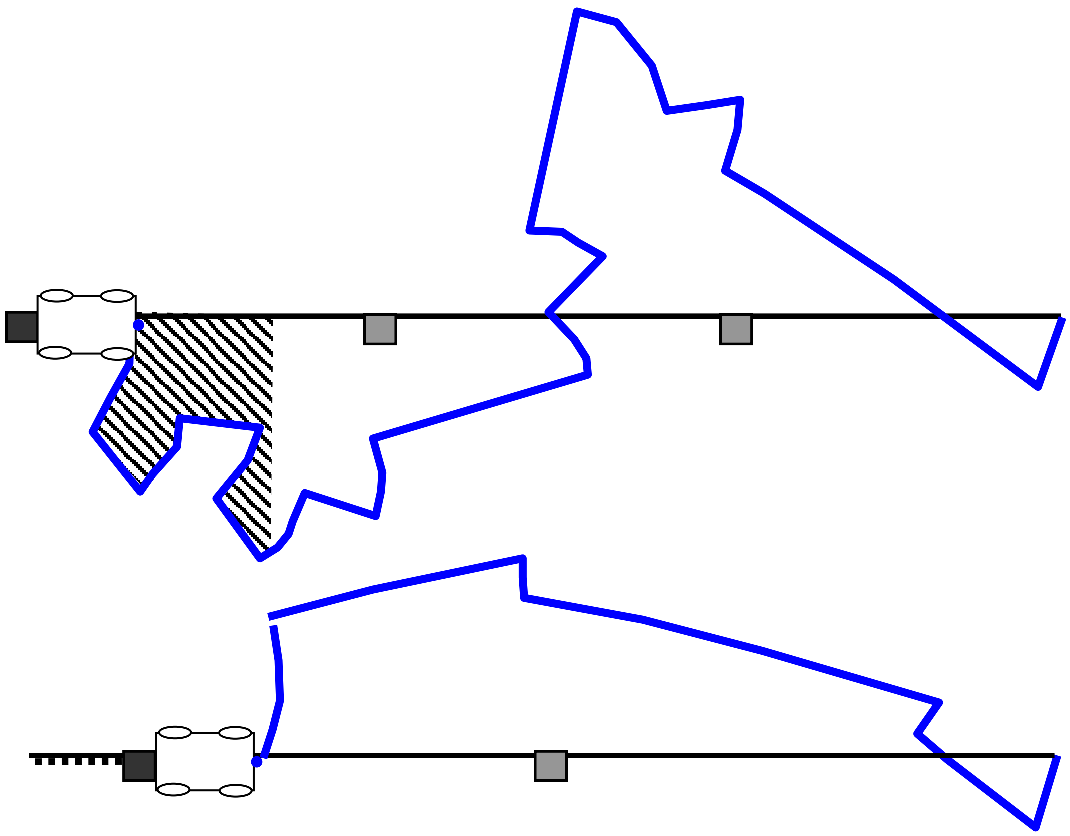


Figure 4-2: 2-obstacle slalom course (top) and 1-obstacle slalom course (bottom) showing the additional area in the 2-obstacle trials.
The start position is at the right, and the end position is at the left. The robot ended farther back in the 1-obstacle course due to the long straw mounted on the block in its gripper.

4.2.1 Participant's Rating of Difficulty of Tasks

The participants rating of difficulty of the training tasks is shown in Table 4-11.

Not all participants were asked all questions.

Table 4-11: Ratings for difficulty of training tasks

	Really easy	**Easy**	**So so**	**Hard**	**Really hard**
Access method test	M01 M02 M03				
Robot only	M02 M03				M01
Robot with blocks		M03	M02		M01
Robot with pen up/down				M03	
Robot with pen dotted line				M02 M03	
Robot, manipulation, and communication			M03		M01

4.2.2 Operational Competence Controlling the Robot

The results of the final robot operational accuracy test controlling the robot through the SGD are in Table 4-12.

Table 4-12: Robot operational accuracy test controlling the robot with the SGD

Participant	**Time (mm:ss)**	**Accuracy (actual/ideal)**
M01	7:57	1.53
M02	6:30	1.13
M03	9:28	1.16

4.3 Math Measurement Sessions

4.3.1 Teacher Assessments

Teacher ratings for conceptual understanding and procedural knowledge each participant in the Level 1 and Level 2 lessons are shown in Table 4-13 to Table 4-18. Ratings for communication in Level 1 and Level 2 lessons are shown in Table 4-19. Any ratings that were assessed as not yet adequate or adequate are marked with comments made by the teacher. If the teacher made no comment, then the investigator added a comment based on the video observations. More details regarding what the participant said and did during the lessons are presented in Section 4.4 regarding observation of the process of using the communication and robotic system.

Legend for all Teacher Assessments, Tables 4-13 to 4-18:

Activity: Main (M), Practice (P), Adapted (A)
O - when assessed in a session where only observation was used.
X - when assessed in a session where the robot and/or observation was used
italics - Investigator's comment rather than the teacher's
NA = Not Applicable

Table 4-13: M01's Level 1 assessments of conceptual understanding and procedural knowledge

Conceptual Understanding	Lesson	0	1		2			3
	Activity	M	M	P	M	P1	P2	M
Compare	Excellent	xo	x	xo				x
	Proficient							
	Adequate				x	x	x	
	Not yet adequate							
	Notes:				1	3	5	
Sort	Excellent		x					
	Proficient	NA		NA	NA	NA	NA	NA
	Adequate							
	Not yet adequate							
	Notes:							
Order	Excellent							
	Proficient	NA	NA	NA				Not scored
	Adequate					x	x	
	Not yet adequate				x			
	Notes:				2	4	6	

Procedural Knowledge	Lesson	0	1		2			3
	Activity	M	M	P	M	P1	P2	M
Compare	Excellent		x	xo				x
	Proficient	x					x	
	Adequate					x		
	Not yet adequate				x			
	Notes:				A	C		
Sort	Excellent		x					
	Proficient	NA		NA				NA
	Adequate							
	Not yet adequate							
	Notes:							
Order	Excellent							
	Proficient	NA	NA				x	Not scored
	Adequate					x		
	Not yet adequate				x			
	Notes:				B	D		

Notes

Lesson 1 Level 2 Main

1 Did not understand that distance was represented by strings

2 Although the middle string was the shortest, she called it middle

A Did not use baseline

B Did not understand baseline concept

Lesson 1 Level 2 Practice 1

3 Did not use baseline until 3rd string, with heavy prompting

4 Needed explanation three times that strings represented distance

C Did not use the baseline until the 3rd try

D Did not use the baseline until the 3rd try

Lesson 1 Level 2 Practice 2

5 Did not understand that the 4th object could be compared to the other 3

6 Could do it after demonstration

Table 4-14: M01's Level 2 assessments of conceptual understanding and procedural knowledge

Conceptual Understanding	Lesson Activity	3			
		M	P1	P2	P3
Compare/ Order	Excellent				x
	Proficient				
	Adequate	x		x	
	Not yet adequate		x		
	Notes:	7	10	11	
Overlap/gap	Excellent	x	Used magnetic rods		
	Proficient	xo			
	Adequate				
	Not yet adequate				
	Notes:				
Estimation	Excellent		NA	NA	
	Proficient				
	Adequate				x
	Not yet adequate	o			
	Notes:	8			12
Orientation	Excellent		NA	NA	NA
	Proficient				
	Adequate	o			
	Not yet adequate				
	Notes:	9			

Procedural knowledge	Lesson Activity	3			
		M	P1	P2	P3
Compare	Excellent	x	x	x	
	Proficient				x
	Adequate				
	Not yet adequate				
	Notes:				
Order	Excellent			x	Did not do
	Proficient				
	Adequate				
	Not yet adequate	x	x		
	Notes:	E	F		
Multiple Units	Excellent	x	x	x	
	Proficient				x
	Adequate				
	Not yet adequate				
	Notes:				

Notes

Lesson 2 Level 3 Main

7 Does not understand that she is using non-standard units to measure, not concrete items (like strings)

8 Said Gingy would be 100 tall

9 After measuring, she said standing Gingy would be 100 (actually 9)

E Did not know if 8 or 9 was bigger (until looked at numbers page)

Lesson 2 Level 3 Practice 1

10 Does not connect that the number represents length.

F Struggled to order them, but knows 3 greater than 2

Lesson 2 Level 3 Practice 2

11 Could do concept, but needed support

Lesson 2 Level 3 Practice 3

12 Estimate OK (9 when actual was 12) but couldn't explain reasoning.

Table 4-15: M02's Level 1 assessments of conceptual understanding and procedural knowledge

Conceptual Understanding	Lesson	0	1	2	3
	Activity	M	M	M	M
Compare	Excellent	o	x	x	x
	Proficient				
	Adequate				
	Not yet adequate				
	Notes:				
Sort	Excellent		x		
	Proficient	NA		NA	NA
	Adequate				
	Not yet adequate				
	Notes:				
Order	Excellent			x	x
	Proficient	NA	NA		
	Adequate				
	Not yet adequate				
	Notes:				

Procedural Knowledge	Lesson	0	1	2	3
	Activity	M	M	M	M
Compare	Excellent		x	x	
	Proficient	o			Bsln. Taped
	Adequate				
	Not yet adequate				
	Notes:				
Sort	Excellent				
	Proficient	NA	x	NA	NA
	Adequate				
	Not yet adequate				
	Notes:				
Order	Excellent			x	
	Proficient	NA	NA		Not scored
	Adequate				
	Not yet adequate				
	Notes:				

Table 4-16: M02's Level 2 assessments of conceptual understanding and procedural knowledge

Conceptual Understanding	Lesson / Activity	3 M	4 M	5 M
Compare/ Order	Excellent			x
	Proficient		x	
	Adequate	x		
	Not yet adequate			
	Notes:	1		
Overlap/gap	Excellent	xo	Rods	NA
	Proficient			
	Adequate			
	Not yet adequate			
	Notes:			
Estimation	Excellent		x	x
	Proficient	x		
	Adequate	o		
	Not yet adequate			
	Notes:	2		
Orientation	Excellent		NA	x
	Proficient	o		
	Adequate			
	Not yet adequate			
	Notes:			
Appropriate choice of unit	Excellent	NA	x	NA
	Proficient			
	Adequate			
	Not yet adequate			
	Notes:			
Choice of unit affects #	Excellent	NA	x	NA
	Proficient			
	Adequate			
	Not yet adequate			
	Notes:			

Procedural knowledge	Lesson / Activity	3 M	4 M	5 M
Compare	Excellent		x	x
	Proficient			
	Adequate	x		
	Not yet adequate			
	Notes:	A		
Order	Excellent		x	NA
	Proficient			
	Adequate	x		
	Not yet adequate			
	Notes:	B		
Multiple Units	Excellent	x	x	Did not do
	Proficient			
	Adequate			
	Not yet adequate			
	Notes:			
Single Units	Excellent	NA	NA	x
	Proficient			
	Adequate			
	Not yet adequate			
	Notes:			

Notes

Lesson 2 Level 3 Main

1 His use of fractions may have confused him

2 First time he said 40 (actual 7) but became good at it quickly

A He needed concrete visuals to fully understand concept

B He needed concrete visuals to fully understand concept

Table 4-17: M03's Level 1 assessments of conceptual understanding and procedural knowledge

Conceptual Understanding	Lesson / Activity	0 / M	1 / M	2 / M	3 / M
Compare	Excellent				
	Proficient	x	x		x
	Adequate			x	
	Not yet adequate				
	Notes:			1	
Sort	Excellent	NA		NA	NA
	Proficient		x		
	Adequate				
	Not yet adequate				
	Notes:				
Order	Excellent	NA	NA		Not scored
	Proficient			x	
	Adequate				
	Not yet adequate				
	Notes:				

Procedural Knowledge	Lesson / Activity	0 / M	1 / M	2 / M	3 / M
Compare	Excellent	x	x		Bsln. Taped
	Proficient				
	Adequate			x	
	Not yet adequate				
	Notes:			A	
Sort	Excellent	NA		NA	NA
	Proficient		x		
	Adequate				
	Not yet adequate				
	Notes:				
Order	Excellent	NA	NA		Not scored
	Proficient			x	
	Adequate				
	Not yet adequate				
	Notes:				

Notes

Level 1 Lesson 2

1 Did not line up strings along a baseline

A Did not line up strings along a baseline

Table 4-18: M03's Level 2 assessments of conceptual understanding and procedural knowledge

Conceptual Understanding	Lesson / Activity	3 M	4 A	4 P	5 M
Compare/ Order	Excellent				
	Proficient	x			
	Adequate		x	x	
	Not yet adequate				x
	Notes:		4	6	8
Overlap/gap	Excellent		Rods	x	x
	Proficient	xo			
	Adequate				
	Not yet adequate				
	Notes:				
Estimation	Excellent		NA		
	Proficient				
	Adequate			x	
	Not yet adequate	o			x
	Notes:	2		7	9
Orientation	Excellent		NA	NA	
	Proficient				
	Adequate				
	Not yet adequate	o			x
	Notes:	3			10
Appropriate choice of unit	Excellent	NA	No choice	x	NA
	Proficient				
	Adequate				
	Not yet adequate				
	Notes:				
Choice of unit affects #	Excellent	NA			NA
	Proficient			x	
	Adequate				
	Not yet adequate		x		
	Notes:		5		

Procedural knowledge	Lesson / Activity	3 M	4 A	4 P	5 M
Compare	Excellent	x			
	Proficient			x	x
	Adequate		x		
	Not yet adequate				
	Notes:		C		
Order	Excellent	all same		NA	NA
	Proficient				
	Adequate		x		
	Not yet adequate				
	Notes:		D		
Multiple Units	Excellent			x	
	Proficient		x		
	Adequate	x			x
	Not yet adequate				
	Notes:	B			E
Single Units	Excellent	NA	NA	NA	
	Proficient				
	Adequate				x
	Not yet adequate				
	Notes:				F

Notes

Level 2 Lesson 3 Main

2 Said 30 (actual 9) in craft sticks. Then said 10 in straws when it should be < 9 because straws smaller than craft sticks

3 Said 10 (actual 7), it took 3 demonstrations to understand concept

B Did not put straw at end of string

Level 2 Lesson 4 Adapted

4 Did not put first rod at the end of the string

5 Said numbers measured in rods and straws could be compared

C Did not put first rod at the end of the string

D Did not use data to answer question until prompted

Level 2 Lesson 4 Practice

6 Forgot that numbers must be measured in same unit

7 *It was 9 rods and she said it would be 12 toothpicks (actual 18) but toothpicks are half as long as rods*

Level 2 Lesson 5 Main

8 Did not understand that measuring with single and multiple copies gives the same number

9 Did not get concepts of straight = curvy and single=multiple therefore estimates off

10 Did not understand that straight and curvy are the same number of units long

E Errors probably due to robot control

F *Put last dot at end of pipe cleaner rather than end of unit.*

Table 4-19: Teacher's assessments of participant's communication during lessons

Commu-nication	Level	1							2							
	Lesson	0	1		2			3	3				4			5
	Activity	M	M	P	M	P1	P2	M	M	P1	P2	P3	M	A	P	M
M01	Excellent	x	x	xo												
	Proficient	o				x	x	x								
	Adequate								x		x	x				
	Not yet adequate				x					x						
	Notes:				a				b	c	d	e				
M02	Excellent	o	x		x			x								
	Proficient				x								x			x
	Adequate								x							
	Not yet adequate															
	Notes:								f							
M03	Excellent		x													
	Proficient	x			x			x	x					x	x	
	Adequate															x
	Not yet adequate															
	Notes:															g

Notes

M01
- a Although the middle string was the shortest, she called it middle
- b Said EA was tallest because she's an adult (did not use the numbers)
- c Said "longer fork foot" when asked how do you know, she said she was guessing
- d Struggles to communicate her reasoning
- e Struggles to communicate her reasoning, but can answer Y/N questions

M02
- f Required prompting

M03
- g Gave 1-word answers, needed prompting

The teacher generally commented that problem solving (uses appropriate strategies to solve problems) was not measureable since the activities were very teacher directed. She noted that the participants required a lot of assistance to transition from one task to another, particularly M01 (e.g., transitioning from un-winding string on pathways to pulling them straight to compare them). Table 4-20 lists the strategy suggestions made by the participants in the lessons.

Table 4-20: Comments regarding problem solving which were noted by the teacher.
Teacher prompts are in parentheses

Level Lesson	**Participant**	**Teacher's comment**
L1L2	M02	Suggested to "Move the ramp" to keep the cars from bumping in to each other as a new car came down the ramp.
	M02	Suggested to "get a tape measure" when asked how to tell who went the farthest.
	M03	Suggested to "Tape down the (string)" after being shown potential supplies that she could use to see which car when the farthest.
		After being asked how she would like to tape down the string she began moving the robot down the ramp towards a car location tape mark.
	M02	Suggested to "put the string so it is stretchy" after being asked what was the next step after spooling out each string to the car location tape mark.
L1L3	M02	Suggested using "string" to measure the pathways because "it turns".
	M03	Suggested using "sring" (string) because of the "long b-e-n-d-s" in the pathway.
	M02	After unwinding the string along the pathways, he suggested to "move it (the string) nearer (to what?) the string".
	M03	After unwinding the string along the pathways, she suggested to use a "tape measure" to compare them.
L2L3	M01	Said that string was better than straws to measure people because it was "thinner".
L2L5	M03	Suggested using the "pen" if the teacher only had one unit to measure with, although she needed a hint about how she used the item previously.

4.3.2 Reliability of Teacher Assessments

The agreement between the teacher and the External Teacher for conceptual understanding was 71%, for procedural knowledge was 50%, and for communication was 88%. The combined average was 70% and the breakdown is shown in Table 4-21.

Table 4-21: Percentage agreement for items selected for reliability coding

	Agree	Not agree	Total	% Agreement
Conceptual understanding	12	5	17	71%
Procedural Knowledge	7	7	14	50%
Communication	7	1	8	88%

The percentage agreement was also calculated for when the teacher and the External Teacher's ratings were within one level of each other, on the four point scale. With this method, the agreement for conceptual understanding was 94%, for procedural knowledge was 93%, and for communication was 100%. The combined average was 96% and the breakdown is shown in Table 4-22. The evaluation team and EAs confirmed the assessments of the teacher and verified the identified gaps in knowledge.

Table 4-22: Percentage agreement for items rated within one level

	Agree	Not agree	Total	% Agreement
Conceptual understanding	16	1	17	94%
Procedural Knowledge	13	1	14	93%
Communication	8	0	8	100%

4.4 Observation of the Process of Using the System for Math Activities

Data collected from observations of the math lesson videos are presented in this section including the amount of time spent in each portion of the lesson, a description of manipulation events and a description of communicative events.

4.4.1 Time Spent in each Portion of the Lesson

Table 4-23 shows the total time spent by the participants in each of the main lessons and Figure 4-3 shows a distribution of the time spent in each portion of the lesson. Note that M02 was the only participant to use the activity manipulation mode of directing the teacher (in Level 1 Launch) and since M03 performed an adapted Level 2 Lesson 4, the time she spent in each portion of the lesson is not shown in Figure 4-3 for that lesson only. Total time spent in the practice activities is shown in Table 4-24 and includes some set up and break time. Time in the Level 1 Lesson 3 extension activity to draw your own "who went the farthest pathway" was approximately 15 minutes for each participant.

Table 4-23: The total time spent in each of the main lessons (hh:mm)

	L1 L0	L1 L1	L1 L2	L1 L3	L2 L3	L2 L4	L2 L5
M01	0:24	0:24	0:34	0:26	1:39	NA	NA
M02	0:41	1:00	1:27	0:56	1:47	1:24	0:44
M03	0:37	0:45	1:08	1:02	1:28	1:40*	1:44

* M03 performed an adapted Level 2 Lesson 4

Table 4-24: Total time (hh:mm) for additional practice activities for M01 and M03 (including set up and breaks)

M01			M03
L1L1	**L1L2**	**L2L3**	**L2L4**
Practice 1 0:26	Practice 1 0:55 Practice 2 0:43	Practice 1 1:12 Practice 2 0:13 Practice 3 1:08	Practice 1 0:58

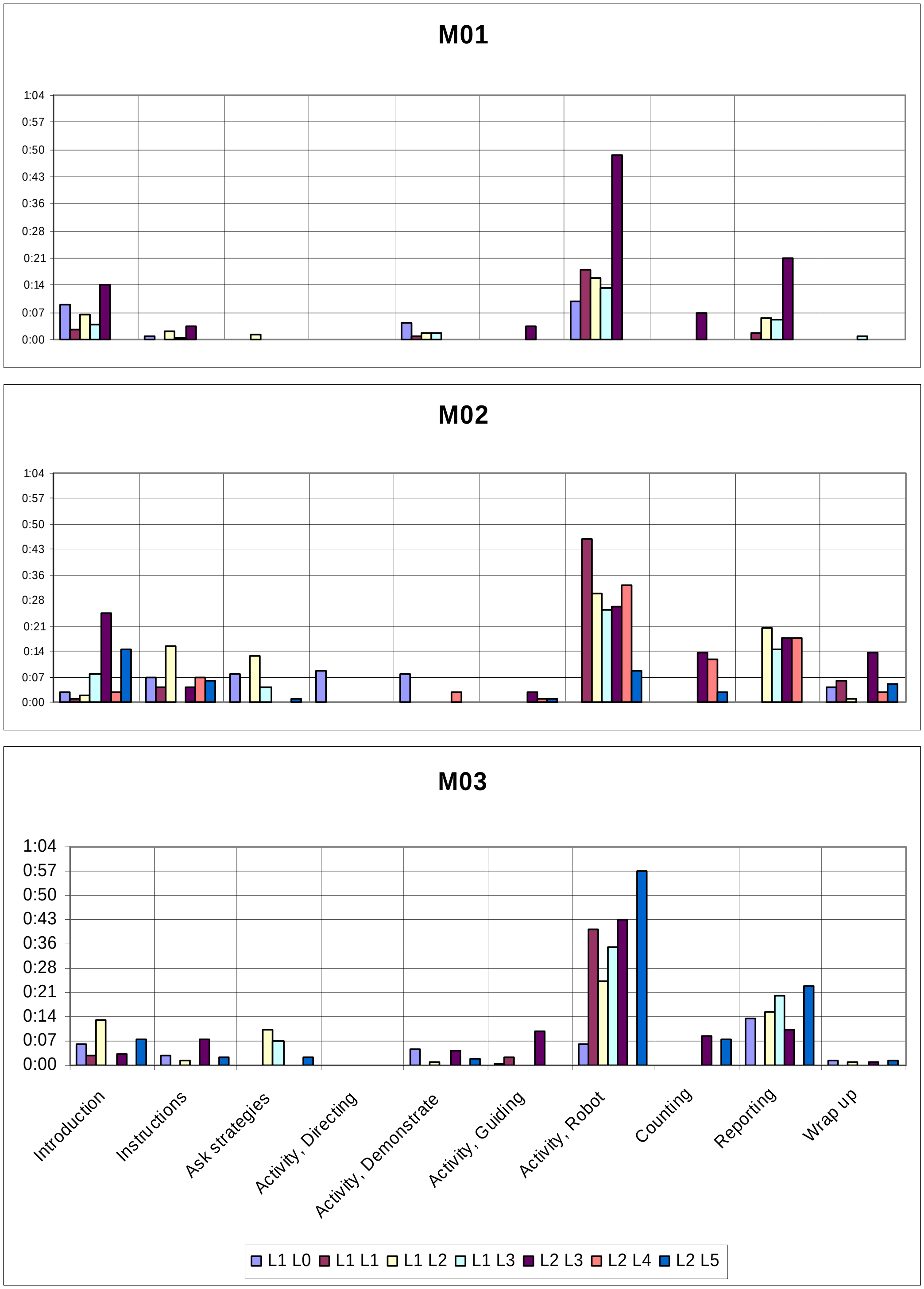


Figure 4-3: Distribution of the time (hh:mm) spent in each portion of the activity in each lesson.

4.4.2 Manipulation Events

The results presented in this section are a brief summary of how the participant performed the manipulation tasks including any interesting events and trends. A detailed account of how the participant performed each manipulative task in each lesson can be found in Appendix E. Appendix E contains:

- the tasks where the participant observed the teacher perform the manipulation (from the Revised Lesson Plans, Appendix B)
- the tasks that were the responsibility of the participant to perform using the robot (as determined from the task analysis, Appendix A),
- a description of how the participant performed the task, and
- notes regarding any special situations.

Level 1

Please refer to Table 3-6 in the Methods section for a summary of the tasks and how the participant was expected to perform the task with the robot in Level 1. Table 4-25 shows each task performed with the robot for the main Level 1 lessons and an indication of how quickly the participant "got" it. The following list describes which tasks were used in which lessons and any differences between lessons:

- "Place items parallel" and "Line up ends of items" were common to all of the lessons. In Level 1 Launch (L1L0 Compare) and Level 1 Lesson 1 (L1L1 Bins) the items to compare were items like pencils (mounted on top of the robot) and toy rakes (mounted on top of blocks). In Level 1 Lesson 2 (L1L2 Ramp and Car) and Level 1 Lesson 3 (L1L3 Pathways) the items to compare were strings taped to the back of the robot. These tasks specifically used skills assessed by the teacher in the procedure of comparing items.

- "Grasp block under second item" and "Put item in appropriate bin" were only used in L1L1 Bins. Putting the item in the appropriate bin used the skill of sorting items (shorter, same, longer).
- "Release car" was only used in L1L2 and did not necessarily require any procedural skills for measurement, but it allowed the participant to carry out the tasks required to solve the problem.
- "Unwind string" was used in L1L2 Ramp and Car to measure the distance from the bottom of the ramp to the location that each car stopped and it was used in L1L3 Paths to measure the distance along each of the pathways. This task used the procedural skills of determining the appropriate start and stop location and accurately following the pathway, but were not specifically assessed by the teacher in the procedure of comparing items.

Table 4-25: Level 1 tasks with an indication of how quickly participants "got" it
Legend:

+ Participant performed the task appropriately on the first try
o Participant performed the task appropriately after one or two prompts
- Participant did not perform the task appropriately even after prompting

Manipulative Task	Participant	L1L0	L1L1	L1L2	L1L3
Release car	M01			+	
	M02			+	
	M03			+	
Unwind string	M01			o	+
	M02			+	+
	M03			+	o
Place item parallel*	M01	o	+	+	+
	M02	+	+	+	+
	M03	+	+	+	+
Line up ends of the items*	M01	o	o	-	
	M02	o	+	+	
	M03	o	o	-	NA
Grasp block under 2nd item	M01		+		
	M02		+		
	M03		-		
Put item in appropriate bin*	M01		+		
	M02		+		
	M03		+		

* These tasks specifically used skills assessed by the teacher under procedural knowledge

In general, the participants performed most tasks appropriately and as expected.

The following boxes list observations of when the participant performed the tasks inappropriately, or with alternative strategies. The boxes are separated into tasks specifically used to assess the procedure of comparing items (Box 4-1), those which were not specifically assessed by the teacher, but allowed the participant to carry out the procedure (Box 4-2), and tasks from the extension or practice activities (Box 4-3).

Box 4-1: Observations of tasks in Level 1 which specifically used skills assessed by the teacher in the procedure of comparing items

<u>Place items parallel</u>

M01: In L1L0, she did not move the robot so that the items were parallel on the first item (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.

- In L1L1 Bins, she grasped the first comparison item again. After prompting to compare them first, she made the items parallel.

M02: In L1L0, he manipulated by directing the teacher what to do based on situations that she set up for him to evaluate and repair:

> Teacher: "I could put [the items] like this." [crooked]
> M02: "Move it straighter."

<u>Line up ends of items</u>

M01 and M03: In L1L0 Compare, they needed reminders to line up the ends.

- In L1L1 Bins they continued to need reminders
- In L1L2 Ramp and Cars they did not line up all three strings
- In L1L3 Pathways, lining up the ends was Not Applicable because the teacher suggested that the strings be left taped down to the start position (participants only had to pull the strings straight and close to each other to compare them)

M02: In L1L0 Compare, his instructions for directing the task were:

> Teacher: "What if I put it like this?" [offset by about 15 cm]
> M02: "Down a little bit"
> [the teacher moved the item until M02 nodded]
> Teacher: "Why did you stop there?"
> M02: "It is in the centre"

- In L1L1 he lined up the back end of the referent (on the robot) and the comparison item (not the front end as expected) and it took some discussion to understand that was what he was doing.

<u>Put item in appropriate bin</u> (M01 did 4 items, M02 did 10, and M03 did 6)

M02 and M03: In L1L1 Bins they each put one item that was about the same size as the referent into the wrong bin (but immediately noticed their mistake when the teacher checked their work by manipulating the items herself).

All participants used the strategy that if they could tell just by looking at the items, then they did not need to use the robot to line them up side by side (they could just "eye ball it" and place it in the appropriate bin).

- **M02 and M03** lined up two items each which were noticeably different lengths from the referent, otherwise, they used the strategy appropriately.

Box 4-2: Observations of tasks in Level 1 which were not specifically assessed by the teacher, but allowed the participant to carry out the procedure

Grasp block under second item
M03 did not approach the blocks from an appropriate angle so parts of the item prevented the robot's gripper from getting close to the block.

Release car (L1L2 Ramp and Cars Only)
All participants seemed to really enjoy this task and none had problems.

Unwind string
M01: In L1L2 Ramp and Cars, she began to un-wind the string between the stop location tape marks rather than from the end of the ramp to each stop mark.
M02: He had no difficulty with this task and also completed a worksheet with three pathways which required very good robot operational control skills.
M03: In L1L3 Pathways, she did not stop at the appropriate end point on the first path, even though she had previously indicated to the teacher where the end was.

- She had problems backing up to get back on the path.
- She requested more tape than was necessary to keep the string on the straight portions of the path, and did not request enough at the bend in the path.

Box 4-3: Observations of additional tasks in Level 1 which were not shown in Table 4-25

Making your own "Who went the farthest" pathway
All participants seemed to enjoy this task.

- **M01's** first path was too difficult to solve, so the teacher gave her heavy prompting to make the other two pathways simpler.
- **M02** and **M03's** paths were appropriate for someone to solve and they were creative about what the paths represented. **M02's** was a race track for his video game characters and **M03's** was pathways to the mall for her friends

Ordering (assessed by reporting verbally rather than manipulation except for M01's L1L2 Practice 2 Ordering Straws)
M01 placed three straws in order along a baseline (although, not lined up on the baseline very well until prompted to fix them), but had trouble understanding what to do with the fourth straw.

Draw lines (only M01 performed this activity, L1L1 Practice - drawing lines that were shorter than, same as, and longer than a referent).
M01: After prompting to line up the robot pen at the end of the referent for the first line, she accomplished the rest of the activity appropriately.

Level 2

Please refer to Table 3-7 for a summary of the tasks in Level 2 and how the participant was expected to perform each task with the robot. Table 4-26 shows each task performed with the robot for the main Level 2 lessons and an indication of how quickly the participant "got" it. The participant's procedural skills for accurately comparing and using multiple and/or single units were assessed through these tasks (except for "grasp the unit"). The following list describes which tasks were used in which lessons and any differences between lessons:

- "Grasp the unit" was used in all lessons. The non-standard unit was affixed to the top of a block and the participant grasped it with the robot gripper.
- "Place unit on baseline", "place next unit tip to tip with previous unit", and "place last unit on other baseline" were common to all lessons with the following slight variations in using the robot:
    - In all Level 2 lessons the participant used the **robot and gripper** to measure with multiple copies of a unit. The only thing that changed between lessons was the unit (affixed to the top of a block and held by the robot gripper) and the item to measure.
        - In L2L3 Heights the units were straws and the item to measure was a picture or string representing the height of people.
        - In L2L4 Giant/Baby Steps the units were rods or toothpicks (with magnets so they snapped together) and the item to measure was a string representing the length of the giant or baby steps.
            - In M03's L2L4 Giraffe, she used straws (with no magnets) and toothpicks (with magnets) and the item to measure was body parts on a picture of a Giraffe.
        - In L2L5 Snakes, measuring with multiple units, the units were toothpicks with magnets, and the item to measure was a pipe cleaner representing a snake. The pipe cleaner was bent into a C-shape to represent the wavy snake.
    - In L2L3 the participants used the **robot and "off"** method in at least one of the measurements using multiple units. With this method, the straws were stored on top of the robot and the participant placed them by asking the teacher to take a straw "off".

The teacher placed the straw directly below where it laid on top of the robot.

- They were allowed to choose the method for their third measurement, **robot and gripper or robot and "off"**

- In L2L5 Snakes where the participant measured with single copies of a unit, the **robot and pen** was used to: place at mark at the baseline, then place another mark one unit length away (i.e., tip to tip) by moving the robot forward by only one unit length (using a robot program), then place the last mark as close as possible to the other end of the baseline.

Table 4-26: Level 2 tasks with an indication of how quickly participants "got" it
Legend:

+ Participant performed the task appropriately on the first try
o Participant performed the task appropriately after one or two prompts
- Participant did not perform the task appropriately even after prompting
The manipulation method of driving the robot and saying **"off"** is in **bold**
The manipulation method of driving the robot with the gripper is in normal text
The manipulation method of driving the robot with the pen to mark units was used in L2L5 with single units
Tasks which were not completed by the participants are in grey
Mult. Str. = Multiple units and a straight snake
Sing. Str. = Single units and a straight snake
Mult. Wavy = Multiple units and a wavy snake
Sing. Wavy = Single units and a wavy snake

		L2L3			L2L4	L2L5			
		Measurement #							
Manipulative Task	Part.	1st	2nd	3rd	*	Mult. Str.	Mult. Wavy	Sing. Str.	Sing. Wavy
Grasp the unit	**M01**	**+**	**+**	+					
	M02	+	**+**	+	+			+	+
	M03	+	**+**	+	+	+	+	+	+
Place unit on baseline	**M01**	**o**	**+**	+					
	M02	+	**+**	+	+			+	+
	M03	o	**o**	+	o	+	+	+	+
Place next unit tip to tip with previous unit	**M01**	**o**	**o**	o					
	M02	+	**+**	+	magnet			+	o
	M03	o	**o**	+	o	+	-	o	o
Place last unit (at integral unit) at the other baseline (end of item)	**M01**	**+**	**+**	+					
	M02	+	**+**	+	+			+	+
	M03	o	**+**	+	+	+	+	-	-

* M03's L2L4 Practice Giraffe is presented here since it used the same manipulative tasks as M02's L2L4 Giant/Baby steps.

In general, the participants performed most tasks appropriately and as expected. Boxes 4-4 and 4-5 list observations of when the participant performed the tasks inappropriately, or with alternative strategies. The task of "Place next unit tip to tip" for Level 2 Lesson 5 Snakes is treated separately since measurements were performed in multiple ways, i.e., on a straight and wavy snake and with multiple and single units (using the **robot and gripper** and **robot and pen** methods respectively). Figure 4-4 illustrates issues described in Box 4-5.

Box 4-4: Observations of tasks in Level 2 which specifically used skills assessed by the teacher in the procedure of comparing items and measuring with multiple and single non-standard units

<u>Place unit on baseline</u>

M01: In L2L3 Heights she began by driving the robot along the full length of the gingerbread man, instead of stopping at the baseline.

M02: In L2L3 on his second measurement, when using the robot and "off" method, he drove the robot to the far end of the string instead of the close end.

- It was expected that he would drop straws off as they drove the robot along the length of the string. With his strategy, he had to drive the entire distance from the start position for each subsequent straw.

M03: In L2L3 Heights she required repeated prompting for:

- her first measurement (using the robot and gripper method) - she required a concrete demonstration of where to stop the robot so that the end of the unit was lined up with the end of the string.
- her second measurement (using the robot and "off" method) - she had a difficult time understanding where the straw would be placed on the table with respect to where the straws were lying on top of the robot.
- In L2L4 Giraffe she had problems lining up on the baseline in her first measurement, but became proficient after that.

<u>Place next unit tip to tip with previous unit</u>

M01: In L2L3 Heights, in her first trial (using the robot and "off" method) she left gaps between the units:

- at first the teacher compensated and placed the straws tip to tip and said, "I know you want it there because you told me to do it that way before" (when M01 observed the teacher measuring with craft sticks she indicated with a head shake that leaving gaps was not appropriate).
- by the fifth straw, the teacher stopped compensating and placed the straw exactly where the robot stopped. If there was a gap (or overlap), M01 moved the robot backwards (or forwards), indicating to move the straw accordingly.

- Subsequently, she occasionally hit the forward movement accidentally and needed prompts to use the little forward movements to be more accurate.

M03: In L2L3 Heights she required repeated prompting for:

- her first measurement (using the robot and gripper) - she began by placing her second straw beside the first straw instead of tip to tip.
- her second measurement (using the robot and "off" method) - she left gaps between units (as above, did not understand where the straw would be placed).
- In L2L4 Giraffe (using the robot and gripper), she overlapped the second straw with the first on a couple of measurements (probably due to pressing and holding too long), but corrected by backing up the robot.

<u>Place last unit at the other baseline</u>

All participants had trouble with rounding up or down when counting the straws.
M03: In L2L3 Heights, in the first measurement she placed an eighth straw when the string was only slightly longer than seven straws.

- In L2L5 Snakes (measuring with **single copies** of a unit using the **robot and pen)**, she put the last mark exactly at the end of the pipe cleaner instead of an integral unit length from the previous mark (i.e., much less than one unit in length) (See bottom left illustration in Figure 4-4).
- She did this for both the straight and curvy snakes, in spite of being prompted on the correct procedure after the straight snake.

Box 4-5: Observations of the task "Place next unit tip to tip" for Level 2 Lesson 5 Snakes. Figure 4-4 illustrates issues described here.

	Straight snake	**Wavy snake**
Multiple units using robot and gripper	Appropriate	**M02** opted not to do this because it was "too hard"**.** **M03** went 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, resulting in the robot being at right angles to the pipe cleaner: • she drove directly toward the pipe cleaner and placed the units at right angles to the snake • she eye gazed at the teacher to request her to turn the units to make them tip to tip.
Single units using robot and pen	**M03** needed prompting to use the paperclip program to move the robot ahead by exactly one unit length (i.e., tip to tip). • She tended to use the little forward movement which resulted in some pen marks being closer than one unit apart and some farther. Otherwise appropriate.	**M02** sometimes moved ahead using the unit program and then turned, which caused his marks to be too close together.

	M03 eventually used the following 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 did, move ahead using the unit program

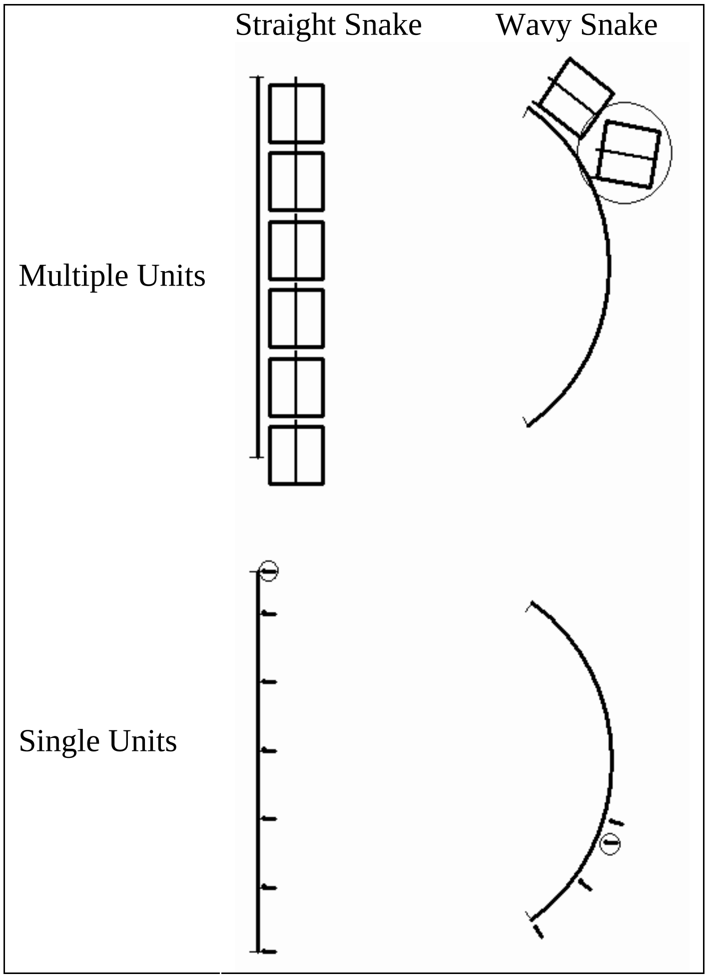


Figure 4-4: Straight and wavy snakes measured in multiple and single units. For the multiple units, a toothpick placed on top of a block was used as the measurement unit. For single units, the participant advanced the robot a unit interval and then placed a pen mark. Circles indicate places where the participant had problems.

4.4.3 Communicative Events

This section describes how the participant performed the communication portions of the lessons. The results presented in this section are a summary of what the participant said in Level 1 and Level 2 including any interesting events and trends, and a summary of the number and mode of communicative events follows. A detailed account of what the participant said in each lesson can be found in Appendix F and it contains:

- the questions asked of the participant in approximate chronological order (from the Revised Lesson Plans, Appendix B)
- a description of what the participant said, and
- an indication of whether the reporting occurred during observation or robot manipulation

In the first lesson, the participants were asked to say the measurement words that they already knew. M01 did not generate any words independently, but she repeated some vocabulary after the teacher showed her the symbol pathways. M02 generated many words independently quickly selecting several from his fast foods SGD page (e.g., "small, large, medium"). M03 tried to spell "measure" and gazed at the centimetres on a ruler nearby.

The concepts which were assessed by the teacher in Level 1 are shown in Table 3-12 and the observations made regarding the communication of the participants is presented in the following boxes, using those concept headings. Box 4-6 lists observations regarding the concepts specifically assessed by the teacher; Box 4-7 lists other observations. The communication consisted of reporting about the results of each lesson problem and the participants were also asked for their reasoning for how they came up with their answers.

Box 4-6: Observations of communication in Level 1 which was specifically assessed by the teacher for conceptual understanding

Legend: Prompts from the teacher in composing a message are shown in parentheses within the quotation marks indicating participant utterances.

Compare (In L1L0 Compare)**:**

M01 gave 1-word answers (e.g., "shorter", "long").

M02 reported using full sentences (e.g., "One is bigger than the other one." or "They are both the same with longer [length]"). Reasoning: His explanation for how he knew which was longer was "I looked at the thing and I looked at the pencil, so I came with my answer."

M03 reported in short sentences, e.g., "It is longer".

Order

M01: In L1L2 Ramp and Cars, she gave 1-word answers (e.g., "farthest", "green"), however her answers were not correct.

- In L1L2 Practice 1 (Fake Strings) she continued to give 1-word answers & answers were correct.
- In L1L2 Practice 2 (Order Straws) she used 2 and 3-word sentences (e.g., "red taller green", "yellow longest") & answers were correct.
- In L1L3 Pathways she said a 2-word sentence about which string was longest, "blue longs". Reasoning: M01 did not say that the character that went the longest also went the farthest until the question was broken into 1-word responses.

M02 ordered using full sentences, e.g.'s:

- In L1L2 Ramp and Cars, "Yoshi is the longest string". Reasoning: M02's explanation about what Yoshi having the longest string meant was, "He is the fastest". After a reminder to use the word "farthest" he said, "He is the farthest and long string."
- In L1L3 Pathways, "B(Bowser) went farther than Y(Yoshi)". The reason he knew that was "I looked at the strings to see which one is farther". He indicated he understood that the longest string meant the farthest distance.

M03 reported in full sentences, e.g.'s:

- In L1L2 Ramp and Cars, "The blue went the furthest"
- In L1L3 Pathways, "The green went seven inches" (which was determined to mean "The green went the middle"). Reasoning: Rather than relating the length of the string for how she knew that blue went the farthest, she answered "10 inches". After guidance from the teacher with eye gaze choices, she indicated she understood that the longest string meant the farthest distance.

Box 4-7: Other observations about communication in Level 1

Word endings: At first **M01** seemed to randomly choose endings to the comparison words, e.g., “long" + "-s, -er, -est, -ing” or relied on the teacher to read the endings aloud. However, over time she began using the endings appropriately more often and with less prompting.

Vocabulary symbol pathways: **M03** had difficulty remembering the symbol pathways on her SGD to say some math words (e.g., she asked in almost every lesson for the pathway to the word "short").

Vocabulary term "middle":

M01: In L1L2, when asked about the distance that the pink truck travelled, she said “middle” (actually visibly the shortest string, but she had placed it between the two other strings).

M03: In L1L2, she said “The red went in medium” and when asked if she meant it was the middle string length or placed in the middle, she selected the latter (actually the middle string length but placed on one of the sides).

- As mentioned above, she said "The green went seven inches" when reporting about the middle string (her mother suggested it was because she did not know what to call the middle string.)

Vocabulary term "inches": **M03** used the term “inches” several times (e.g.'s: in L1L0 she said “Book is 2 i-n-c-h-s”, in L1L2 Ramp and Cars she said “10 inches”, and in L1L3 Pathways she said, "The green went seven inches").

- She needed to be reminded to only answer "shorter", "same as" or "longer"
- In all cases, her perception of the size of an inch was not accurate (sometimes a few mm and sometimes 20 cm each).

In Level 2 there was very little verbal communication compared to Level 1. Part of the reason for this is because some of the reporting time was used to enter the results into worksheets (in the original lessons children wrote on worksheets, in this study the participants entered their results into electronic worksheets on the tablet computer). The concepts which were assessed by the teacher in Level 2 are shown in Table 3-12 and the communication of the participants is presented in Box 4-8, using those concept headings. Since L2L5 Snakes involved multiple concepts at once, it is presented separately in Box 4-9. Other observations in Level 2 are listed in Box 4-10.

Box 4-8: Observations about communication in Level 2 which was specifically assessed by the teacher for conceptual understanding

Legend: Prompts from the teacher in composing a message are shown in brackets within the quotation marks indicating participant utterances.

Compare and order

M01: In L2L3 Heights, she did not order the heights because she did not understand that she was comparing non-standard units rather than concrete items, but she could identify the biggest number. Reasoning: Her reason that person was tallest was because she was an "adult".

In the practice activities she compared rather than ordered:

- In L2L3 Practice 1 she reported on the toy items and said, "longer fork foot" and "block taller foot" (not mathematically correct). Reasoning: Gave no explanations, but identified which number was biggest.
- In L2L3 Practice 3 she reported on the jump lengths and said, "EA M01 same", and "you shorter (than who?) EA Me" (not mathematically correct).
- Reasoning: In L2L3 Practice 2 she knew why an item was shortest ("scissors 1" [unit long]) and why the shovel was longest ("3" [units long]).

M02: In L2L3 he had decided to count the units using fractions, and ordered with 5 ½ bigger than 6 (but understood 5 ½ < 6 after guidance from the teacher). Reasoning: M02's explanation for how he knew which person was the tallest was "I looked" and he was an adult.

- In L2L4 Giant/Baby steps, he said he could not order the giant steps, but ordered appropriately with teacher guided yes/no questions. He ordered the baby steps independently.

M03: In L2L3, she did not order because "we are all the same".

- In L2L4 Adapted Heights she reported "Same (who?) G(ingerbread man) and me" and "Mom is the shortest". Reasoning: Her mom was shortest because "Mom 13" and "[the other] 2 [numbers were] 14s".

Estimation

All participants had high estimates for the gingerbread man height in craft sticks at the beginning of L2L3 Heights: **M01** said "100", and both **M02** and **M03** said "30" (when the actual was 9).

- **M01** only estimated one more time in L2L3 Practice 3 and she was 3 off.
- **M02** did three additional estimates in L2L3 and his estimates were from 0 to 3 straw units off and in L2L4 Giant/Baby he was from 0 to 2 rod units off.
- **M03** did one additional estimate in L2L3, for the gingerbread man's height in straws, she said "10" (actual 7) which was inadequate since straws were visibly longer than craft sticks (9 craft sticks). She did two more estimates in L2L4 Giraffe which were 1 straw unit off and 6 toothpick units off.

Level 1 Lesson 3 Pathways is listed here because participants estimated which path they thought was the longest:

- **M01** and **M03** changed their predictions, to the correct answer, after they unwound the strings along the pathways with the robot.
- **M02** also predicted the correct pathway prior to unwinding strings and his reasoning was, "it looks longer".

<u>Orientation</u>
All participants had incorrect answers in L2L3 Heights (if the gingerbread man is 9 craft sticks lying down how tall is he standing up?): **M01** said 100, **M02** said 40 and **M03** said 10.

- Both **M01** and **M02** quickly got the concept that the gingerbread man would be the same number of units laying down and standing.
- **M03** took several concrete demonstrations to understand.

<u>Choice of appropriate unit</u>
Both **M02** and **M03** chose appropriate units to measure long (and short) items and gave <u>reasons</u> why it was appropriate (e.g., for M02, "straws are longer than the rod" and for M03, "straws (why?) longer").

<u>Choice of unit affects number (</u>can you compare measurements made in different units?)

- **M02** understood the concept quickly and gave the <u>reason</u> that, "straws are longer than the rod".
- **M03** indicated she understood the concept, but was not able to give a <u>reason</u>.
- Neither **M02** nor **M03** suggested a strategy for what to do in order to compare them (i.e., measure both items with the same unit).

Box 4-9: Observations about communication regarding concepts in Level 2 Lesson 5 Snakes

<u>Estimating</u> (If participant understood that snakes should be the same length no matter if it was straight or curvy or if they measured with multiple or single units their estimates should have been the same number for all four combinations)
M02's estimates were correct after the first estimate.
M03's second estimate was correct, but her other three were incorrect:

- She estimated correctly for the multiple=single units concept on the straight snake but did not estimate correctly on the wavy snake.

Box 4-10: Other observations about communication in Level 2

Additional math problems:
Some of **M03's** activities incorporated some additional math problems:

- In L1L1, she wrote a sentence about the sorting activity, i.e., "6/3=2" (i.e., six items divided into three bins equals two items per bin).
- In L2L4 Adapted Heights she wrote a word problem, "10 + 3 = 13" (i.e., "If the bottom part of your mom is 10 rods long and she is three rods long on the top then how many rods long is she all together?").

Math communication outside of the study: **M03** told her SLP that he was “two paper clip longer”, based on her Adapted L2L4 Heights activity results.

4.4.3.1 Number and mode of communication events

An overall summary of the number and mode of communicative events is presented in this section. The percentage of agreement between Coder 1 and Coder 2 for coding communication events and mode was 72% for M01, 80% for M02, and 71% for M03. Due to the lower agreement for M01 and M03, discrepancies in coding were investigated further. There were some differences in coding as an Initiation versus a Response and since M03 used multiple modes of non-verbal communication, some events were coded as using different modes. To compensate for these issues, the sum of Initiations plus Responses and the sum of non-verbal gestures (eye gaze plus head nods/shakes) are used in the data charts below. Since the initiations were subsumed into one code with responses, a list of the nature of the types of initiations made by the participants and some examples are presented in Table 4-27. Also, the coders identified several instances where the participants used the mode of using the robot to communicate an idea. Since this is a mode that was not specified in Clark and Kirton's (2003) coding protocol, a short description of the situations where the research assistants coded that the participant used the robot to communicate and some examples are shown in Table 4-28.

Table 4-27: A list of the types of things about which the participants initiated conversation, and some examples

Spontaneously saying vocabulary, even though the teacher was not expecting it	
M02	'stick', instead of talking about the referent as a 'thing'
M02	'match', after the teacher introduced the word baseline, and how he could use match up
M02	'tape', the answer to a previous question
M03	'Short', after the question 'Can you think of any words that we used during our lesson?'
M03	'Far', after the teacher said that M03 will be comparing how far each of the cars go
M03	'Near', after the question 'Can you think of any words that we used during our lesson?'
M03	'Scissors', after discussion about how to request to cut the string
Spontaneously reporting on results before being asked	
M03	'long', in reference to the car that she felt went the farthest
M03	'blue longest', changed her prediction after un-winding the strings
M03	Eye Gaze at tablet because she wanted to enter her number
To request the teacher or investigator to do something	
M01	'EA', wanted to compare her height to her EA
M01	'head', pointed out that the robot's head was not on
M03	Eye Gaze at teacher to indicate she was having difficulty grabbing the block
M03	Eye Gaze at teacher to indicate that a block needed to be adjusted
M03	Eye Gaze at teacher to indicate she wanted the teacher to make a tick mark along the pipe cleaner
To indicate knowing how to do something technical	
M02	'I know', referring to how to make the SGD output to the tablet computer via the USB cable
To indicate they did not understand a question or what to do	
To indicate they were tired	

Table 4-28: Type of situation and some examples where the research assistants coded the participants as using the robot to communicate.

Communicative initiations	
M02	Moved robot which seemed to indicate that he wanted the robot in a new position before the teacher added the new felt marker
M02	Moved robot backwards to tease the teacher as she was about to touch it
M03	Put robot pen down too far to demonstrate the thing that she was trying to explain that she was worried about (since the teacher and her mom did not understand her gestures)
Natural response during an activity	
M02	Robot beeped when he pressed Stop - seemed to indicate the response to 'are you done?'
M02	Closed gripper in response to question 'Do you want the card in your gripper, or not?'
Response to questions during robot activities like, "is this where you want the item to be placed?"	
M01	Backed up the robot to indicate where the straw should be placed, in response to the question, 'Is this where you want it?'
M02	Moved the robot to indicate where the tape should be placed, in response to the question, 'If I taped it right here it would be just a little bit off'
Response to a question like, "do you want to move the robot back or should we do it?"	
M01 M03	Backed the robot up in response to the question, 'Do you want us to move the robot back or are you going to move it back yourself?'
Response to teacher questions about the procedures for the activity	
M03	Moved the robot, in response to the question 'If you had to measure the rake, what would you do?'
M03	Began to move the robot after the teacher asked, "What should we do with all these strings now. You can either tell me or show me with the robot."

Figure 4-5 a, b and c shows a distribution of the communication modes used in the "doing" and "talking" portions of the main lessons for each participant. Note that M01's SGD output events are generally 1 to 2-word utterances whereas M02 and M03's are generally sentences. The following communicative events were not included in the charts:

- Obligatory events when the participant requested "tape" in L1L3 or for the straw to be taken "off" in L2L3.
- Obligatory events when the participant said the final number after counting units in the Level 2 lessons
- Infrequent events: e.g., M01 once groaned to indicate displeasure at having to answer another question, M02 once wiggled to indicate "me", and M02 and M03 once pointed towards an item on the table with his/her arm
- M03's gestures which were interpreted by her mother: e.g., "forgot" (used 6 times), "confused" and "worried" (used once each).

The following events were subsumed into other codes:

- M03's communication using the letter board was coded as SGD output
- M03's verbalizations for "yeah" were coded as nods since she usually did both at the same time

Figure 4-5 a)

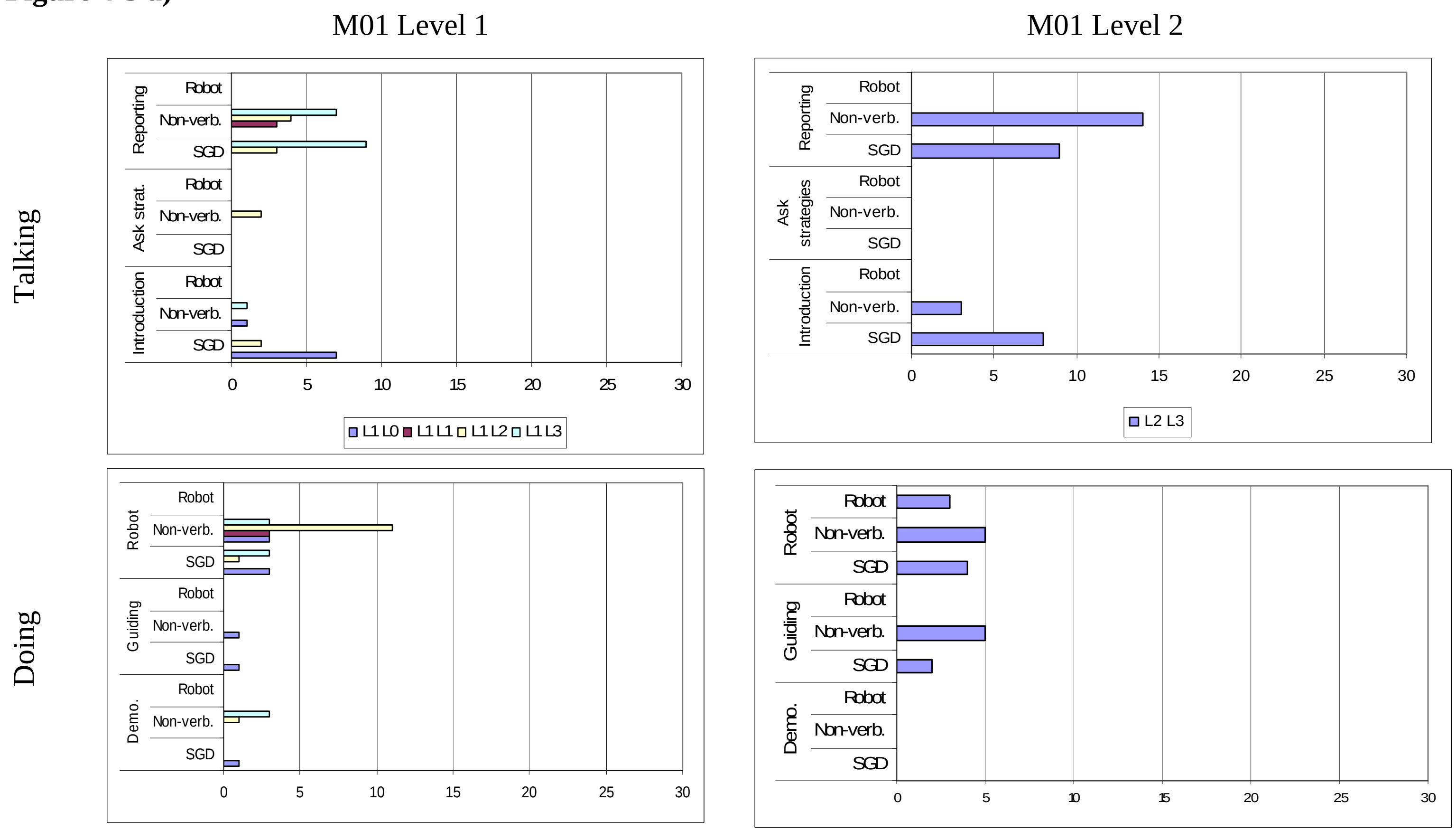

M01 Level 1
M01 Level 2
Talking
Doing
Reporting
Ask strat.
Introduction
Ask strategies
Robot
Guiding
Demo.
Robot
Non-verb.
SGD
0
5
10
15
20
25
30
L1 L0
L1 L1
L1 L2
L1 L3
L2 L3

Figure 4-5 b)

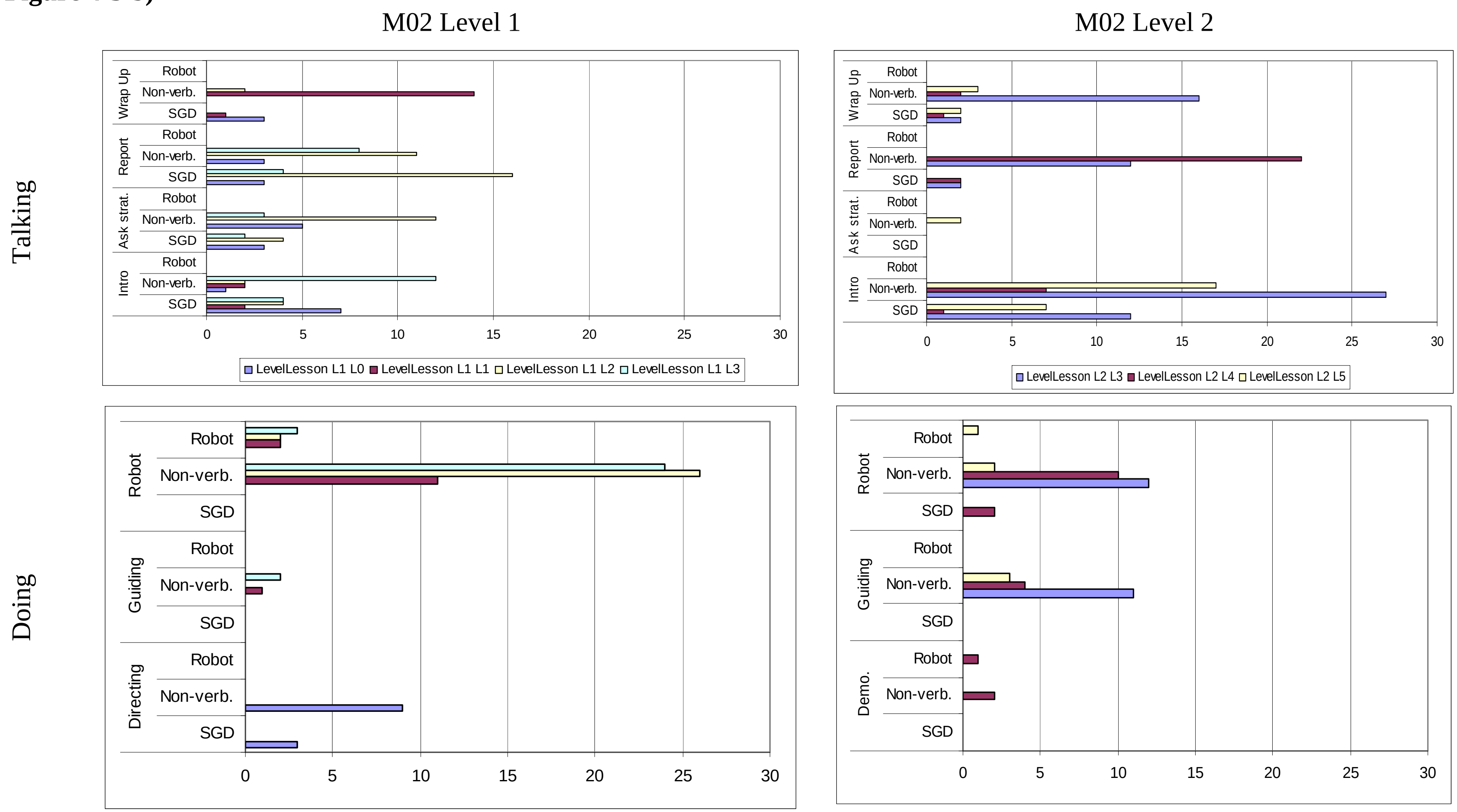

M02 Level 1
M02 Level 2
Talking
Doing
Wrap Up
Report
Ask strat.
Intro
Robot
Non-verb.
SGD
0
5
10
15
20
25
30
LevelLesson L1 L0
LevelLesson L1 L1
LevelLesson L1 L2
LevelLesson L1 L3
LevelLesson L2 L3
LevelLesson L2 L4
LevelLesson L2 L5
Guiding
Directing
Demo.

Figure 4-5 c)

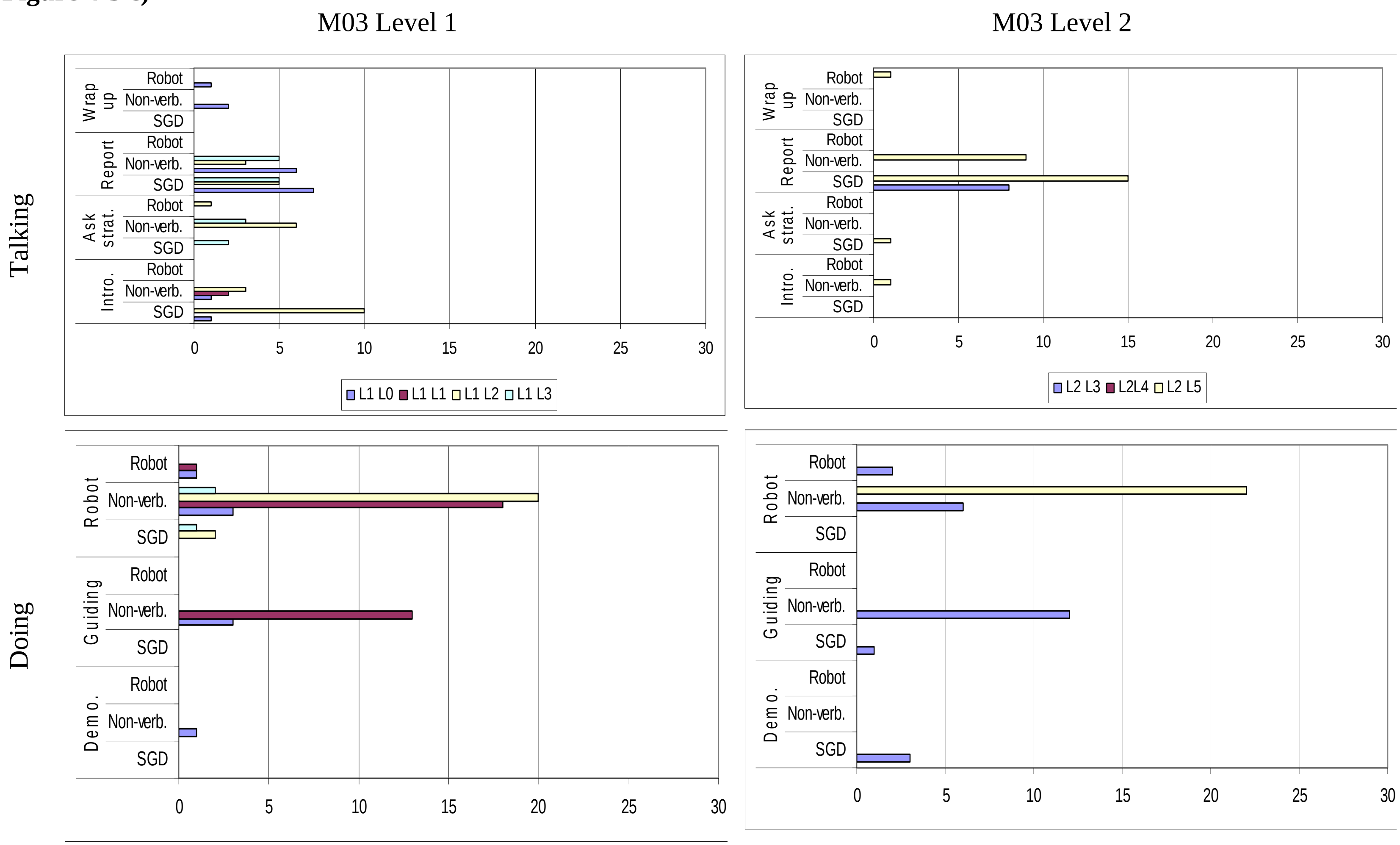


Figure 4-5: Count of communication events for each participant according to mode used in the "doing" and "talking" portions of the lessons.

Observation of the videos of the sessions revealed the following points regarding communication:

- All participants switched easily between robot and communication modes. Occasionally, a participant accidentally fell out of the robot mode by hitting the cell to switch to the core vocabulary page.
- M01 and M03 forgot things during the lessons, for example, keeping the value of estimates or measurements in mind or pathways for vocabulary items.
- M01 sometimes expressed displeasure when asked to communicate, e.g.,
  Teacher: "Can you end that word for me?" M01: Shook head no
  Teacher: "Are you ready to make sentences?" M01: Shook head
  Teacher: "I have one more word question" M01: Groaned

4.4.4 HAAT

Observation of the videos of the sessions revealed characteristics of the activity and AT system (SGD, robot, interface) that limited the effectiveness with which the tasks were achieved using the system (Table 4-29). Also, observations revealed features and characteristics of the participant that limited the effectiveness with which the tasks could be achieved with the robot (Table 4-30).

Table 4-29: Characteristics of the activity and AT system (robot, SGD interface) that limited the effectiveness with which the tasks were achieved using the system and the techniques used to compensate

HAAT Element	**Limitation**	**Compensatory techniques**
Activity	Participants could not see how the ends of the referent (or unit) on the robot lined up next to items when the items were far away (i.e., **parallax**: when objects seem to shift relative to one another depending on the angle of view)	• The orientation of the table and/or items on the table were changed or the items were brought closer to the participant. • A card or file folder was placed at the end of the item (which bent over when the participant went too far) • The teacher or investigator held their finger at the end of the referent or unit and also at the end of the item to line up with (e.g., in L1L3 the teacher put one finger on the spool at the back of the robot and the other finger on the start position on the pathways).
	Adapted items were sometimes difficult to manipulate: E.g., the straw units on the blocks sometimes bent so they did not line up exactly.	• The teacher or investigator straightened the straws. • Magnets were used so the units would snap together. Commercially available toy building rods worked very well. Also, a custom-made solution with magnets taped on to blocks was used, but these occasionally changed polarity causing gaps between units (e.g., in M03's L2L5 the measurements using multiple and single units were not the same due to gaps).
AT - Robot	The robot steps were sometimes too big to stop exactly on the baseline or match units tip to tip.	• If the participant attempted to move forward and backward to get closer to the baseline, the teacher interpreted this as an indication that they were trying to line it up and she placed the item in the exact location.
	The robot did not drive perfectly straight.	• The teacher or investigator nudged the back of the robot straight while the participant drove the robot. • Participants sometimes compensated by making a small turn.
AT - Robot to human interface	In L2L5 a toothpick was placed on top of the robot to help gauge how far the robot would go when using the toothpick	This was not a problem for measuring straight items, but it was for measuring the curvy item because the participants used an unexpected strategy. Instead of turning first and then using a toothpick program movement, M02 and M03 used the toothpick program and then turned. This resulted in the space between their marks being shorter than a toothpick, so they needed to use short forward

	program, but the toothpick was too far away from the pen tip to be useful.	movements until the space was the length of a toothpick. • To compensate a toothpick was taped to the side of the robot near to the pen tip
	M01 and M03 had difficulty understanding where to place the robot to make comparisons with items. E.g.: a) lining up the end of the referent (which was between the **robot arms**) with the end of the comparison item b) lining up the **robot spool** exactly where they wanted the string to be taped	a) When a referent and/or unit was placed on top of the robot, it was placed with the front end between the robot arms, which were directly over top of the front axel and wheels. For example, in L1L1 with the referent on top of the robot, participants were expected to line up the elbow of the robot arm to the end of the comparison item, and in L2L3 with the straws on the robot, they were expected to line up the bottom of the wheel with the end of the straw already on the table. To compensate: • the teacher pointed to the arm elbow and the end of the comparison item • a straw was taped to the side of the robot near to the table b) When the participant was unwinding string with the robot, the expectation was that the teacher would tape the string exactly under the spool. At first, M01 and M03 tended to request tape when the string was laying overtop of the desired location. To compensate: • the teacher pointed under the spool and said "this is where the string will be taped/cut" and then the participant moved the robot appropriately
AT - SGD Interface	Using the same cells for gripper open/close and for pen up/down caused selection errors, especially for M01.	This did not cause accuracy problems unless the participant made the pen go down so many times that the robot rose off of its wheels and set down in a different position (which happened for M03 occasionally). If so, the teacher or investigator placed the robot back in the original position.

Table 4-30: Characteristics of the participant that influenced the effectiveness with which the tasks were achieved

<table>
<tr><th>HAAT element</th><th>Observation</th><th>Comment</th></tr>
<tr><td rowspan="3">Human Skills and abilities</td><td>Preferences for switch sides for step scanning and view of the workspace influenced how well the participant utilized the press and hold strategy for attaining repetitive forward movements.</td><td>The following is a summary of the participant's preferred side of head for moving and selecting in step scanning, side of their body where they preferred to view the workspace, and how frequently and how well they used the press and hold strategy.
<table>
<tr><th></th><th>Move switch</th><th>Select switch</th><th>Workspace</th><th>Hold strategy</th><th>How accurate?</th></tr>
<tr><td>M01</td><td>left</td><td>right</td><td>right</td><td>frequently</td><td>accurate</td></tr>
<tr><td>M02</td><td>left</td><td>right</td><td>left</td><td>infrequently</td><td>accurate</td></tr>
<tr><td>M03</td><td>right</td><td>left</td><td>left</td><td>frequently</td><td>slow to release</td></tr>
</table>
M02 tended to use the strategy he independently discovered which was to run the giant step program and then press STOP at the target location for driving long distances.</td></tr>
<tr><td>M01's limits in operational competency limited her accuracy on the math tasks.</td><td>M01 frequently accidentally hit the first item in the scan row causing her to make the robot move beyond the target position. The investigator suggested putting a benign item in the first cell but the participant insisted that the forward movement command be placed there.
M01 was not interested in having a button to go forward a small distance added to the display, but the investigators insisted. She usually only used it with prompting, but sometimes used it independently to more accurately line up the robot on the baseline.</td></tr>
<tr><td>M03's robot problem solving strategies limited her success in accomplishing some tasks.</td><td>This was particularly evident in:
L1L1 when M03 did not approach the blocks affixed to the items from an appropriate angle where the robot's gripper could grasp them (see Box 4-2)
L1L3 when she had difficulty getting back on to the second pathway when unwinding string because backing up was difficult for her (See Box 4-2)
L2L5 when she did not use an appropriate approach angle to line up multiple items on a curvy object it resulted in the units being off of the target location and at odd angles to each other, not tip to tip (See Box 4-5 and Figure 4-4).</td></tr>
</table>

4.5 Effectiveness, Efficiency, and Satisfaction of Using the Various Methods for "Doing"

Efficiency of the various modes of manipulation (directing the teacher, observing the teacher and manipulating with the robot) for the tasks in the video clips was evaluated in terms of time. The time that it took to do one complete measurement task with each method is shown in Table 4-31. The table contains a brief description of the task but for a more detailed description of the task in each video clip see Table 3-13 in the methods section.

Table 4-31: The time that it took to complete one complete measurement with each method

Lesson & participant	Short description of video clip	Mode of manipulation	Time
L1L0 M02	Compare items	Directing the teacher	9:12
L1L1 M02	Compare items then put in bin	Observation of teacher	0:21
		Manipulating with the robot	4:18
L1L2 M03	Pull strings and line up ends	Observation of teacher	1:03
		Manipulating with the robot	1:27
L2L3 M01	Lay straws tip to tip to measure gingerbread man	Observation of teacher	3:34
		Manipulating with the robot	10:46
L2L4 M02	Lay toothpicks tip to tip to measure baby step*	Observation of teacher	1:03
		Manipulating with the robot	2:01
L2L5 M03	Use single copy of unit and robot pen to measure straight snake	Observation of teacher	0:39
		Manipulating with the robot	4:54

* includes reporting result into a worksheet on the tablet computer

The evaluation team's comments on how well the participant could portray what they knew about the concept being discussed in each video clip are listed in Table 4-32 **(i.e., effectiveness)**. The team also made several general comments regarding effectiveness that will be presented in the discussion section.

Table 4-32: Quotes from the Evaluation Team regarding effectiveness of each manipulation method, directing the teacher, observing the teacher and doing the task with the robot.

Lesson	Mode	Quotes from the evaluation team
L1L0 M02	**Direct**	**Teacher1**: [Effectiveness] was fine because you found out the concept that you wanted to find out. [Lining up the centres] made its own logical sense, even though it is not the way that we want to teach him how to measure it.
L1L1 M02	**Observe**	**OT1**: In the observation we don't know what he's thinking. He's just giving you a response.
	Robot	**OT1**: By him operating the robot, he demonstrated 'okay I need to line it up in order to really see which one is small, big and bigger'.
L1L2 M03	**Robot**	**Teacher1**: I think she knew what she was doing. You can tell by the way she drove. She was crooked at one point and she made it straight. So she knew she had to be parallel to the other one. So she knows what she has to do to have an effective comparison. And no one told her. **OT2**: The only way I think she could have demonstrated her knowledge more effectively, is if she would have moved her wheelchair to come around the side of the table to see for herself. **SLP**: I think within the resolution of the equipment, she was effective at demonstrating her knowledge.
	Observe	**Teacher1**: [It would] have been very difficult to see [therefore the teacher bringing the strings closer was an important thing to do.]
L2L3 M01	**Observe**	**SLP**: She was effective for that mode of dialogue, evaluator initiated with yes no questions or one word answers. **Teacher1**: The teacher did not put a lot of demands on M01 in terms of communication (e.g., "lay them straight touching") because she just wanted to find out the math concept - some kids would make the same mistakes over and over.
	Robot	**OT1**: When I saw kids doing this before, the kids who didn't get it, really didn't get it, and M01 is doing it. **SLP**: She's not racing way ahead, she's not overlapping **OT2**: She demonstrates that she knows how to measure much better. With observing she didn't say, 'put another one down, put another one down' **OT1**: She had an opportunity to independently manipulate. She demonstrated that she has a sense about the unit of measurement (she's consistent about what she's measuring) and how to use those units together. I think she demonstrated better with the robot. It was clearer to me than with observing the teacher. **OT2**: - I think in the first one [observing Vicky] she knew, but we're 100 percent sure on the robot one. The first one is more of a multiple choice one.
L2L4 M02	**Observe**	**Teacher1**: It would have been interesting to see if the teacher just kept on going like everything was totally fine and he had to interrupt her, using a command that would have been fairly quick, instead of her saying "is everything okay". Because right now, she's directing him to look at it and see if it's wrong. He's not instigating, you know "it's wrong".
	Robot	Not discussed
L2L5 M03	**Observe**	Not discussed
	Robot	**Teacher1**: When [you guys] said, line up the paperclip, she did it. Nobody pointed to where she should go, they just said, so she knew the vocabulary and she knew what to do. **SLP**: I thought it was effective, because everybody questioned what she was doing. You can get the wrong answer and still be effective in your demonstration.

The Adult User of AAC's comments on what worked and did not work with respect to using the robot in the lessons are in Table 4-33.

Table 4-33: AAC device user's comments after viewing the full math lesson videos

Lesson	Comments
L1L1 M02	I think it's neat that he can measure things by himself by using the robot.
L1L2 MO3	I think the robot helps kids understand the concepts of near, far, etc. by letting them manipulate objects to demonstrate the concepts in a concrete manner.
L1L3 MO1	I think by using the robot for math concepts, like measuring, it makes the concepts more real and easier to understand for someone who does not have the ability to manipulate objects independently. It takes the complexity of the terminology away. The concepts do not seem as foreign.
L2L3 MO1	I think they should just measure the gingerbread man and leave the other stuff out. Did the measuring [the gingerbread man, their own height and a friend] by using the robot really add to the student's understanding of the concept of length?
L2L4 MO2	I think having somebody comparing giant steps to the robot is neat because he/she can actually see the differences [between his/her own with the robot and someone else's steps]
L2L5 MO3	I think it's neat because using her device to control the robot she can actually do the measuring herself. People learn better and remember longer by doing the manipulating themselves.

Table 4-34 shows the **participant's preference** for doing the activities: by guiding the teacher how do it, by doing it themselves with the robot, or by using a combination of doing it with the robot and asking the teacher to place the units based on the robot location.

Table 4-34: Participant preference for doing activities.

	Observe and guide teacher	**Combination**	**Do with robot**
Level 1 Lesson 1 - Bins		Not an option in these activities	M01 M02 M03
Level 1 Lesson 2 Ramp			M01 M02 M03
Level 1 Lesson 3 Pathways			M01* M02 M03

Level 2 Lesson 3 Gingy, Self, Friend		M02**	M01 M03
Level 2 Lesson 4 Giant/Baby steps	M02	Not an option in these activities	M03
Level 2 Lesson 5 Single units and straight snake	M02		M03

* M01 went on to say that she preferred to tell the teacher what to do for the portion of the activity where the teacher solved the pathways drawn by the participant. Her reason was, "I want job teacher".

** M02 said the reason why he liked the teacher to do it was because it was "Easier". However, when given the choice for which method to use for the last item, he chose using the robot with the gripper.

The Evaluation Teacher1 made a comment regarding participant satisfaction while watching the videos:

> "[In L1L1 bins lesson] I noticed at the end when he was smiling, he knew he did it. He did it all on his own. So, his perception of what he can do wasn't the same as when you held it for him and he looked over. Look at this, this is one more thing that I can do on my own, and now his list is getting bigger."

There were some events coded regarding participant satisfaction that resulted from the observation of the videos:

- After M03 compared and sorted three items in L1L1 bins lesson she was asked if she would like to stop the activity at that point, but she expressed that she loved using the robot and wanted to continue, so she compared three more items.
- All of the participants, especially M01, drove the robot around while the investigators were setting up for the next activity.
- All of the participants had perseverance to complete the activities with the robot, even if they were tired.

4.6 Post Study Participant Surveys

The results of the "attitudes survey" are shown in Table 4-35. M01 was asked an alternative statement #4 because her education assistant said the initial answer was probably influenced by the participant's dislike of math in general. M03 was asked an alternative statement #3 in order to establish which tasks were easy compared to others. In the follow-up interviews with their EAs and mothers M02 and M03 were asked to verify that the investigator interpreted their answers correctly. Both M02 and M03 increased their answers from "a bit" for statement #2 to "a lot" during the interview.

Table 4-35: The results of the "attitudes survey".
The shaded areas indicate alternate questions from the original survey.

	Not at all	**not really**	**sort of**	**a bit**	**a lot**
1) I liked using the robot to work on measurement					M01 M02 M03
2) The robot helped me understand measurement				M01 M02^{1st} M03^{1st}	M02^{2nd} M03^{2nd}
3) The robot was easy to use			M02		M01
Alternate question for M03 - The robot was easy to use in each of these activities: pulling strings, pushing blocks, wavy objects			M03 wavy objects	M03 pulling strings	M03 pushing blocks
4) I would like to use the robot to learn other math concepts	M01		M03		M02
Alternate question for M01 - I would like to use the robot to learn other SUBJECTS					M01
5) I like using the robot to do measurement more than I liked telling my EA what to do			M02	M01	M03*
6) The robot helped me answer the questions that the teacher asked me (M01 was not asked this one)				M02	M03

* M03 spontaneously said "I like to do that all by myself"

Table 4-36 shows the participant's rating of each of the activities they performed with the robot from liking it a lot to not liking it. M01 spontaneously said "I like color" in the first robot accuracy test session and then again in her post interview where she said "color toy awesome" (determined to mean that coloring with the robot was awesome). M02 and M03 said that they liked using the robot in the additional Level 3 activities that they tried (where they used standard units by having a centimetre ruler or a metre stick attached to the robot). All of the participants indicated that they would be interested in using the robot for counting items independently.

Table 4-36: Participant's rating of the activities they performed
Note: Not all participants did all activities, and not all participants were asked about all activities.

Level & Lesson		**Did not like it**	**Liked it so so**	**Liked it a lot**
L1L1	**Bins**	M01 M02* M03		
L1L2	**Ramp and Cars**		M01 M03	M02
L1L3	**Pathways**		M01 M03	M02
	Draw your own Pathway			M01 M02 M03
L2L3	**Heights**	M02**	M03	M01
L2L4	**Choose appropriate unit**	Not asked, similar task to L2L3		
L2L5	**Measure with single units (robot and pen)**	M03		M02
Practice Lessons and Activities				
L1L1	**Draw Lines**			M01
L1L2	**Order Straws**			M01

L3	**Trial using robot for measuring with cm and m**			M02 M03	

* M02 indicated that there were too many items in this activity, if there were fewer items, the activity would have been better.

** M02 indicated that the items were too long, and that if they were shorter then it would have been better. He made a rapid movement of his head between his switches to indicate that the activity required too many switch hits.

5 DISCUSSION

This study investigated the use of an integrated augmentative communication and Lego robotic manipulation system developed for use in math measurement activities. Three descriptive case studies were performed where participants performed Level 1 and Level 2 lessons from the Math Makes Sense curriculum (Pearson Education Canada, 2007; 2008) which were taught by a special education teacher. Participants used their own speech generating communication device (SGD) for the "talking" portions of the lessons and a low-cost Lego robot for the "doing" portions of the lessons. Before performing the lessons the participant's communicative competence was measured to establish the operational, linguistic, social and strategic skill that could be expected from the participants during the talking portions. The participants also performed training on the use of the Lego robot to ensure that they could control the robot for functional math activities. This chapter discusses the Lego robot and SGD interface design, the participant's communicative competencies, robot training results and answers to the three research questions:

1. Can children with physical and communication limitations demonstrate and explain their knowledge of math concepts using an integrated communication and robot control system in math measurement activities?

2. What are the key features and characteristics of the student, activity, integrated communication and robot control system, and context that limit system usability?

3. What differences are there in terms of effectiveness, efficiency, and satisfaction using the integrated communication and robotic control system to do the manipulative tasks compared to other modes students may use such as observation of the teacher, responding to questions, or directing the teacher?

5.1 The Robot System and SGD Interface

A Lego robot was developed with design features to make it possible to accomplish many of the hands-on tasks in math measurement lessons. A task analysis of the Math Makes Sense Level 1 and Level 2 lessons resulted in a list of tasks which could be accomplished by using a robot or with assistance from a teacher. The tasks were consistent with Enders' dynamic AT model (Enders, 1999), described in Chapter 1, where some were to be accomplished by the participant with the robot, and others by the teacher. The key features of the robot to accomplish the tasks were a gripper, a moveable pen, and a spindle to hold a spool of string. The key feature of the environment required to accomplish the tasks was to mount the items to be manipulated on either the robot, or a block so that the robot could grasp them with the gripper.

The participants used their own SGD to control the robot. Integration of doing tasks and talking about them was easily attained by using the IR output capability of the SGD. Using their own SGD provided the participants with the benefit of using the language system and access method with which they were already familiar. It addressed the limitation in previous robot studies where it was difficult to find an appropriate access method for children with severe physical limitations to control the robots.

The participants were involved in decisions about their SGD control interface. They had differing skills and preferences which resulted in interfaces which varied in navigation system, symbol type and organization. For instance, having the robot commands available alongside the core vocabulary (the layout recommended by the investigator) was preferred by M01 (she said it was "easier"). M02 and M03 preferred to use a separate page for robot commands with the symbol to switch to core vocabulary in the first scan position. They all easily switched between "doing" and "talking" modes, but pages may have been easier for M02 and M03 since they had more experience using their SGDs than M01.

M02 and M03 preferred words on their robot commands page instead of symbols since they had better reading skills than M01. The color coding for left and right turns was utilized by all three participants. For M01, the symbols for the large and small movements seem counter intuitive (large cursor movements were depicted with small segmented arrows) but they were used since she had previous experience using the Mouse commands page, so the functionality was parallel.

The organization of the symbols (particularly the first scan position) was influenced by participant preference and will be discussed with respect to HAAT elements (Section 5.4). Since the emphasis in this study was to use core vocabulary, no effort was made to provide vocabulary on the robot commands page. However, quick hit vocabulary items such as, "that's not what I meant", or "you're doing it wrong", could be placed on the robot controls page to reduce the need to switch between modes.

5.2 Pre-Existing Competencies

M02 and M03 had both done math measurement lessons within the past two years, where their education assistant (EA) manipulated the items for them. M01 had no exposure to math measurement concepts within the past two years.

All participants had a minimum receptive language level of grade 2 on the PPVT receptive vocabulary test. Hence, it can be assumed that the language level in the Level 1 and Level 2 math lessons was likely appropriate for the participants. If the participants did not understand vocabulary or instructions, they all asked the teacher to clarify. Wilms (1996) indicates that scores on the PPVT are a "relatively good predictor of later school success". Interestingly, ranking the participants from the highest to lowest standard score on the PPVT results in M02 being greater than M03 who was greater than M01, which is the same ranking as their performance on the math lessons in this study.

The story re-tell protocol identified a spread of abilities across participants. There were limitations in the protocol to elicit social or strategic skills, but informant interviews verified if the participant had those skills. Given that M02 and M03 did very well on the re-tell task, the teacher and investigator expected that the participants would be able to communicate their understanding of math concepts adequately. Hence, any difficulty communicating in the math lessons would be due to their difficulty with math concepts, not language limits. However, given M01's performance on the re-tell task, the teacher and investigator expected that she would have more difficulty expressing her thoughts regarding math concepts. All participants showed they had skills to correct misunderstandings or request clarification or help when needed. By observing the re-tell task, the teacher learned the strategies used by the participant and the level of cueing needed by the participants.

The SGD access method operational test results showed that all participants had sufficient initial accuracy to begin the study, but they did not show improved motor accuracy and time over the course of the study. Both M02 and M03 were experienced users who had used their systems regularly for many years, at least 5 and 6 years respectively, therefore their two-switch step scanning skills had probably hit a plateau. Between the two of them, M02 had the only error, which was making a selection one column too early. In contrast, M01 was a fairly irregular SGD user, who only had her device for 2 ½ years. Observation of the video for M01 showed that her errors in the first two tests were due to selecting a cell as a means to quickly escape from scanning an incorrect row (causing an error). By the third test she waited for the cursor to finish incorrect scan cycles without clicking (causing increased time) and her errors were only due to selecting one column too early. Hence, over the course of the study, M01 learned a strategy to reduce errors even though it was slower.

Since M02 changed language system and grid array size part way through the study, he did not have after math task data to compare to his initial and after training data. However, his quarter-row-column (Q-R-C) and row-column (R-C) scanning comparison data show that he was very accurate with the new grid size and both scanning methods. The test results also verified to M02 that Q-R-C scanning did not have a time advantage. Though it was discussed that Q-R-C could have an advantage when he used the frequency layout for communicating, he continued to use R-C scanning for the remainder of the study.

The SGD access method operational test tested only operational competence using the access method, and eliminated linguistic, social or strategic competence requirements from the test. The robot facilitated tasks in the math lessons placed additional demands on the participants. Participants had to 1) ascertain the relative orientation between the robot and the item to be manipulated, 2) determine the required robot movement to go in the desired direction, 3) determine which symbol on the SGD would result in the desired movement, and 4) select that symbol from the grid array. Performing this operational test, independent of robot movement or symbols, allowed evaluation of the participant's motor accuracy and efficiency at selecting symbols independent of the cognitive demands of the activity. From the results, the teacher and investigator expected that M02 and M03 would be almost 100% accurate using their selection method, so any operational problems that they had in performing the functional math or language tasks may be due to cognitive demands of the task. Although M01 performed at 75% or better, it was expected that M01 may sometimes be inaccurate using her selection method.

Due to the participants having various experiences using robots, there was an emphasis on training the control of the robot to bring the participants to sufficient levels of competence. All participants easily accomplished the familiarization task. This is not surprising since the participants obviously have causation, negation, binary, and sequencing skills evidenced by the operational competence with which they used their SGDs (scanning requires these skills). They showed creativity in performing the tasks in unexpected ways (i.e., knocking one set of blocks over and then backing up to knock over the other set).

Visual observation of the slalom trials data in Figure 4-1 shows that, generally, accuracy decreased and time increased for M01 and M02 as the trials became more involved. M03's data do not show the same trend for accuracy, but there was an environmental factor which probably influenced this result. The paper used for her trials was smaller in width than the paper used in the trials for M01 and M02 so M03 was probably influenced to stay away from the sides of the paper regardless of the task. M02's improvement in accuracy in his trials with blocks was likely due to re-programming smaller turn increments (at his request). M02's large decrease in accuracy in the first trial with the pen (up/down twice) was probably due, in part, to having to change the direction of travel of the robot in order for him to see the pen (from driving away from himself to driving towards himself). Examination of data regarding the number of incorrect selections of left and right turns showed that he increased from 0 to 1 in the earlier trials to 4 to 7 in these trials. Changing the direction of travel was also a factor for M03, but it manifested as only left/right turn errors rather than overall area error (increasing from 0 to 1 to 4). The direction of travel did not change for M01 since she could see the robot pen from her preferred side for viewing the workspace and her frequency of left/right errors did not change.

The time to make a dotted line along the 2-obstacle course was the highest for all participants. M03's time was particularly high because she frequently chose to use the small forward and turn movements, instead of the larger ones. It is likely that she chose them because they were in the same scanning quadrant as her pen up/down command. Because of the small movements, her accuracy improved over her other trials. Accuracy of the dotted line trials for M01 and M02 was not notably different from other 2-obstacle trails.

The time for the 2-obstacle task with unwinding string and asking for it to be taped down was higher compared to other 2-obstacle trials (excluding the trials with the pen), in spite of the fact that asking for "tape" should not add much time to the trial since the participants had the word cued up on their message windows. M02's time on this task was very high because it included time when he was considering how to make the string follow along the dotted line that he just made and time to explain to the investigators what he was doing ("How can I follow the dotted line"). M03's straw trial with communication took longer than the straw only trial because of finding vocabulary, but she also had lower accuracy. Unfortunately, M01 did not perform a pen up/down twice trial with manipulation only, so her communication trial cannot be compared to anything, but her time was higher than previous trials because she struggled to find vocabulary (even with prompts) and her accuracy was about the same as her lowest accuracy in a 2-obstacle course.

Time was expected to increase as the trials progressed because of the added requirements of gripping objects and/or switching to communication mode and finding vocabulary. However, a decrease in accuracy is not necessarily expected, so the decrease that was shown may point to an added cognitive load.

M02 and M03's reporting on the perceived difficulty of the tasks (Table 4-11) supports that they found the trials to be more difficult as the trials became more involved: using the Robot Only was really easy; using the Robot and Blocks was easy for M03 and so-so for M02; and using the Robot and Pen was hard for both. M01, an inexperienced SGD user compared to M02 and M03, found all of the tasks involving the robot to be "really hard" (although she clearly enjoyed using the robot in all activities). M01 had considerable trouble remembering to raise and/or lower the pen in the dotted line trial, so her "dots" were sporadic and sometimes dragged along for 20 cm. In addition, she forgot to go around one of the obstacles in this trial - which may be an indication that the cognitive load in this trial was very high. M02 and M03 had some trouble at the beginning of the trial, but became quite rhythmic with raising/lowering the pen and moving by the time they passed the first obstacle. The only participant who was asked about adding a communication requirement to the Robot and Blocks trial, M03, found it to be "so so" (an increase from "easy").

As expected, M02, who had the highest accuracy in the slalom trails, had the highest accuracy in the final operational accuracy test. Likewise, M01, who generally had the lowest accuracy in the slalom trials, had the lowest accuracy in the final accuracy test. However, M03's accuracy on the slalom trails was similar to M01's yet her final accuracy test was as good as M02's. M03's time was slower than M02 on both the slalom trails and the final operational accuracy test, but the participants were told that accuracy was the most important criteria. A possible explanation for M03's good performance on the final accuracy test could be that the test was much less involved than the slalom trials (in the test she only had to turn, then go forward towards the target, then adjust slightly to hit the target) and she may have transferred these skills from her experience as a power wheelchair driver.

M01 and M02 went through the full training protocol, whereas M03's was abbreviated partly due to her insistence that she already had used the robot for two years. The abbreviated training appears to be justified based on her performance on the final robot operational test. The main required skills in the math activities were: to stop the robot lined up on a line, maneuver in 2-dimensions, line up units tip to tip, and switch between robot control and communication mode. The accuracy required in the math activities was similar to the distance between obstacles in the 2-obstacle training trials. Time was not a factor since the participants were given as much time as they needed to perform the math activities. The results of the slalom training show that the participants were able to maneuver in the 2-obstacle trails. It was observed that participant performance deteriorated as they moved to increasingly complex tasks, and this information was used in reflecting on the contribution of cognitive load on participant accuracy in the math activities.

Introducing domains (robot control, manipulation, and communication) one at a time during the training protocol not only provided an opportunity for the participants to practice manipulating the items that they needed to use in the subsequent math activities, but also provided an opportunity for the investigators to evaluate the effect of adding manipulation and communication demands on top of robot control

5.3 Question 1: Demonstrate and Explain Knowledge

1. Can children with physical and communication limitations demonstrate and explain their knowledge of math concepts using an integrated communication and robot control system in math measurement activities?

After establishing the level of competence that could be expected with respect to communication with their SGD, and performing training with the Lego robot and the expected manipulation tasks, three participants performed math measurement lessons. Based on what they did with the robot and said with the SGD, the teacher was able to assess each participant's performance regarding Conceptual understanding, Procedural Knowledge, Problem Solving and Communication in each of the lessons. Although the teacher and External Teacher's inter-rater reliability was only 71% for the exact rating on a four point rating scale, the reliability for ratings which were adjacent on the scale was very high, 96%. The teacher's ratings (Tables 4-13 to 4-18) show that, in general, the participants performed well with earlier concepts, then began to be challenged as the lessons progressed, and improved when concepts were repeated in practice lessons. M01 was challenged quite early, in Level 1 Lesson 2 (L1L2 Ramp and Cars), when she did not understand that the distance the cars travelled was represented by strings, and she only performed the first lesson in Level 2 and three practices because the concepts were challenging for her. M02’s performance was proficient and/or excellent in all concepts and procedures except for L2L3 Heights because he did not order the heights properly since he decided to use fractions. His Education Assistant (EA) said later that he had only touched on fractions previously, but that he may have heard his classmates using them. M02's EA suggested that he may have tried to use them "to go a step further if he thought that the [measuring the gingerbread man activity] was too easy", and M02 agreed with her. M03 did well in Level 1 except for L1L2 Ramp and Cars when she did not lay the strings along the same baseline. Her performance decreased in Level 2 as she became challenged with higher concepts.

The teacher was able to assess each participant's procedural knowledge based on the activity output of manipulation with the robot and she was able to assess the participant's conceptual understanding and communication (uses appropriate language and explains reasoning) based on the activity output of communication using their SGD or non-verbal communication. These manipulation and communication activity output events revealed a number of insights into how the participants understood the math procedures and concepts.

5.3.1 Doing Procedures

In Level 1, participant use of the robot allowed the teacher to assess if the participant could carry out procedures to accurately compare concrete items, and in Level 2 it allowed assessment of the procedures to accurately compare items measured with multiple or single non-standard units. The teacher also assessed sorting in Level 1 and understanding that gaps between units affects accuracy in Level 2 from watching what the participants did with the robot. Conversely, the teacher assessed ordering by what the participants said (except for one practice activity for M01 ordering straws). The teacher's ratings of procedural knowledge seen in Tables 4-13 to 4-18 correspond with the summary of the observation of robotic manipulation events seen in Tables 4-25 and 4-26. When the teacher gave a participant a rating less than excellent or proficient, it corresponds to when the participant had difficulty "getting" the robot task for that procedure.

To compare items in Level 1 participants needed to follow the procedure of "Place items parallel" and "Line up ends of the items". Referring to Box 4-1, after some practice for M01, all participants demonstrated the skill to "Place items parallel". Also in Box 4-1, none of the participants demonstrated the procedure to "Line up ends of items" (the referent and the comparison item). M02's strategy of lining up the centres was reasonable, but not the best strategy. So, even though M02 and M03 had been exposed to some math measurement previously, none of the participants had learned this basic concept. M02's EA said afterwards that when she held items up for him she probably never said, "you have to line up at the end". The teachers on the Evaluation Team and the External Teacher agreed that when they are demonstrating for the students they sometimes forget to explain what they are doing:

> [Evaluation Teacher2] We do these things for these kids all the time, forgetting that [doing it] is a big part of learning. They have limited experiences and the ones that they do get are very different.

Interestingly, even though M01 and M03 demonstrated that they knew the concept of lining up items in earlier lessons, they did not generalize the concept to subsequent lessons (See Box 4-1 and Box 4-4). The baseline concept was presented in several formats; in the early lessons the participant needed to line up two items (e.g., a pencil and a toy rake) and then three strings, and then in Level 2 they lined up the ends of a non-standard unit (e.g., a straw) and a picture or string.

M01 and M03 had problems with the concept at the beginning of each new baseline format, but using the robot gave the participants experience in using baselines in different formats and revealed their misunderstanding of the fundamental concept.

All participants managed the task of "Put item in appropriate bin" for the procedure of sorting. Despite being told that if they could tell just by looking, they didn't have to line up the items, M02 and M03 measured two items each of which were visibly different in length from the referent. This could be because they are cautious, or because the robot gave them the impression that the items were longer.

In addition to placing the non-standard unit on the baseline in Level 2, the participants also needed to "Place the next unit tip to tip with the previous unit" and "Place the last unit as close as possible to the end baseline" in order to accurately measure with non-standard units. Referring to Box 4-4, all participants demonstrated that they knew the skill to not overlap or leave gaps between the units (i.e., place units tip to tip) when measuring with multiple units. M02 demonstrated the concept immediately and M01 and M03 needed some repetition of the tasks before they demonstrated the skill independently. After the participants demonstrated that they knew the skill of not overlapping or leaving gaps, then the magnetic units were used because they snapped together which made the procedure easier to accomplish with the robot. As seen in Box 4-5, M03 had problems with not overlapping units when measuring with single units (i.e., she did not use the unit program between making pen marks thus the units were tip to tip). One reason for her problem could be that it was her first time using programs stored in the robot and replayed from the SGD, whereas M02 had used them in his L2L4 Giant/Baby steps lesson.

Referring to Box 4-4, only M03 had trouble placing the last unit at the end of the item when measuring with multiple units**,** however, she quickly learned this skill. Also noted in Box 4-4, M03 had problems with this task when measuring with single units and failed to round up to the nearest integral number of units (i.e., she made a pen mark at the end of the baseline instead of at a unit length). It is interesting that she performed better with multiple and 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 (See Fig 3-5). When measuring with single units, the participant only sees pen marks along the snake, and since the participant had access to all commands, the small forward command can easily be used instead of the program command.

The other manipulation tasks in the lessons (Box 4-2) did not specifically correspond to measurement skills, but they were necessary to carry out the procedure to solve the problem. The Evaluation Teachers supported that it was important for the participants to be able to do these tasks: "These kids haven't gotten to do those things. It's their first time experiencing that stuff. So that's good."

5.3.2 Talking About Concepts

After doing the math lesson activities with the robot, the participants reported on their findings. In Level 1, the things the participant said with their SGD and non-verbal responses allowed the teacher to assess the concepts of comparing and ordering concrete items (the concept of sorting was assessed instead by how the participants manipulated the items with the robot) and in Level 2 it allowed assessment of the concepts of comparing and ordering items measured in non-standard units, estimation, orientation, choice of appropriate unit and how the choice of unit affects number of units needed (Table 4-13 to Table 4-18). The teacher also assessed the participant's communication, in terms of using appropriate language and explaining reasoning, (See Table 4.19). The teacher's ratings of concepts and communication correspond to observations of the participant's communication in Box 4-6 to Box 4-9. There were many interesting observations that revealed participant understanding of concepts.

Each participant's use of language to report their findings in Level 1 (See Box 4-6) is consistent with their performance on the story re-tell. M01 generally answered in 1-word utterances (not always mathematically correct) and needed prompting to expand to 2 or 3-word answers. The teacher often phrased questions so that M01 could answer with 1-word or yes/no answers. After practicing, M01 eventually said 3 word sentences (e.g., "green shorter red"). Perhaps after practicing with the activity, she was comfortable enough that she could focus on talking. Or, with enough modeling from the teacher, she understood what was expected of her. M02 was articulate in his reporting. M03 used good short sentences, and at times tried using higher level math terms than were expected ("centimetre", "inches"). M03's EA did not understand why M03 would use the unit of inches (See Box 4-7) since they use centimetres in school, except in industrial arts class. M03's mom suggested a few possible reasons: from watching television shows from the United States, when we say our height, or her SGD has the word "inch" because it was made in the United States.

Reporting in Level 2 was partially accomplished by the participant entering their measurement results into worksheets on a computer. Although this was sometimes time consuming or awkward during the lesson, it was reinforced by the Adult User of AAC and the Evaluation Team Teachers that filling in the worksheets was a beneficial activity. In general, all participants answered questions from the teacher about the results with short answers (M01 said a 4-word sentence with prompting in her third practice, and M02 and M03 generated fewer and shorter sentences than in Level 1 - See Box 4-8) . The teacher frequently ascertained 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 (See Box 4-6 and Box 4-8, <u>Reasoning</u>). M01 needed prompting and questions to be broken into yes or no responses in both Level 1 and Level 2. M02 explained his reasoning fairly well in Level 1, however, he sometimes needed prompting (in the form of yes no questions) in Level 2. M03 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. Based on their performance in the story re-tell, M02 and M03 should have been capable of explaining themselves, so their lack of responses in Level 2 probably means that they did not have explanations of their reasoning about math concepts or problems.

Regarding the concepts of comparing and ordering in Level 1, doing the lessons with the robot gave the participants an opportunity to practice with comparison and ordering words with objects that they manipulated and measured themselves. The participants used words with which they were already somewhat familiar (e.g, shorter, longer) while comparing and ordering concrete items (e.g., toys, strings). Some weaknesses were identified and the participants had opportunities to practice with them, for instance, M01's word endings (e.g., short**est**, long**er**) and M01 and M03's use of the word "middle" (See Box 4-7).

In Level 2, comparing and ordering was done with numbers representing the length of items in non-standard units instead of concrete items. M01 did not understand this concept and needed three practice lessons. Interestingly, when M02 ordered the heights and lengths he used numbers (e.g., "6 5½ 7 7¼") whereas M03 used words (e.g., "Mom is the shortest") and only referred to the data in the worksheet when prompted. This manner of reporting is consistent with how the Evaluation Team classified the participant's strength areas (from a list in Layton & Lock, 2008); M02 is strong in logical thinking and visual/spatial skills and M03 is strong in interpersonal skills and "although she may not be strong linguistically, secondary to her disability, she loves to write and tell stories".

M01 basically compared heights and lengths rather than ordering them, (e.g., "block taller foot") and only used numbers when prompted. The Evaluation Team classified M01 as visual spatial, so that does not correspond with her preference for words over numbers. However, her teacher and EA reported that she generally dislikes math and numbers. M01 had trouble ordering, but she could identify the biggest number. M01'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.

All of the participants' first estimates of height, before making any measurements, were very high (between 3 and 10 times too much - see Box 4-8) despite both M02 and M03 having previously done some estimating in school. After more estimating, and then using the robot to measure and confirm their estimates, their estimates improved (See Box 4-8 and also Table 4-14, 4-16, and 4-18). M03's performance in estimation went down for the last Snakes lesson, but accurate estimates in that lesson were dependent on understanding multiple concepts, which she did not understand. M02 became very accurate at estimating and sometimes estimated the exact number of units required. In one of his early estimates, he thought he would be shorter than a friend his age, but it turned out that he was taller. This is interesting because perhaps he felt that he was shorter because he was usually in a wheelchair looking up at his friend. Measuring his own height gave him an opportunity to compare himself to other things and people in his environment. M02'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. M03's EA supported this idea, but also commented that M03'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 M03's estimates would have become better even if she was just observing the measurements. However, it was interesting in the Pathway activity in Level 1 that both M01 and M03 changed their guess, to the correct one, about which path they thought was the longest after they had un-wound the strings along the pathway. It is possible that manipulating the robot along the path gave them a better feel for the distance along the paths.

The EAs reported that none of the participants had much prior experience with the concept that changing the orientation of items does not change their length and all participants had incorrect first answers regarding this concept. The lessons covered in this study did not provide any more practice with this concept except for the last lesson about Snakes which presented the concept in a different format (straight versus wavy snakes instead of standing versus lying down). That lesson also involved understanding the concept that the snakes should be the same length regardless if they were measured with multiple or single units. Only M02 got these concepts. M03 seemed like she had the concept that multiple and single units would give the same number when she measured the straight snake, but lost it with the wavy snake. Due to multiple concepts being covered at once and the added demand of using the robot to measure with single units (the manipulation required to use the robot and pen was rated as "hard" by the participants), the high cognitive load could have prevented M03 from remembering the concept, or generalizing it to the wavy snake.

Both M02 and M03 chose appropriate units and gave reasons (See Box 4-8), but at first they did not have the concept that the length of objects which were measured with different units could not be directly compared to each other. M02 got it quickly, but M03 did not. The teachers commented that this is a difficult topic for kids. However, it is important because it relates to life skills such as dealing with units of time (converting minutes and hours to the same unit). M03's EA commented how she continued to have problems with units of time.

Although there were not many events which were coded as communicative initiations (Table 4-27), looking at them shows what was motivating to the participants. The utterances were about saying vocabulary or results when the teacher was not expecting it, requests to do something during the activity or for help when doing things with the robot. Comparing her own height to her SLP appeared to be a motivating activity for M03 because she told her SLP outside of the math session that he was only 2 paper clips taller than she was (Box 4-10). These examples show that the participants were motivated to participate in the lessons, rather than be passive.

5.3.3 Integration of Doing and Talking

Please refer to the distribution of communication modes used in each portion of the lesson shown in Figures 4-5 a, b and c. Regarding the "doing" portions of the lessons, the communication mode that the participant chose during the different manipulation modes depended on the situation:

- In demonstration mode, of course, there was not much communication because participants were not necessarily asked for input.
- In the manipulation mode where M02 directed the teacher how to manipulate, he used SGD output, and non-verbal responses to teacher directed communication such as "nod when I should stop moving it".

- In the manipulation mode when the teacher manipulated and the participant guided, all participants used a lot of non-verbal communication because of the way the interaction was framed with the teacher asking yes and no questions and giving eye gaze choices.
- In the robot mode, there was not much SGD output because participants were focused on accomplishing the task and also they did not have vocabulary available on the SGD robot control page. All participants used a lot of non-verbal communication partly due to the teacher confirming what he or she was doing with the robot, and asking if he or she wanted anything adjusted. Interestingly, when the robot was available to them in this mode, all participants used the robot to communicate as well. As seen in Table 4-28, during the "doing" portions, the participants used the robot as a means to point and say "not there, over here" and also to say "let me do it". M02 also teased the teacher by moving the robot away when she was going to reach for it, a trick that typical children like to play on others.

Regarding the "talking" portions of the lessons, communication events during the "Ask strategies" portion of the lesson were low for all participants in all communication modes. However, M03 used the robot as a means to say, "I'll show you what I mean" for a strategy in one of the lessons. She also used it to show the teacher and her mother what she meant when she tried to explain something that she was worried about (putting the pen down too far and possibly harming the robot). The amount of SGD output and non-verbal communication was consistent across the Introduction and Reporting portions for each participant.

The high non-verbal communication shows that the teacher was also asking yes and no questions and giving choices to answer with eye gaze.

The participants also augmented robot use with communication. An example of this was when M02 was comparing items to sort into bins and he lined up the back ends of the referent and comparison item instead of the front ends (See Box 4-1). It took some discussion to establish that was what he was doing and the Evaluation Team pointed out that the teacher may not have given him credit for the concept if he could not communicate what he was doing with the robot:

> [SLP] What is ironic about that is that he demonstrated it accurately, and still needed language to show that he could do it. So I think that the powerful message here is that robots alone will not help teachers know what students know. That you need the students to be able to explain what they have done and that you need the combination of language plus the robotic skill to do it.

Another example of needing both manipulation and communication was when M01 was attempting to lay down her first straw to measure the gingerbread man, but she was not on the baseline yet. This was possibly due to the fact that the participant was far away from the straw and foot of the gingerbread man, and they possibly looked lined up due to parallax (Table 4-29). The teacher asked her to clarify where she was aiming with the robot, and M01 replied "foot".

5.3.4 Problem Solving

The result that all of the participants required a lot of assistance to transition between activities, in spite of having done procedures in previous lessons, was not surprising to the Evaluation Team Teachers. The evaluation team suggested this may be because the participants went from "being so dependent, to oh my goodness I need to remember everything". They were also not surprised that the participants did not offer many strategies to solve problems since students who use AAC may not have the experience of offering solutions, may lack confidence, and may have become passive.

> [Teacher2] Even though they are fairly proficient on their device and using it to talk, they are still kind of sitting back because, number one it's a huge amount of pressure on them because everybody is waiting. But they just don't have that confidence and they are not used to that expectation on them.

M02 and M03 did suggest some procedural steps and strategies (See Table 4-20). Interestingly, after using strings to solve the Ramp and Cars problem, M02 and M03 suggested using string to solve the pathways problem, and gave a reason why string was a good tool to use. So, after getting experience doing the activity they were able to apply the strategy to a new problem. Because M03 had the robot available to her in the Ramp and Cars lesson, she was able to respond to the teacher's question about what to do next by moving the robot to demonstrate her idea instead of articulating the idea.

5.3.5 Carry Over Skills

There was some qualitative evidence that participant learning extended beyond the study. M02's EA noticed that his understanding of measurement improved when he went back to school and she attributed it to him being able to do things hands-on with the robot.

> [M02 EA] I think that the robot definitely helped him understand how to measure because it was like hands on for him verses the year before when we were having problems

M03's EA felt that M03 retained her math skills over the summer because of participating in the study, resulting in less time needed for review.

> [M03's EA] When she came back to school after the summer was over we zipped through math at the beginning of the year. I was blown away at all the stuff she knew, without us having to go over and review.

M01's teacher stated that M01 benefited from the activities because she was involved in solving problems, a side of the participant that she does not generally see because they focus on life skills.

> [M01's Teacher] It was nice for me to see a side of her doing these puzzles, because I focus on life skills, like money and accounting.

M01's mother noticed some carry over skills in M01's skill at operating her switches for communicating with her SGD and navigating in power wheelchair trials.

> [M01's mom] Right after she was working the first time [the pilot study] she got better, then the second time [this study] the difference was just amazing. It really excited her and got her interested in her switches and just from that she's got so much more control and ability to say what she wants to say.
> [M01's mom] I swear it's the work she did with the robot that has made her such a good wheelchair user.

5.3.6 Summary

Participants were able to demonstrate their knowledge of math concepts using an integrated communication and robot control system in math measurement activities. The teacher was able to assess each participant's procedural knowledge based on the activity output of manipulation with the robot and she was able to assess the participant's conceptual understanding and communication (uses appropriate language and explains reasoning) based on the activity output of communication using their SGD or non-verbal communication. Many gaps in participant conceptual, procedural, and problem solving knowledge were identified, and performance improved with practice. Communication was multimodal during the lessons; the participants used SGD output, non-verbal communication and when the robot was available, they used it to communicate, too. In addition, having access to integrated communication and manipulation enhanced the effectiveness of both demonstrating and explaining math concepts and procedures (each was used to augment the other).

5.4 Question 2: Key HAAT Elements

2. What are the key features and characteristics of the participant, activity, integrated communication and robot control system, and context that limit system usability?

HAAT (Human, Activity, Assistive Technology and Context) elements which limited the usability of the system were identified to investigate the effectiveness of using the robot as an assistive technology (AT) tool. The Activity and AT-robot issues identified in Table 4-29 limited the accuracy with which participants could perform tasks, but the strategies used by the teacher and/or investigator compensated for the limitations (also identified in the table). The compensation strategies merely augmented the robot and/or environment and allowed the participant to perform the tasks with the required accuracy. For example, the Activity issue of parallax was easily compensated by bringing items closer to the participant or by indicating the endpoints of items. The Activity issue of drooping straws was compensated with magnets which snapped together, but they were not used until the participant had already demonstrated that they knew the concept of lining up units tip to tip. The magnets also compensated for the AT-robot issue of movements not being small enough to get exactly tip to tip (due to sending a discrete IR command from the SGD). The strategy when the teacher placed the item in the exact location if the participants moved the robot forward and backward in an attempt to get as close as possible was described by Evaluation Teacher1 as similar to when children with less severe disabilities attempt to do a task. If the teacher sees the child's intention and that they are close, the teacher will put the item where it is supposed to be (she essentially behaves like the magnet did). The AT-robot resolution issue of not driving straight was easily compensated by nudging the robot. Since Lego robots are inexpensive they were expected to have some inaccuracies, but they had sufficient capability to accomplish these tasks with some compensatory strategies by the teacher.

There were some issues with the "robot to human interface" regarding positioning of items on the robot and understanding where to place the robot to compare to items in the environment, mostly for M03. Although, the robot was built as low as possible (only as high as the control unit and motors), placing items (the referent, or unit) on the top of the robot was not vertically close enough to the target item or location with which participants needed to compare. The evaluation team teachers suggested that it was a lot for participants to visualize and remember (the cue was, "the end of the item is between the robot arms, which are overtop of the axel, which is over top of the wheel"). A better solution would be to mount the units, items, and spool adjacent to the robot lying on the surface of the table.

The "SGD to human interface" issue regarding the multiple function of the gripper open and close commands as also pen up and down commands was problematic for M01 and M03. They frequently selected the wrong command (open, instead of close, to make the pen go down, and vice versa). To resolve the issue the commands could be separated. None of the participants wanted to add separate commands, possibly due to the tradeoff in increased time to scan to the new items. Other assistive robot research has reported that participants had problems understanding what robot function would result from selecting symbols on the scanning array (Prazak et al., 2004). The participants did not have problems understanding the mapping of other SGD symbols/words to robot functions.

The skills and abilities of the participants identified in Table 4-30 also limited the accuracy with which participants could perform tasks. For example, the best accuracy using the press and hold strategy to make the robot go long distances was attained when the participant's "select" switch (as opposed to the "move" switch) was on the same side as their view of the workspace (true for M01 and M03, but not M02). This way they could keep their eye on the robot in the workspace while they held the switch down with their head. Participants needed medium skill at releasing the switch for this strategy and M01 and M02 had high skill at this, but M03 had low skill and she held the switch too long. M03 told the investigator that she loved that she learned the press and hold strategy because she began to use the strategy with her DVD program at home to scan through options and release her switch on the option she wanted. It is possible that her experience using that program influenced her sense of timing for releasing her switch to control the robot, making her hold the switch down too long. Since M02's preferred side to view the workspace was not optimal for using the press and hold strategy he did not use the strategy often. For driving the robot long distances M02 preferred to use the strategy he discovered on his own (selecting the Giant step program command and then hitting Stop at the target location). During SGD design, he positioned the Stop command in the first cell of his scan array (the command with the highest demand for exact timing). In this way, he could set the robot in motion, cue up his scanning highlight to the first position, keep his eye on the robot, and then select Stop at the appropriate time. This strategy usually worked for him, but when it failed, the robot was far off target.

It was observed by the investigator and Evaluation OT1 that the participants selected the first item in their scan array without looking at it, so being able to access the robot command in the first position using motor memory was very functional for M02, and also M01. M01 insisted that the robot forward movement be the first symbol in her scan array. She had a tendency to select it accidentally, but the convenience of having the robot movement in the first position must have outweighed the inconvenience of having to fix her errors. M01 had the robot commands on the top row of her core vocabulary instead of on a page, and one disadvantage to this layout was the high number of switch hits required to access commands far from the initial scan position. This was probably a factor in her reluctance to use the small forward command which was located 7 positions from the scanning start position.

M03's problem solving strategies limited her accuracy in performing the tasks in the lessons (see examples in Table 4-30). This was surprising because M03 was accurate in the robot training and operational test, however, grasping items and backing up were not part of the training protocol. So adding those tasks to the protocol would be helpful.

When using the robot in the lessons, the participants generally were able to use the robot with sufficient accuracy for all tasks except for measuring the wavy snake (a pipe cleaner bent into a C-shape). This task was not trivial, regardless of whether the participants were measuring with multiple units using the robot and gripper or if they were measuring with single units using the robot and pen. M02 opted not to measure the wavy snake with multiple units since he already knew that it would be the same length as the straight snake, and he said it would be, "too hard". With his competence in robot operational skills and problem solving skills he would probably have been able to do it. M03 did not know that the wavy snake and straight snake would be the same length, so she needed to measure it. However, as shown in Box 4-5 and Figure 4-4, she had difficulty measuring with multiple units and she was accurate only because she acquired help from the teacher to make the units tip to tip by eye gazing at her.

Both M02 and M03 had difficulty measuring the wavy snake with single units (Box 4-5 and Figure 4-4) and participants rated the corresponding manipulation task in the robot training sessions as "hard" (Table 4-11). Since M02, with his competent robot operational skill, had problems with this task it is probably too much to expect students to do tasks such as this without additional training on strategies, or by using robot programs to reduce the manipulation demands on the user.

M03 answered the lesson question about preference for measuring with multiple versus single units differently than we would expect typical children to answer the question. We would expect typical children to say that measuring with single units is easier because you only need one, and M02 said this, but M03 said she preferred using multiple units. However, she had trouble using the robot and pen for measuring with single units (Box 4-5), and since she received a lot of assistance from the teacher in her multiple unit measurement the result was very accurate. So, this probably influenced her choice.

Participant responses to the statement "The robot was easy to use" in the attitudes survey given after the study reflect that measuring the wavy snake was not easy (Table 4-35). M03, who replied to statements regarding each type of task, indicated that the statement was "so so" true for measuring the wavy snake. M02, who was asked the statement in general, indicated "so so" as well. It was determined that he meant that some tasks were easy and some tasks were hard, with measuring the wavy snake being hard. M01 did not perform that task, but her response to the statement is interesting. She previously rated all robot training tasks as "really hard", but indicated that the statement "The robot was easy to use" was "a lot" true for her after doing the math tasks. There are several possible explanations for her change in answer regarding ease of use: being timed in the training tasks made them hard, the tasks in the math lessons were easier than the training tasks, or she became more proficient using the robot over time so it became easier. Or, she may not have understood the question.

Some interesting events were observed which may point to the cognitive load of adding the need for the participants to use the robot as a tool on top of the regular learning load in lessons. Both M01 and M03 had trouble keeping results in memory during the lesson, for example, the height that they just measured or where to stop the robot even after previously indicating the intended location (e.g., M03 in Box 4-2). Also, M03 had a hard time remembering the vocabulary pathways (e.g., M03 asked in almost every session for the pathway to "short"). She knew where the vocabulary was located on her previous language system, but had recently changed to a new system. Her mother reported that remembering pathways was not usually an issue for M03. One possible explanation for the problems remembering things could be that they were thinking about the math concepts as well as operating the robot, thus overloading their working memory.

The evaluation team commented on the cognitive effort of using the robot in the math activities, "Not only do they have to know all the commands for the robot (where they are located, etc.) but they also have to remember all the steps for this activity". In spite of these cognitive loads, the teacher and evaluation teachers all noticed that the participants remembered the math concepts from one session to the next.

In addition to using the robot as a tool, the participants also seemed to appreciate the personalization of the robot. They noticed when the wrong head was on the robot, or missing, and requested for it to be replaced. They used names to refer to the robot, such as "toy" and "Mac" (M01), "truck" (M02) and "row box" and "Lavonie" (M03). M03 corrected the teacher and investigator every time they mistakenly called the robot a "he" instead of a "she".

In summary, these HAAT system observations indicate that the using the robot as a tool in these math lessons had some limitations, but they were easily compensated for by the teacher in a way that was not judged as influencing the activity that the participant was doing. Only one activity, measuring the wavy snake, was too difficult to be accomplished with the robot. The robot was instrumental in giving the participants access to the tasks which allowed them to carry out the procedure and also to the tasks which were specifically assessed by the teacher for procedural knowledge. Although using the robot may have added cognitive demands to the task, the participants were learning the concepts.

5.5 Question 3: Effectiveness, Efficiency, and Satisfaction

3. What differences are there in terms of effectiveness, efficiency, and satisfaction using the integrated communication and robotic control system to do the manipulative tasks compared to other modes participants used such as observation of the teacher and responding to questions, or directing the teacher?

In the math lessons in this study, there were natural examples of using different manipulation modes to accomplish tasks. Effectiveness, efficiency, and participant satisfaction was examined in the modes of directing the teacher, observing the teacher and guiding her by responding to questions or using the robot.

5.5.1 Effectiveness

Effectiveness was examined by obtaining opinions from the Evaluation Team regarding how well the participant could portray what they knew about the concept being assessed (Table 4-32).

M02 used the manipulation mode of directing the teacher in Level 1 Lesson Launch (L1L0 Compare - See Box 4-1). Given that he had the highest independent communicative competence of the participants on the story re-tell pre-test, he probably had the highest probability of getting his thoughts across to the teacher about what to do. As noted in Table 4-32, directing the teacher was effective "because [the teacher] found out the concept that [she] wanted to find out". However, the Evaluation Team pointed out that the skill level of the participant at knowing how to direct would be a factor which would contribute to the effectiveness of this method. They said that "often times the kids don't have experience directing" and may have difficulty with the role of having complete control:

> [Teacher1] Because this is a lot for our more passive kids. [They feel that] not only do I need to know math, but I am expected to do this. You are not going to show me and I either agree or don't agree [i.e., guide the teacher], but I am totally in control.

Students would need modeling of how to direct the teacher to do these math activities. Suggestions for how to direct the comparing activity were discussed, but they were deemed to be too difficult for young children (e.g., "move it like around the clock, to nine o'clock" is not feasible if the child cannot tell time, or "turn it right, right, right, right, right, right" would be difficult for scanning users).

Higginbotham et al (Higginbotham et al., 2009) investigated the effect of priming vocabulary for AAC use in three different task types with non-disabled adult students, where one student was the user of AAC and the other was the partner. One of the tasks was a collaborative puzzle solving task where they directed each other to select and place tangram puzzle pieces. In another task, the AAC user instructed their partner to follow a route on a map, but they could not see each other's maps. The workload of these instruction-giving tasks was rated by both the AAC user and the partner as significantly higher than the third task, a narrative re-tell task. If these instruction giving tasks presented a high workload for adults, then expecting a child to instruct someone to manipulate items to measure them might be unrealistic. Another limiting factor, pointed out by the Evaluation SLP, was that M02 was using a finite language set to give his instructions. The adults in the Higginbotham study had the use of word prediction and spelling (i.e., an unlimited vocabulary).

The skill level of the teacher at facilitating directing would also be a factor which would contribute to the effectiveness of this method. The evaluation team noted the complexity of the situation where the teacher played three roles: the robot role to respond to M02's instructions, the teacher role to help him think about the concepts, and the language model role for SGD vocabulary suggestions.

> [SLP] It makes it so that M02 doesn’t have any real predictability in terms of how he is supposed to relate to this teacher. Is she being a teacher now, is she being my robot now, or is she trying to show me a better way how to say the stuff?

When the teacher learned to separate the roles better, it allowed M02 to use her as a tool more effectively. The teacher did the robot role by slowly moving the item until M02 indicated when to stop, then she did the teacher role and inquired why he stopped where he did, and he replied "it is in the centre".

The team felt that when the participants used the mode of observing the teacher and guiding her via teacher directed questions, the participants portrayed what they knew effectively by responding appropriately. However, the limitation was that the participants only made decisions from a finite list of options presented by the teacher and did generate their own way of doing the problem. Another limitation mentioned was that the team "did not know what [the participant] was thinking".

When using the manipulation mode of controlling the robot the Evaluation Team's general consensus was, "I think with [observing] we knew, but we're 100 percent sure on the robot one". They also commented on how the participants demonstrated that they knew the procedures (e.g., to line up the items, to make the strings parallel, to not leave gaps or overlap the items). The main factor mentioned which would limit a student from showing what he or she knows by using a robot would be the student's operational skills at controlling the robot. In this study, participants spent a considerable amount of time learning operational control of the robot in the training sessions to reduce the risk that their operational skills would limit performance in the math lessons. The only operational concerns were M01's accidental forward hits and reluctance to use the small forward movements and M03's difficulty maneuvering the robot to grasp blocks and orient them properly (Table 4-30). Despite the participant's operational concerns, or the Activity and AT-robot issues discussed previously (in Question

2), the Evaluation Team teachers felt that they could ascertain what the participants were intending to show about what they knew when they used the robot.

Two observations were made regarding the effectiveness of the different modes. In both observations, the teacher first did the task by manipulating the objects and asking for participant guidance and then the participants did the same task with the robot. In the first observation, after watching the teacher M01 did not line up the items parallel nor match the ends with the robot in Level 1 Launch (Box 4-1). One reason that the participant may not have seen the similarities between what the teacher did and what she was expected to do was that the teacher had held the items up vertically with the table as the baseline, rather than holding the items horizontally as the participant did with the robot. In the second observation, the orientation of the measurement items was the same; the teacher placed non-standard units on a horizontal plane on the gingerbread man picture (starting at the foot and then tip to tip with each other). While observing the teacher, M03 did not say at first that leaving gaps between items was wrong, but eventually she indicated that it was incorrect. However, neither M01 nor M03 replicated the procedure at first when given the opportunity to do it on their own with the robot (Box 4-4).

Each method of "doing" had a different level of control over the outcome for the participant. When the teacher demonstrated a manipulative task, the participant had no contribution to the outcome. When the teacher manipulated items while asking the participant questions for guidance, the participant had some contribution to the outcome, but it was dependent on the questions from the teacher. When the participant directed the either the robot or the teacher to make the movements, then the outcome was entirely the contribution of the participant. This is similar to when a user of augmentative and alternative communication (AAC) and a communication partner converse. At one extreme, the communication partner generates most of the resultant message and at the other extreme the user of AAC generates most of the message. Often the partner and user of AAC cooperate to co-construct a message, putting them somewhere along the middle of the spectrum.

Just as with co-constructing messages in communication, there was some give and take where the teacher and participant negotiated (consciously or not) how much each person would contribute to the outcome in these manipulation tasks. For instance, part of the video clip that the Evaluation Team saw showed the situation described in Box 4-4 where, at first, the teacher was compensating for M01's inaccuracy by placing the straws tip-to-tip when she stopped the robot too far ahead. But, by the end of the measurement, the teacher stopped compensating and placed the straw exactly where M01 stopped the robot and in response, M01 backed up the robot to be more precise. It was at that point that the evaluation team was convinced that the participant knew the concept. They said when the participant controlled the robot, the participant controlled the outcome, and it took the question of authorship out of the question.

There is value in students having full control over the math tasks because, as the Evaluation Teacher1 said, "they need to judge how far it needs to go [otherwise] the teacher does it the way she wants to and guides where it should go." In order for students to have full control over the output of a manipulative task, they need good skills in directing someone or directing the robot. Having the skills to direct others is very important for this population in order to meet their needs for managing their care, participation, etc. However, as discussed previously, the skill required to verbally instruct someone to manipulate items is advanced. The AAC user must have good linguistic, operational, social, and strategic competencies. However, when directing the robot, the primary skill the AAC user must have is good operational competencies and as the Evaluation SLP pointed out, "for some reason operational skills are almost the easiest ones."

The comments from the Adult User of AAC pertained more to the point of view of the participant using the robot as a learning tool. She commented that it was "neat" that the participants could do things by themselves and she felt it would help them to understand because they were manipulating things in a concrete manner so they would remember longer. The Evaluation Team Teachers, the External Teacher and the EAs also felt that the robot was an effective method for learning because the participants were doing things themselves, it was motivating, and it helped to actively engage them in the lessons:

> [Teacher1] I think she is learning the concepts because she is doing it. She is being forced to do it.
> [M03's EA] The thing about using a robot is they are doing it themselves so it's great learning for them, versus I have got a meter stick and I am measuring you and you are this tall. Well how long is that going to stay in your brain?
> [M02's EA] Who can learn when you just show them a ruler?

> [External Teacher] There’s nothing to say [the EA] couldn’t hold up the pen and say 'Where do I start?' but it's not as much fun as doing it with the robot. If [the EA] did do it [the participant] was probably off in another world because it’s not fun and it’s not motivating. That’s what learning is all about, keeping the child engaged and motivated to want to do more.
> [Teacher2] She is so much more engaged in it [with the robot, than without].

The participants also seemed to feel the robot was a good learning tool. All participants responded "a lot" to the statement "The robot helped me understand measurement" (Table 4-35). They also responded positively to the statement "The robot helped me answer the questions that the teacher asked me". M02 only responded "a bit", but his answer was probably influenced because he knew some answers without having to use the robot (e.g., in the straight/wavy snakes with multiple and single units were all the same size). A better question would be "The robot helped me to solve the problems that the teacher asked me".

5.5.2 Efficiency

The efficiency of the different methods in terms of time was as expected: observing was faster than using the robot or directing the teacher to accomplish tasks (Table 4-31). Observing was 8 times faster for the snake measuring task and between 1 and 3 times faster for pulling strings and placing non-standard units. M02 performed essentially the same task, compare two items, with three different manipulation modes, directing the teacher (9:12 minutes), using the robot (4:18 minutes, including putting the second item in a bin), and observing and guiding the teacher (0:21 minutes).

The efficiency of both manipulation modes where the participant has full control over the outcome (directing the teacher and the robot) is low compared to observing the teacher. So the Evaluation Team and participant EAs cautioned that in situations where time is limited, it may be necessary to move the amount of control towards the teacher (i.e., the teacher performs more of the "doing" task). For example, the adult user of AAC suggested that the teacher, instead of the participant, should draw the baseline in M01's pathway problem. This is a good solution as long as the participant is aware of the concepts and/or procedures which are being done for them.

> [Teacher1] MOST important is balancing what we want our students to get out of the activity with the understanding that everything they do does take longer.

In a fast-paced classroom setting it may also be necessary for the teacher or EA to facilitate generation of math language and reasoning (i.e., the teacher performs more of the "talking" task).

> [M02's EA] It all depends on what it is that you are wanting to get out of him. If you are trying to get the facts out and the answers, sometimes he doesn't have time to tell you all those words that you really want to hear. If he has all the time in the world, that is when he needs to use those words. But if you are trying to get through, you might provide those words for him and use yes and no questions.

5.5.3 Satisfaction

Satisfaction was evaluated from the results of participant preference between manipulation modes (Table 4-34), the post-test survey (Table 4-35), and participant ratings of the activities (Table 4-36). All of the participants preferred to use the robot instead of observing the teacher in the Level 1 activities but in Level 2 there were some differences (Table 4-34). M01 and M03 continued to prefer to use the robot instead of observing the teacher, however, M02 began to prefer observing the teacher over using the robot. Interestingly, when M02 was asked to choose the method to measure the last item in the first lesson of Level 2, he chose to use the robot with the gripper instead of asking the teacher to take the straw "off". Hence, the participant's choice did not indicate his satisfaction with the robot and gripper method to accomplish activities.

Participant responses in the post study survey (Table 4-35) reflect these participant preferences and indicate satisfaction with the robot. M03 said that the statement "I like using the robot to do measurement more than I liked telling the teacher what to do" was "a lot" true for her. M01 said the statement was "a bit" true. That rating was likely lower than M03's because there was one extension activity where she preferred telling the teacher what to do. The draw your own "Who went the farthest" pathways activity was framed around M01 being the teacher and she said she enjoyed it because "I want job teacher". M02 said the statement was "sort of" true for him.

Arthanat et al. (2007) state that "the user’s satisfaction with the [assistive technology] device is in essence derived on the basis of the effectiveness and efficiency of participation in activities". Effectiveness, from the participant's point of view would be how accurately they could accomplish the tasks using the robot as a tool. This contrasts with effectiveness from the teacher's point of view being how well the participant could demonstrate their understanding of concepts and procedures. Efficiency would relate to the amount of time and effort to do the tasks. The influence of effectiveness and efficiency on satisfaction does not appear to be true for M01 and M03. They were very satisfied using the robot regardless of their accuracy, length of time or effort. In M03's words, "I like to do that all by myself".

The influence of effectiveness and efficiency on satisfaction appears to be true for M02. His satisfaction with the robot system to accomplish tasks was influenced by accuracy, length of time and effort. The manipulative task in the first two lessons of Level 2 involved moving blocks, which he rated as only "so so" in difficulty during robot training. However, there were other factors that affected accuracy and length of time of the tasks. Placing the straws tip to tip was difficult for reasons mentioned in Table 4-29, so he appreciated the strategy of being able to move the robot near to the target location (gross motor) and then asking the teacher to place the straws (fine motor) to gain the required accuracy. In the Giant/Baby steps lesson the units had magnets so lining up tip to tip was not an issue, but both lessons required going long distances (due to his tall height and the robot's long program) and his strategies to drive the robot long distances required high effort on his part. He did not always use the press and hold strategy so he had to perform a lot of switch hits. Or, if he used his strategy (of selecting the Giant step program and then pressing Stop), he had timing pressures on him to stop at the correct time.

As discussed previously, measuring the wavy pipe cleaner in L2L5 Snakes was a difficult activity for both M02 and M03 (Box 4-5 and discussed under Question 2). However, when the participants rated how much they liked each lesson activity, M02 said that he liked using the pen to measure in L2L5 "a lot" (Table 4-36). This seems to be inconsistent with his preference to observe the teacher in this activity, however, the lesson involved measuring both a straight item and a curvy item and he probably liked measuring the straight item, but not the curved item. As seen in Table 4-36, all participants liked all of the activities involving the pen, except M03 did not like using the pen to measure the snakes (which is understandable given the difficulty she had, Table 4-30). All participants also rated the sorting into Bins activity lower than the other activities. M02 indicated that it would be better if there were fewer items which were closer to the bins. Consistent with his preferences above, M02 rated measuring Heights as low compared to the others, but he agreed with his EA that he would have liked it more if the items to measure were shorter.

M02's decision to choose to observe the teacher in the Level 2 activities is consistent with how the Evaluation Team classified him as strong in logical thinking (he preferred observing the teacher because, in his words it was "easier") and visual/spatial skills (the robot did not go exactly where he wanted it to go but the teacher compensated for that). M01 and M03 were less concerned about being exact and perhaps since they are teenagers, they have a stronger drive for independence regardless of how long it takes.

All participants responded to the statement "I liked using the robot to work on measurement" that it was "a lot" true for them (Table 4-35). Responses were mixed for the statement "I would like to use the robot to learn other math concepts" (as in Adams et al., 2008a). M01 disliked math in general, but was interested in using the robot for other subjects. M03, who also was not fond of math, was neutral about learning more math concepts, but inquired about how the robot could be used in other subjects. The Adult user of AAC commented that she used to dislike math because she was fearful of it. She felt that "practice and experiences with math would hopefully have helped me overcome my fear of it" and she felt that the participant's "experiences doing math with the robot it would help take the scariness of math away." M02 responded "a lot" to this statement, and his EA inquired later if the robot could be used for geometry.

Summary

Using the robot appears to be a more effective way for participants to "show what they know" than observing the teacher and guiding her based on her questions. It took the question of ownership out of the equation. Participants have the same level of control over the outcome when they direct the teacher to manipulate items as when they control the robot, but using the robot to do it may be easier in terms of linguistic, social and strategic demands. Using the robot also has some perceived benefits in terms of effectiveness as a learning tool Participants appear to appreciate being able to use the robot instead of watching the teacher do the math activities (as long as changes can be made to the activities to make them less long). Using the robot took a long time compared to observing the teacher, but there were benefits in terms of effectiveness and participant satisfaction.

5.6 Summary

The purpose of this study was to examine how an integrated communication and robotic system, composed of a student's own speech generating device (SGD) and a low cost Lego robot, could be used with participants to demonstrate and explain their understanding of math concepts, to investigate the usability of the system, and to compare effectiveness of the system with other methods that participants might use to manipulate objects in math sessions. The underlying theories for the approach taken were that being able to perform hands-on learning activities enhances student learning experiences, that integration of manipulation and communication is important in math learning experiences, and that assistive robotic technology could be used to compensate for manipulative limitations and give participants access to the math lessons.

5.6.1 Hands - On Learning Experiences

The integrated communication and robotic system enabled participants to demonstrate their knowledge of math procedural knowledge by manipulating items with the robot. There were many examples where participant limitations in understanding were revealed when they used the robot to accomplish a task. For instance, at the beginning of the study, when asked to compare two items, none of the participants knew to line them up at the ends. The teachers and EAs agreed that this was probably because they always did that portion of the procedure for the participants and did not explain what they were doing. So, when the participants had the opportunity to demonstrate what they knew, a gap in their knowledge was revealed. Based on subsequent experiences of lining up objects in different formats of baseline, they learned the concept and generalized it to other problems. An example of having hands-on experiences influencing understanding is how all participants improved in estimation skills over the course of the study, attributed by the EAs to the participants making repeated measurements themselves. M02's EA stated, "There is no question that hands on activity is the way he likes to learn".

There were instances where the participants watched the teacher demonstrate a manipulation activity, and then subsequently did not perform the manipulation the same way with the robot. These examples may indicate that students do not fully comprehend procedures and concepts when they observe someone else do them. But, because they were asked to do the manipulation themselves, their limitations in understanding were revealed.

These examples reveal the benefit to teachers when participants do tasks hands-on instead of observing the teacher. Teachers found that when the participant used the robot, they felt the participant was more able to show what they know and it took the question of ownership out of the equation.

5.6.2 Integrated Manipulation and Communication Learning

In addition to demonstrating procedural knowledge through manipulation with the robot, the integrated communication and robotic system enabled participants to explain their understanding of math concepts by communicating. They used their SGD and non-verbal communication to report on results and explain their reasoning. There were many instances when the integration of manipulation and communication was beneficial. Participants developed language ability based on meaningful experiences (e.g., string in the middle position versus the middle size length). When the participants had the robot available, they used it as an additional mode of communication (e.g., to tease the teacher). They augmented what they were saying by using robot movements (as if to say, "Here, I'll show you what I mean") and they augmented what they were doing with the robot by using their SGD to speak (as if to say, "No, that's not what I'm doing"). The SGD did not have to be removed from in front of the participant in order for them to access the robot for manipulation, and vice-versa (pointed out as a problem previously in Light & Drager, 2002). This way the math lesson could flow as the curriculum is designed with students doing activities and talking about them.

The assessment rubric asks the teacher to rate if students can "explain and demonstrate" concepts, but at times, the teacher in this study assessed participant understanding of concepts based on what the participant did with the robot rather than what they said to her. For example, understanding of sorting was assessed by evaluating if the participants placed the items into the correct bins. Also, the concept that overlapping or leaving gaps affects accuracy, was assessed based on participant responses when she manipulated the items or by how they used the robot to place units. Conversely, ordering was done with verbal responses because pulling strings into the correct order would be very time consuming with the robot and require a lot of assistance from the teacher to keep the strings from tangling. Thus, the participant and teacher used the appropriate mode for the situation. Doing the activities with the robot gave the participants a way to show what they knew without necessarily using speech, which is a strategy suggested for teaching students for whom English is a second language; ask students to demonstrate measurements rather than explain concepts.

5.6.3 Assistive Robots for Manipulation

Prior to using the integrated communication and robotic system as a tool in the math lessons, the participant's underwent training in controlling the robot where they learned robotic control, and then manipulation of the items used in the math activities, and then switching between robot control and communication mode. This helped to assure that they would have adequate control of the robot and be able to use it as a tool in order to demonstrate mathematical knowledge.

Use of the Lego robot controlled via the participant's SGD enabled the participants to actively participate in the math lessons. In other studies where assistive robotics have been used in educational activities, the robot was used as a compensatory means to replace the hands. In other words, participants used the robot to perform pick and place tasks which were part of a procedure in a curriculum topic area (e.g., to lift an item close to the nose to smell it for a unit on senses in Howell et al., 1996). The robot in the present study gave the participant access to those types of tasks (e.g., drop items down a ramp, unwind string along a pathway), but it also was used as a tool to perform procedures which were specifically assessed in the math curriculum (e.g., place the end of a unit lined up at the end of the comparison item). So, being able to use the robot in this study was key to accessing the curriculum topic.

Using the HAAT model (Described in Chapter 1) identified, not only characteristics of the assistive technology (the Lego robot and SGD interface), but also the participant, and activity that limited the usability of the robot as a tool in these lessons. One lesson, measuring a wavy snake with single units, was the only lesson that was too complex for the participants to be able to accomplish easily with the robot. However, the other lessons were appropriate and any limitations identified were easily compensated for by the teacher or by environmental modifications in a way that was not judged as influencing the activity that the participant was doing. The participant and teacher's negotiation of appropriate time to use the robot, the SGD, the teacher and/or strategies was consistent with Ender's Dynamic Support Triangle (Enders, 1999) (Described in Chapter 1). The task analysis of the math lessons revealed that the participant would not be able to perform all the tasks using the robot and that the teacher would have to perform some tasks also. Thus, two sides of the Enders triangle, personal assistant and assistive technology, were used for math activities. Then, while using the robot in the math activities, the participant and teacher augmented robot function with strategies to make it more accurate (e.g., the participant made a turn to make the robot go straight or the teacher nudged it from the back). They also negotiated whether to the AT (robot for manipulation or the SGD for communication), the teacher, or strategies would be used to perform a task.

The efficiency of using the robot was lower than observing the teacher do manipulative activities, but there were advantages in terms of effectiveness (i.e., as a motivating learning tool for participants and as a way to show what they know). User satisfaction was also higher for robot tasks (as long as the number and length of items is reasonable).

5.6.4 Limitations

This study was subject to limitations. It was a small sample size, thus the results are subject to individual strengths and weaknesses. It was a case study design, so the results are not generalizable to other children with different abilities, devices, or activity areas. There was no experimental control so it is not certain if learning was due to the use of the robot, or focused attention on the topic. Another limitation is that the observations coded by the investigator could have been coded and interpreted differently by another observer, i.e., the HAAT elements which limited system functionality and the manipulation data regarding whether participants understood what they were expected to do with the robot. However, the former corresponded closely with comments made by the Evaluation Team and the latter corresponded closely with the teacher assessments. Participants were asked to verify their survey responses and rank the lessons several months after the study and that could have affected how they remembered the lessons. However, they were provided with pictures and videos of the participants doing the activities and these cues seemed to help remind them. The experience level of the new teacher could have influenced results. For example, if she had more experience teaching or working with children with complex communication needs, the participants may have generated more SGD output.

5.6.5 Practical Contributions

This research study contributes to the literature regarding participation in math activities for children with severe physical and communication limitations, by establishing that they can manipulate items in math measurement activities by controlling robots through commercial speech generating devices. Children were able to show their procedural knowledge using the robot, and robot use was key to identifying and improving gaps in knowledge. It showed that manipulation and communication can be interrelated (that participants could manipulate by communicating and communicate by manipulating). The low-cost Lego robots utilized in the study were feasible for use in the math measurement activities, with minimal assistance needed from the teacher. The study contributes to the literature regarding assistive robots for children with disabilities by showing that math measurement is a pertinent area for robotic use. The study provides guidelines for developing robot-SGD approaches to math opportunities and challenges are identified.

5.6.6 Future Work

This study set the groundwork for many future initiatives. The next step of this study will be to determine the opinions of stakeholders regarding social validity of the goals, methods, and outcomes of the study according to the framework proposed by Schlosser (1999) and to establish what is needed to make the robotic system and adapted activities feasible for use in the classroom. Results from this study pointed to other areas where the use of robots in math may be feasible:

- **Level 3 lessons, measuring with standard cm and m units:** Both M02 and M03 tried these lessons (using the robot with a centimetre ruler or a metre stick attached to it) and were very interested in pursuing them. Knowing standard units of measurement is an important life skill, and as pointed out by M03's EA, it is a hard activity in which to involve participants with severe physical disabilities.
- **Counting:** When the participants counted units such as straws with their eyes or with the teacher pointing to the units, their count was sometimes inaccurate. All participants expressed interest in being able to count independently using the robot. It is an important skill because counting is the basis for learning other math concepts (e.g., one-to-one correspondence), and children with CP generally have poor counting skills (Montaru & Camos, 2004).
- **Division:** Seeing that she performed a division equation in the sorting activity seemed to help M03 understand the concept of division ("6 / 3 =

2" in Box 4-10). Manipulating items with the robot could help students to experience representations of multiplication and division in formats additional to those that they do with their EA.

- **Word problems:** M03 used the robot to represent a word problem with concrete manipulatives when she placed rod units to measure her mother's height ("10 + 3 = 13" in Box 4-10). This appears to be a tangible way for children learning word problems, and the integration of communication output would be a key factor.
- **Fractions and rounding:** All of the participants needed some prompting on whether to round up or down when they were counting units. As mentioned previously, M02 used fractions, but inappropriately at first. After seeing the concrete and non-standard items lined up side by side, he was able to understand fractions better. Placing units with the robot and then having a conversation regarding the overlap may be a good way for students to learn about rounding and/or fractions.

Results from this study will inform future research projects. For example, the HAAT system characteristics identified which limited the use of the low-cost robot as a tool in the math lessons will be used to inform collaborations with other institutions on innovative new robotic designs for use by children with disabilities (Cook, Encarnação et al., 2010). The SGD interfaces used by the participants will be used to inform design of interfaces for further integrated communication and robotic studies. The protocol developed for the access method operational test and the communicative competence protocol using the story re-tell will be further developed.

Some interesting ideas arising from this study which are important to pursue are:

- Motor memory control of robots: The fact that participants used the first position of their scanning array with out looking at it is interesting. This leads to the question if participants can use muscle memory to control the robot. For example, can participants learn switch patterns which map to robot movements (e.g., select with left switch and select with left switch = forward robot movement, or select then move then select = backwards)? This could lead to participants being able to control the robots with no cognitive load to remember robot commands.

- There is a need to investigate better methods for controlling robots via scanning. M01 and M03 were good at using the press and hold strategy in this study whereas M02 developed his own strategy of setting the robot in motion and then pressing stop. Given that all of the participants had the same diagnosis, it is clear that a "one method fits all" approach is not appropriate.

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7 APPENDIX

7.1 Appendix A - Task analysis of the math lessons for robot design requirements

The purpose of this document was to establish the design requirements of the robot and environment.

The goal was for the participant to perform as many of the manipulation tasks as independently as possible using the robot and strategies for using it, however some portions of the tasks required facilitation by the teacher. This allocation of resources follows the dynamic triangle model proposed by Enders where the sides of the triangle represents Assistive Technology, Strategies, and Personal Assistance. All tasks were designed to be performed on a table (rather than the floor) so the user could see while seated in a wheelchair.

The process was to:

- perform a task analysis on each length measurement lesson of interest from the Math makes Sense curriculum resource (Pearson Education Canada, 2007; 2008)
- categorize the lessons into groups according to the type of manipulative tasks, e.g.,
    - A - Activities which involve holding objects next to each other (and optionally placing them somewhere)
    - B - Activities which involve making lines with a pen
    - C - Activities which involve unwinding and pulling string
    - D - Activities which involve gripping onto objects and then placing them somewhere
    - E - Activities that require the student to make small and large "steps"
    - F - Activities which involve moving a unit length and making a pen mark at each unit length
- similar activities were grouped, and the robot, environment and personal assistance required in order to accomplish the manipulative tasks were established

The contents of this document are:

- Level 1 Lessons task breakdown and Level 2 Lessons task breakdown, including:
    - a brief description of the focus and problem to solve in the activity (from the Math Makes Sense curriculum)
    - the task breakdown
    - categorization of the type of manipulation tasks
- Requirements of the robot, environment and teacher for each category of manipulation task (A-F), including:
    - the task breakdown from Table 1 and 2
    - pictures of the design features
- Other general considerations in the robot design

Legend in the Requirements tables:

italics - the manipulative tasks which the user does not have to perform (because a robot feature or the teacher takes care of it)

bold - the first instance of a required robot or environment feature

Level 1 Lessons - "Doing" Tasks Breakdown

		Level 1 Launch	Level 1 Lesson 1 Comparing Lengths	Level 1 Lesson 1 - Practice	Level 1 Lesson 2 - Ordering Lengths	Level 1 Lesson 2 - Practice	Level 1 Lesson 3 - Strategies Toolkit	Level 1 Lesson 3 - Extension
Math Makes Sense Lesson focus and problem	Focus	Demonstrate prior knowledge of measurement	Compare the lengths of objects to one common referent		Order objects according to length		“Use objects” to solve a problem about comparing lengths	
	The materials and the problem to solve:	Give children a collection of objects. Tell them to choose 2 objects and compare them, then compare with other objects	Give children an unsharpened pencil. Tell them to find objects around the classroom that are about as long as the pencil. Tell them to sort the objects into "shorter than", "about the same as", and longer than" bins.	Give children a referent. Tell them to make something with modeling clay that is about as a long as, shorter than, or longer than the referent. *Instead of using clay, the children could draw lines	Give children a ramp, string, tape, pens and three toy cars. Ask them how they can find out which of the three toy cars travels the farthest past the ramp.	Give children a handful of crayons and the edge of a piece of paper or the inside edge of a shoebox lid as a baseline. Tell them to order the crayons by length, from shortest to longest.	Give children a picture of tracks of three different animals made in the snow. Ask them how to find out who went the farthest.	Give children a piece of paper and a pencil. Tell children to create their own “Which one went the farthest?” problem using curves they draw and then exchange paths and solve the problems.
Task breakdown	Manipulative tasks	hold first object	hold on to pencil	place referent on a piece of paper.	release car down ramp	hold on to item	hold on to string	
		hold second object	hold second object	draw lines next to the referent	mark where the car stops	place it along the baseline	put string at start of pathway	draw curved line on a piece of paper.
		move objects close together, parallel and line up the ends.	move pencil and object close together, parallel and line up the ends.		unwind string from the end of the ramp to the mark for the car	(repeat for all the items)	unwind string along the pathway	(repeat for three paths)
		return object to original location	put object 2 into appropriate bin		cut the string and label it (repeat)		cut the string and label it	
					lay the strings side by side (and match the ends of the strings)		lay the strings side by side (and match the ends of the strings)	
	Category of activity	A See Table A	A See Table A	B See Table B	C See Table C	D See Table D	C See Table C	B See Table B

Level 2 Activities - "Doing" Tasks Breakdown

		Level 2 Lesson 3 **Measuring and Comparing Lengths with multiple copies of non-standard units**	**Level 2 Lesson 4** **Estimating Length and Choosing Units** **Part 1 - Game**	**Level 2 Lesson 4** **Estimating Length and Choosing Units** **Part 2 - Measure steps**	**Level 2 Lesson 5** **Using One Copy of a Unit** **To measure straight and curvy items**
Math Makes Sense Lesson focus and problem	Focus	Measure length to the nearest non-standard unit using multiple copies of a unit, and compare and order objects by length and height using non-standard units	Estimate, measure, and compare lengths, selecting appropriate non-standard units, and relate the size of unit used to the number of units needed		Measure length by using a single copy of a non-standard unit, estimate and measure a length that is not a straight line, and show that orientation does not affect length.
	The materials and the problem to solve:	Give children a large picture of a gingerbread giant (about the height of the child) and string, scissors, masking tape, and craft sticks. Ask them who is tallest? Is it the gingerbread man, you, or your friend?	Players start at one end of the room. On a turn, a player may take 3 giant steps, 2 bunny hops, or 1 heel-to-toe step. The first player to reach the other end of the room wins.	Give children straws, toothpicks, crayons. Estimate, then measure the length of your heel-to-toe step and your giant step. In your group, who has the longest giant step?	Give children a straight pipe cleaner (to be a snake) and some toothpicks and a pen. How long is the snake when it is straight and wavy (bend it in front of them)? Estimate, then measure, using one unit. Compare the length to that obtained with multiple units.
Task breakdown	Manipulative tasks	Make strings the height of the child and a friend.	go to start location	Make a string the length of the heel-to-toe step and the giant step.	Place the pipe cleaner on a piece of paper.
		Lay the gingerbread man picture or one of the strings on the table.	make a giant, bunny hop, or heel-to-toe step	Lay the string out on the table.	Place the non-standard unit beside the pipe cleaner lined up at the end of the pipe cleaner.
		Place the non-standard units end to end along the full length of the picture or string	stop at the end of the table	Place the non-standard units end to end along the full length of the string.	Draw a mark at the end of the unit (the baseline)
					Move the unit so its end is next to the mark and make another mark (repeat until at the end of the pipe cleaner)
		Count the number of units		Count the number of units	Count the number of spaces between marks.
		Record the number		Record the number	Record the number
		Repeat for gingerbread man picture, string of self and string of friend.			Measure again, using multiple copies of the unit - **Same as Level 2 Lesson 3** task breakdown, **Type of activity = D**.
	Category of activity	D See Table D	E See Table E	D See Table D	F See Table F

A - Activities which involve holding objects next to each other and then placing them somewhere

	Level 1 Launch	**Level 1 Lesson 1 Comparing Lengths**	**Required capability of robot**	**Facilitated by teacher**
Task breakdown	*hold first object*	*hold on to pencil*	• **Robot surface low to table** and • **flat surface on back of robot with method to secure first object on the robot** • **A landmark on the robot indicating the location of the end of the object** • (Fig X.1)	• Place item on top of robot.
	*hold second object**	*hold second object**		
	move objects close together and parallel	move pencil and object close together and parallel	• **Forward, backward, left and right directional controls**	
	line up the ends.	line up the ends.		
		hold on to 2nd object	• **Gripper** to grasp and release block (Figure X.2)	
		and put it into appropriate bin	• **Repeat forward directional control with left and right movements to correct direction** to drive across table to bins	
Environment requirements	***second object secured on top of a block** so it is a similar elevation as the object on robot (Fig X.1)			
		hang bins off of table so robot can push object into bin.		

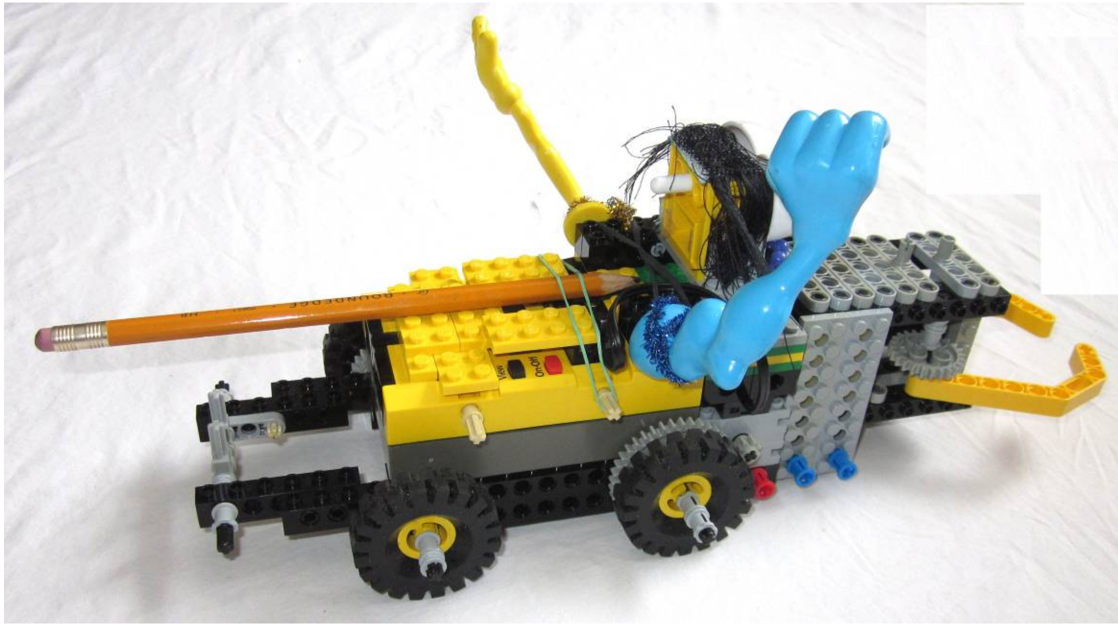


Figure 1: Robot with top surface low to table and flat surface on back of robot with method to secure objects (craft stick referent). Robot arms as a landmark to indicate the location of the end of the object. Figure also shows an item secured on top of a block so the robot can grasp it with the gripper.

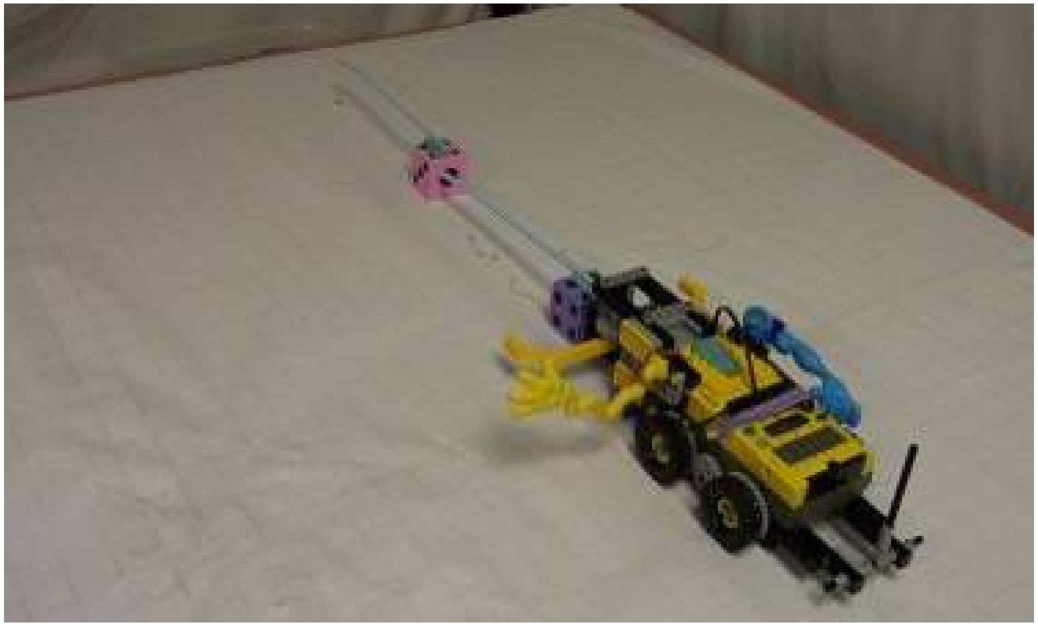


Figure 2: Robot with front gripper.

B - Activities which involve making lines with a pen

	Level 1 **Lesson 1 - Extension**	**Level 1** **Lesson 3 - Extension**	**Requirements of robot**	**Facilitated by teacher**
Task breakdown	*Place referent on piece of paper.*			• Place referent and/or robot on piece of paper.
	bring pen to start location (end of referent) and put pen down	bring pen to start location and put pen down	• Directional controls • **Pen which can be raised and lowered** with pen on the side of the robot so user can see where the pen is drawing (Figure X.3)	
	draw line	draw curved line		
	stop at end location (shorter, same as, or longer line) and lift pen up	stop at end location and lift pen up		
Environment requirements	Legal sized piece of paper	Large piece of paper (2'x3')		

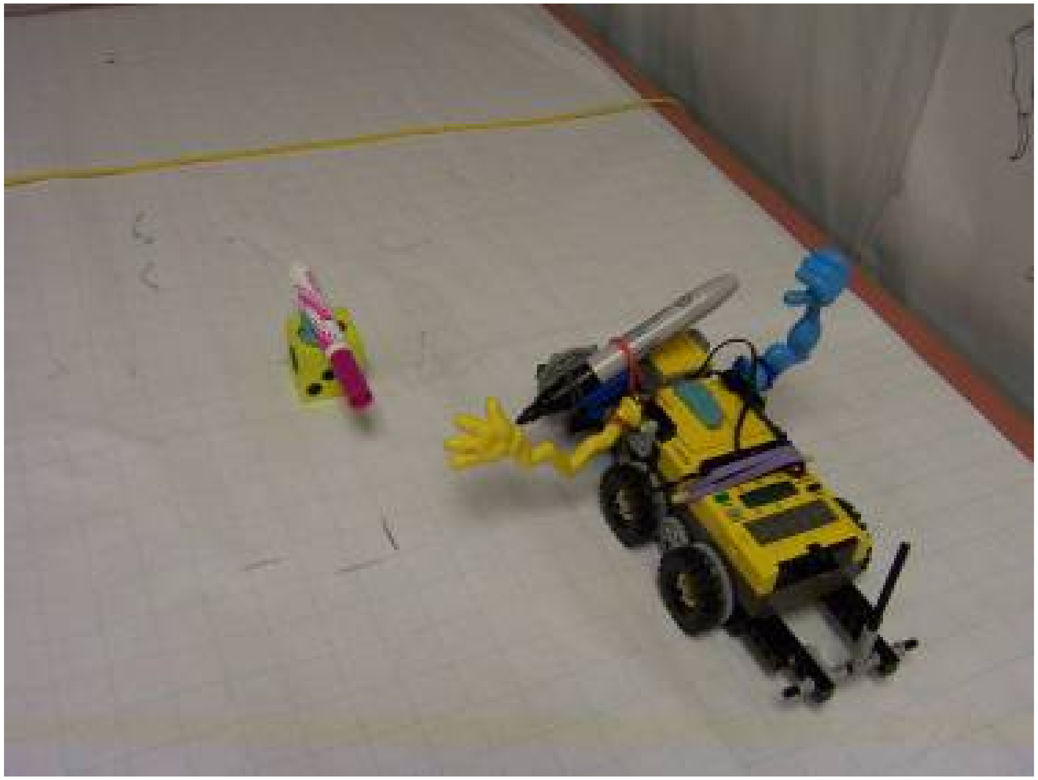


Figure 3: Robot with pen which can be raised and lowered off to side of robot so participant can see where the pen is drawing.


Figure 4: Robot with spindle to hold spool of string

C - Activities which involve unwinding and pulling strings

	Level 1 **Lesson 2 - Ordering Lengths**	**Level 1** **Lesson 3 - Strategies Toolkit**	**Requirements of robot**	**Facilitated by teacher**
Task breakdown	Release car down ramp		• Gripper to grasp and release car at top of ramp.	• Place robot at top of ramp. • Place stopper to keep robot from rolling down ramp.
	Mark where the car stops			• Place tape on location.
	Unwind string from the end of the ramp to the mark for the car	Unwind string along the pathway	• **Spindle to hold spool of string** so string unwinds as robot moves (Fig. X.4) • Directional controls	• Tape string down when requested by user.
	Cut the string and label it	*Cut the string and label it*		• Cut the string and label it.
	Lay the strings side by side (close and parallel)	Lay the strings side by side (close and parallel)	• Directional controls with the piece of string taped to the back of the robot	• Tape the string to the back of the robot. • As requested, straighten string trailing behind robot.
	match the ends of the strings	match the ends of the strings		
Environment requirements		Large replica of the pathways picture, 8 times letter page size (made by projecting image of original picture onto the wall).		

D - Activities which involve gripping onto objects and then placing them somewhere

	Level 1 Lesson 2 - Practice	**Level 2 Lesson 3 Measuring and Comparing Lengths with multiple copies of non-standard units**	**Level 2 Lesson 4 Estimating Length and Choosing Units Part 2 - Measure steps**	**Requirements of robot**	**Facilitated by teacher**
Task breakdown		*Make strings the height of the child and a friend.*	*Make a string the length of the heel-to-toe step and the giant step.*		• Make the string lengths
		Lay the gingerbread man picture or a string on the table.	*Lay the string on the table.*		• Lay the picture or string on the table.
	Hold on to item	Hold on to a non-standard unit*	Hold on to a non-standard unit	• Gripper to hold item or non-standard unit • Directional controls including repeat forward command	• Place units in robot gripper one at a time.
	place unit lined up on baseline (& in proper order)	place unit lined up with end of the picture (or string)**	place unit lined up with end of the picture or string		
	repeat	place another unit tip-to-tip with the previous unit, repeat***	place another unit tip-to-tip with the previous unit, repeat		
		end lined up as close as possible with the end of string	end lined up as close as possible with the end of string		
		Count the number of units	*Count the number of units*		• Point to the unit while the user counts silently in their head.
		Record the numbers	Record the numbers		• Connect USB cable from SGD to computer so user can enter number into worksheet.
Environment requirements	L1L2P: Straws or craft sticks of different lengths mounted on blocks so gripper can grasp block. L2L3&L2L4: Non-standard units (straws, rods, toothpicks) mounted on blocks so gripper can grasp block (Fig X.5)				

Another method was to:
* store the units (a bundle of straws) on the top of the robot, ** place the straw unit by requesting for the straw to be taken "off", and *** moving ahead so the back of the unit was tip to top with the previous unit (I.e., same robot requirements as Task Category A except for the gripper)

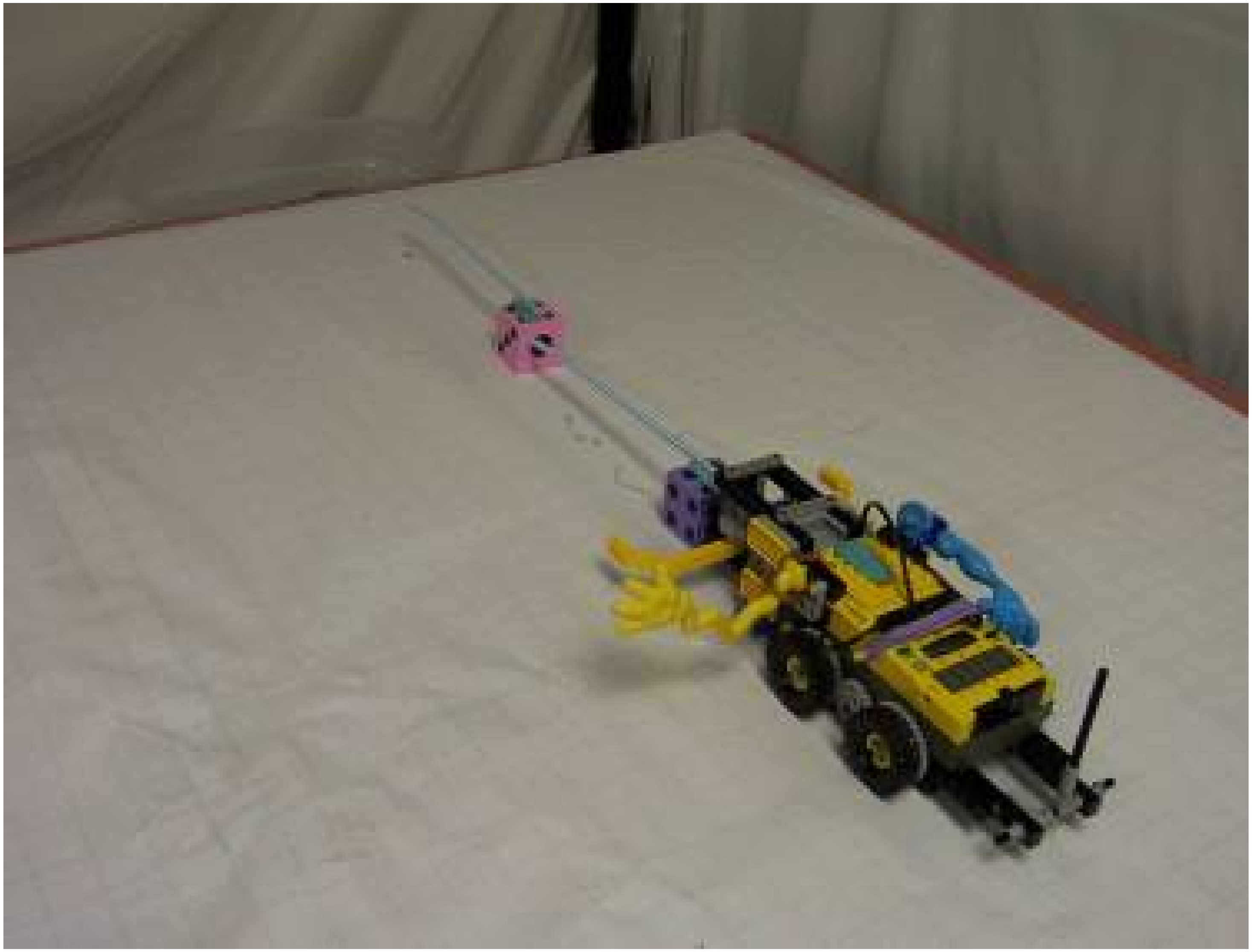


Fig 5: Blocks with straws or units mounted on top so the robot gripper can hold onto the block.

E - Activities that require the student to make small and large steps

	Level 2 Lesson 4 Estimating Length and Choosing Units Part 1 - Game	**Requirements of robot**	**Facilitate by teacher**
Task breakdown	*go to start location*		Place the robot at the start end of the table.
	make a giant, bunny hop, or heel-to-toe step & repeat	**Three robot programs to move the robot forward different distances**	
	stop at end location		Catch the robot if student drives it off the end of the table.

F - Activities which involve moving a unit length and making a pen mark at each unit length

	Level 2 Lesson 5 **Using One Copy of a Unit**	**Requirements of robot**	**Facilitate by teacher**
Task breakdown	Place the non-standard unit lined up at the end of the pipe cleaner, and make a pen mark	• Directional controls • **Non-standard unit on top of robot** for visual cue**. (Fig ?)** • Pen down & up to make a mark.	• Place non-standard unit on top of robot.
	Move the unit along the pipe cleaner so its end is lined up with the mark, and make a pen mark (repeat)	• **Robot program which moves the unit length (e.g.,toothpick).** • If curvy pipe cleaner, make small turns before selecting unit length program. • Pen down & up to mark.	
	Place last pen mark lined up as close as possible with the end of the pipe cleaner	• Pen down & up to mark.	
	Count the number of spaces between marks.		• Point to the space between marks while the student counts in their head.
	Record the numbers		• Connect USB cable from SGD to computer so user can enter number into worksheet.
Environment Requirements	Tape the pipe cleaner to the table so it does not move.		

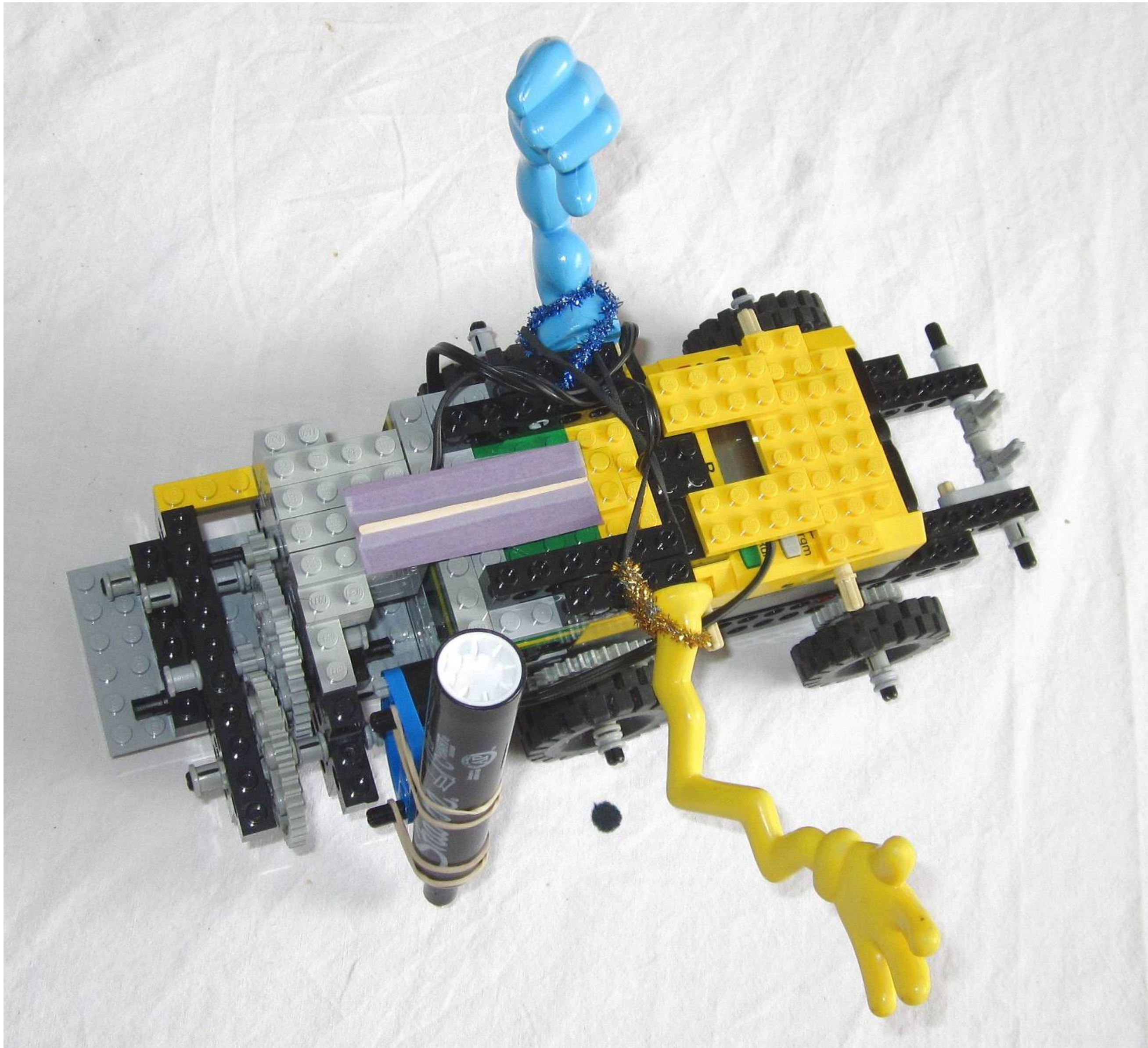


Figure 6: Robot with non-standard unit on top for a visual cue.

Other general considerations in the robot design were as follows:

To ensure that the robot drives forward as straight as possible:	Select left and right motors (A&C) which match in output power
	When programming the speech generating device to send the IR forward command, ensure that both the left and right motor IR commands are pressed at the same time on the Lego remote controller. See Figure 7 for a Lego device which pressed both A & C motor forward buttons at once.
To ensure the robot can fit as close to items as possible:	Ensure the hubs holding on the wheels are as narrow as possible
	Ensure the arms are as tight to the robot body as possible
To balance the robot appropriately when the gripper or pen are not attached to the front of the robot:	Place a block of Lego bricks on the front of the robot to compensate for the gripper (or pen) weight. This makes turning smoother.

Figure 7: A Lego block device which ensures that the left and right motor buttons are pressed at once to obtain straight forward movement.

References

Enders, A. (1999). *Technology for the Next Millennium: Building a Framework for Collaboration* Paper presented at the Association for the Advancement of Assistive Technology in Europe (AAATE). from http://rtc.ruralinstitute.umt.edu/advocacy/technology.htm

Pearson Education Canada (2007). *Math Makes Sense 1*. Toronto, Ontario Pearson Education Canada.

Pearson Education Canada (2008). *Math Makes Sense 2*. Toronto, Ontario Pearson Education Canada.

7.2 Appendix B - Revised math measurement lesson plans

This document contains revised lesson plans based on Level 1 and Level 2 Math Makes Sense (Pearson Education Canada, 2007, 2008) length measurement lessons, including:

- Level 1 Launch, Lesson 1, Lesson 2, and Lesson 3
- Level 2 Lesson 3, Lesson 4 and Lesson 5

The plans contain full lesson details including:

- the Math Makes Sense math vocabulary for Level 1 and Level 2

For each lesson:

- Curriculum focus for the lesson
- Materials needed for the lesson (with adaptations as determined from the task analysis, Appendix A)
- Introduction - including the statements and questions that the teacher said to the student
- Main activity - including the portions of the activity that the teacher demonstrated where the participant may or may not have provided guidance and the portions done with the robot
- Closing including the statements and questions that the teacher said to the student

Boxed areas indicate:

- a description of how the participant was expected to perform the manipulative tasks with the robot and any assistance required from the teacher (as determined from the task analysis in Appendix A) is indicated in boxed areas.
- any minor modifications to the procedure between participants

MATH **WORD WALL WORDS**

LEVEL ONE

Note 1: Vocabulary is modified to accommodate students using Vantage-Vanguard
Note 2: A word wall word board containing these words was created and showed symbol pathways for each word

Launch

- long/longer
- short/shorter
- same, different = *compare

Additional Words: Lesson One

- how long = *length
- match up = *baseline

Additional Words: Lesson Two

- longest
- shortest
- far/farther/furthest

Additional Words: Lesson Three

No new words

LEVEL TWO

Note 1: Vocabulary is modified to accommodate students using Vantage-Vanguard
Note 2: A word wall word board containing these words was created and showed symbol pathways for each word and pictures to describe each word

Word Wall Words: Lesson Three, Four, and Five

- measure
- how long = length
- how tall = height
- thing = unit
- same, different = compare
- from ____to____ = order

Adapted with permission from Math Makes Sense 1 & 2 Teacher Guide Unit 4: Measurement, Pearson Education Canada 2007 & 2008

LEVEL ONE: Launch

COMPARING OBJECTS: shorter than, same as, & longer than

Curriculum Focus:

To compare the length of multiple objects to one common referent object.

Materials:

- Robot + gripper
- Referents: Craft Stick, paper clip, straw, tooth pick -**Referent drawn randomly before lesson**
- Comparison items mounted on blocks - **1 item from each group drawn randomly before lesson**
  - Group 1 (Shorter): scissors, glue stick, tape, marker
  - Group 2 (Same): book, lego blocks, tree, shell
  - Group 3 (Longer): ruler, rake, shovel, paper towel roll

Introduction to Lesson:

- 'Today we're going to work with the robot to help us learn about measurement', 'When we measure, we compare, are they the same length, or different lengths?'
- 'Do you know any measurement words?'
- Introduce word wall words and display pathways for student to view. Explain that these words will be used frequently throughout the lesson and will be reviewed in future lessons. 'Can you repeat after me?'

Main Activity:

Demonstration: Hold up an item to a referent and ask the student whether it is shorter than, same as, or longer than. Cue student to the Word Wall and symbol pathways to help respond.

- The teacher demonstrated comparing two items for M01 and M02, but M03 started immediately by using the robot.

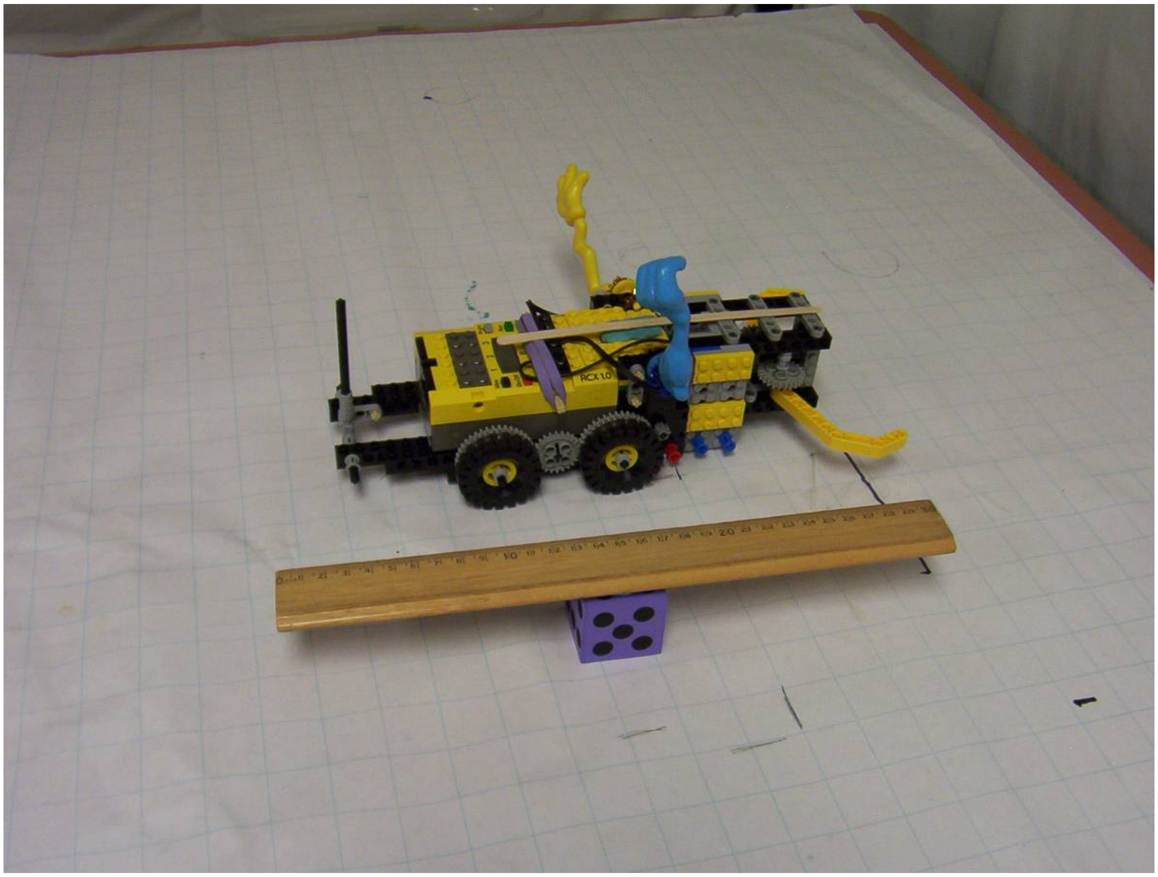
Robot: The student will compare the chosen referent with a randomly drawn item from the shorter than, same as, and longer than categories (2 comparisons in all)

- The referent was attached to the top of the robot
- The participant was expected to drive the robot beside the comparison object, make it parallel and match the ends of the items along a baseline.
- In the case of M02, the robot was unavailable for that session, so he used the manipulation mode of directing the teacher what to do.

Closing:

- "What did you compare? (*The lengths of a pencil, an eraser, a glue stick, and a paperclip*.)"
- 'What can you tell me about these items?' (*The pencil is longer.*)

Adapted with permission from Math Makes Sense 1 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2007, Page 11



Adapted with permission from Math Makes Sense 1 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2007, Page 11

LEVEL ONE: LESSON ONE
COMPARING LENGTHS: Sorting into bins

Curriculum Focus:

To compare the length of multiple objects to one common referent object.

Materials:

- Robot + gripper
- Referent: Unsharpened pencil
- 3 containers (labeled Shorter than, Same, Longer than) taped to edge of table
- Classroom Items (marker, tape, glue stick, scissors, rake, paper towel roll, shovel, ruler, shell, lego blocks, tree, notebook) mounted on blocks
- Grid Paper to lay on table with the layout for the objects

For M01 and M02 10 items were spread around two tables and the layout of the items was the same. To speed up the activity, the last item was brought closer to the participant. For M03, six items were presented in front of her one at a time randomly.

Introduction to Lesson:

- 'Today we're going to work with the robot to help us learn about measurement.' "When we measure, we compare things".
- Introduce word wall words and display pathways for student to view. Explain that during the lesson, these words should be used and can be found by following the Pathway symbols.

Demonstration:

- Find 3 objects around the classroom (shorter than, same as and longer than the unsharpened pencil)
- Hold the items up and ask if the items are shorter, same, or longer. Use a concrete base line to measure items. Explain the importance of 'matching up' the ends to measure.
- 'Now it's your turn!'

Main Activity:

- Explain to the student that the objective of this activity is to find items that are shorter than, same as, or longer than the unsharpened pencil. Each item must be placed into their respective bins.
- Reinforce the concept of the baseline, or "matching up", e.g., 'How are you going to see if the items are shorter, longer or the same?'
- Allow student to compare items and place in bins independently.

- The unsharpened pencil was attached to the top of the robot.
- The participant was expected to compare the referent to an item by driving the robot close beside the item, make it parallel and then line up the ends.

Adapted with permission from Math Makes Sense 1 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2007, Page 12-14

- Then the participant was expected to use the robot grippers to grasp the block affixed to the item, drive the robot towards the bins which were hanging off of the table, slide the object overtop of the appropriate bin, and release the object into the bin.
- After the teacher was sure that the participant understood comparing objects by using a baseline, she told the participant that if they could tell just by looking, then they did not have to match ends before taking the object to the bin.

Closing:

- Take out the items from each bin (one at a time) and measure them against the unsharpened pencil for the student to view. Together, determine whether or not the items were categorized appropriately.
- Make sentences with word wall words.

- Extension activity for M03 only:
  - The teacher asked if she could make a math sentence about the activity (i.e., 6 items divided into 3 bins gives 2 items in each bin).

LEVEL ONE: LESSON TWO
ORDERING LENGTHS: Car & Ramp Activity

Curriculum Focus:

"To order objects according to length".

Materials:

- Robot + gripper
- Ramp
- Toy cars (personalized with motivating characters for M02 and M03)
- String/ Yarn, Scissors, Masking Tape

Introduction to Lesson:

- Prompt the student to see if they can re-call word wall words from lesson one.
- Introduce Lesson Two's new word wall words (*far, farther, furthest).
- 'When we measure things that travel, we measure how **far** they go'

Demonstration:

- Demonstrate the activity to the student: Place the first toy vehicle at the top of the ramp (grasped by the robot). Have the student release the vehicle.
- Ask: 'Do you know a way to keep the next car from hitting the first car?' ('*mark the spot with tape'*).
- Mark and label the car's position with tape.
- 'Now it's your turn to release each of the cars and see which car went the furthest distance.'

Main Activity:

- Release, mark, and label all 3 cars
    - The participants grasped a car at the top of the ramp with the robot gripper and released it when the teacher said, "on your mark, get set, go".
    - The teacher marked and labeled the location the car stopped with a piece of tape.
- Have the student measure the distances using string to measure the lengths of the distance travelled.
    - The participant was expected to drive the robot while unwinding the string behind the robot. He/she started at the bottom of the ramp and was expected to drive to the location was marked by the teacher with a piece of tape.
    - Then teacher cut the string and labeled it
- Pull the string lengths so they can be compared to determine which cars travelled the shortest/ furthest distances.

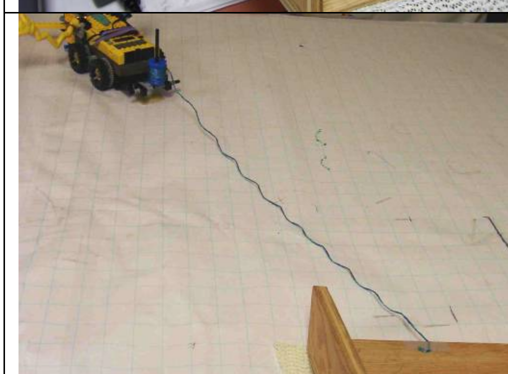
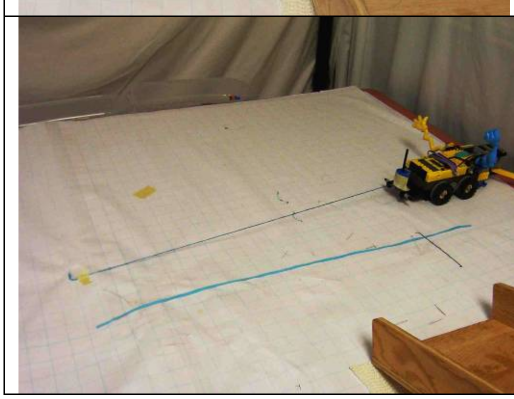
Adapted with permission from Math Makes Sense 1 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2007, Page 16-17

- The teacher taped each string one at a time to the back of the robot.
- The participant was expected to drive the robot such that the strings were pulled parallel to each other and lined up along a baseline so an accurate comparison could be made.

Note: M02 did two races:
- Race 1 by moving the ramp so the cars would not collide (his suggested strategy). The cars went noticeably different distances so he reported just by looking
- Race 2 with the ramp in the same position, but he released the middle car three times so he had three distances to compare which were close in length.

Closing:

- 'What can you tell me about your race?' *('The blue car went the farthest', 'The blue car went farther than the red car')*
- 'How do you know blue went farthest?' (*'The string for the blue car is the longest", "The red car didn't go as far… so it went a shorter distance.'*)

	Releasing the car
	Unwinding the string to see how far the car went
	Lay parallel with ends matched up to compare to other distances

LEVEL ONE: LESSON THREE
COMPARING LENGTH & DISTANCE: Comparing Pathways

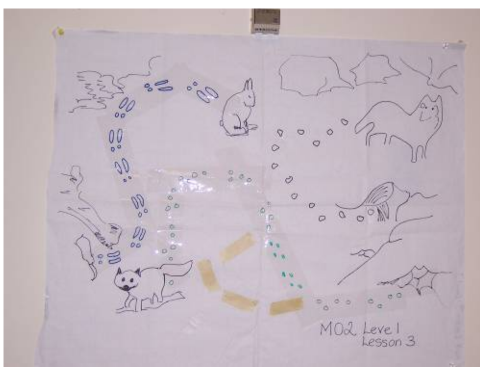
Curriculum Focus:

"Challenge activity 'Using objects' to solve a problem about comparing lengths"
 - no new concepts

Materials:

- Robot + gripper
- 2 Toy characters (personalized with motivating characters for each student)
- 2 different colors of String/ Yarn, Scissors, Masking Tape
- Pathways worksheet: The 3 paths worksheet from the Math Makes Sense materials was enlarged by projecting an image of the original worksheet onto a piece of paper approximately 8 times the original size and tracing it

Since M01 and M03 did not have the operational competency to follow three pathways from the original curriculum, a worksheet with only two pathways was also created (one with an S curve and one with a V curve). M02 did both worksheets (2 & 3 paths).



3 paths worksheet* 2 paths worksheet

* Adapted with permission from Student Page 91

Introduction to Lesson:

- Prompt the student to see if they can re-call word wall words from lesson one or two. Post the words onto the wall as they are being listed and make sentences.
- Explain that instead of measuring the paths of cars, they will be measuring the paths of people; sidewalk paths (or animals in the case of MO2 for the 3-paths worksheet).
- Show the paths to the student and ask them to **Estimate** which path will be the longer path.
- Ask:
    - 'Why do you think it would be hard to guess which path is longer?' ('*The sidewalk paths are not straight*.')
    - 'What do you think we can use to measure these sidewalk paths?' ('*String'*)
    - 'Why?' ('*Because it bends'*)

Adapted with permission from Math Makes Sense 1 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2007, Page 20-21

Main Activity:

- Have the student carry their toy characters in the robot gripper and ask them to measure one of the sidewalk pathways. Ask:
  - 'Where should you start taping the string?' ('*Start on the X*')
  - 'Where should you stop measuring? ('*Stop on the other X*')

> - The participant was expected to measure the pathways by driving the robot along each pathway while the string unwound itself behind the robot.
> - The participant was expected to ask the teacher to tape down the string in order to keep the string along the pathway.

- Follow the same steps for the other sidewalk path using a different colored string.
- Ask: 'What should be our next step?' ('*Straighten out the strings*')
- Compare the two string lengths, remind them of using a baseline if needed.

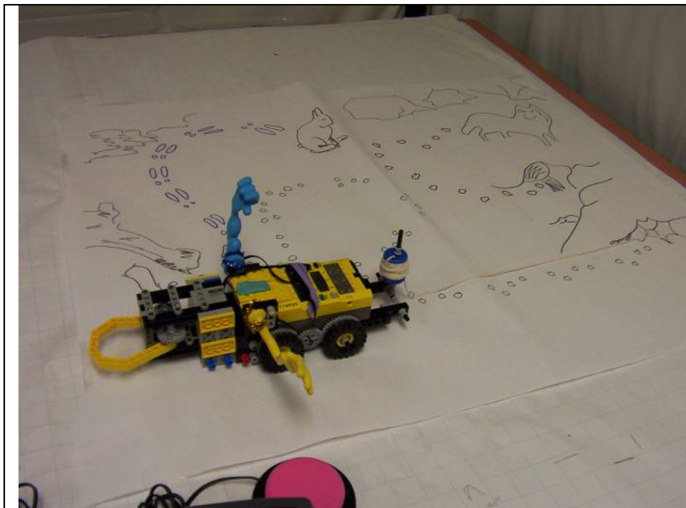
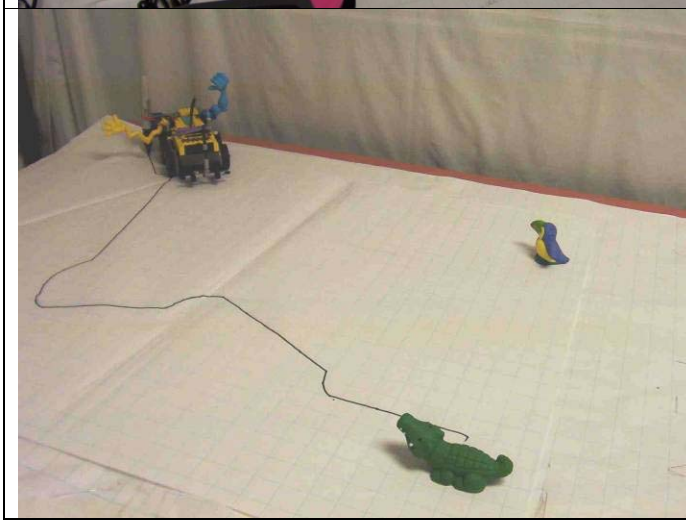
> - The strings were left taped to the start location (the start location was the same for both paths) and the participant was expected to drive the robot with the other end of the string taped to the back of the robot to straighten out each string, and make them parallel.
>   - For M03, a third string was added so that she could compare three distances rather than only two.
>   - For M02 on the 3-paths worksheet, the strings were removed from the worksheet and he was expected to pull the strings straight, parallel, and lined up on a baseline.
>   - For M01, she also pulled the strings up to a baseline drawn on the table. She was expected to pull them parallel and stop with the ends on the baseline

Closing:

- 'Which character travelled the farthest distance?' (*'Character A went the farthest'*)
- 'How do you know that?' ('*The longer string means that the character travelled the farthest distance.'*, '*The shorter string means that the character travelled the shortest distance.'*)

> - Extension Activity: All participants also did the extension activity which was to draw your own "Who went the farthest" pathway problem on a blank sheet of paper.
>   - To draw the pathways, the pen was attached the robot, and the participant put the pen down in the location he/she wanted to start the pathway, drove the robot in whatever path they wanted with the pen down, and then lifted the pen at the location they wanted the pathway to end.
>   - M01's pathway problem was solved by the teacher. The teacher followed the procedure for this lesson, but without the robot, and asked M01 to let her know if she was doing anything wrong (i.e., the session was framed as though M01 was the teacher).

Adapted with permission from Math Makes Sense 1 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2007, Page 20-21

	Unwinding string on the 3 pathways worksheet
	Draw your own "Who went the farthest?" pathways

Adapted with permission from Math Makes Sense 1 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2007, Page 20-21

LEVEL TWO: Lesson 3

MEASURING AND COMPARING LENGTHS: Height's of gingerbread man, self, and friend

Curriculum Focus:

"Measure length to the nearest non-standard unit using multiple copies of a unit, and compare and order objects by length and height using non-standard units."

Materials:

- Robot + gripper
- Non-standard units (**craft sticks, straws, string**) mounted on blocks
- Giant Gingerbread man (The picture of the gingerbread man from the curriculum materials was adapted so that is was 5 feet, approximately the same height as the participants)
- String and scissors
- Worksheet on tablet computer (see end of lesson)

Introduction to Lesson:

- 'Today we are going to measure **how long** and **how tall** objects are. When we measure how long and how tall objects are, we are figuring their **length** and **height.'**
  - Refer to the word wall and the picture descriptors

Demonstration with student guidance with teacher directed questions:

- 'Now, let's review what we already know about measurement by measuring the **length** and **height** of this Gingerbread man.'
  - *Estimate: "*How many craft sticks do you think this Giant Gingerbread man would be?" ("8")
  - "Where should I place the first craft stick?" ("Top of the head, bottom of the foot")
  - *Space out the craft sticks when measuring*-- 'Am I doing this right?' ("no")
  - *Match the sticks end-to-end, but in a crooked line*-- 'What about now?' ("no")
  - *Match the sticks end-to-end in a straight line*-- 'How about this?' ("yes")
  - *Have the Gingerbread man laid out on the table*-- 'How many craft sticks long is the Giant Gingerbread man?' (*"9"*)
  - *Hold the Gingerbread man standing up*-- "How many craft sticks tall is the Giant Gingerbread man?" (*"9"*)

Main Activity:

Measure the length of the Gingerbread man picture, self, and a volunteer in straws.

- 'What's a good way to get a measure of your height?' ('*use string*')

Introducing non standard units
Comparing

- 'Why do we need to measure your height with string first and then measure it with straws?' ('*The straws will fall down*.' '*The string is the same length as my height*.')

• The teacher cut string to the height of the participant and a friend (for M01 it was her EA, for M02 it was a young friend in the day care and an adult day care worker, and for M03 it was her mother).

To measure the picture (or string), the participant was expected to place a unit lined up at one end of the picture (or string) and continue to place units tip to tip (with no gaps, in a straight line) until the last unit was lined up as close as possible with the end of the picture (or string). The participants measured using two methods:	
METHOD 1 **With Robot with gripper**	**METHOD 2** **Teacher assisted + Student Directed**
Using the robot and gripper: • The participant was expected to grasp a straw (which the teacher placed in the gripper), drive the robot to the appropriate location (e.g. at the farthest end of the string, tip to tip with straw, the closest end of the string) and then release the straw unit. • The teacher secured the straw by putting sticky tack under the block. • The teacher placed the robot back to the start position and loaded a new unit into the gripper.	With straws on top of the robot: • The participant was expected to drive the robot and stop lined up with the closest end of the string, and say "off" so that the teacher would remove the straw. • The teacher placed the straw right next to the robot's front wheel which was directly below the straws on the top of the robot. • Then the participant was expected to drive the robot and stop tip to tip with the previous straw and repeat • The participant was expected to stop placing straws when the last one was lined up as close as possible with the end of the string.

- First: Measure the length of the Giant Gingerbread man using Method 1
  - Count the units and enter into worksheet on tablet
- Second: Measure the height of the student using Method 2
  - Count the units and enter into worksheet on tablet
- Third: Measure the height of the friend using the method chosen by the participant
  - Count the units and enter into worksheet on tablet

M02 also estimated before each measurement

<u>Closing</u>:

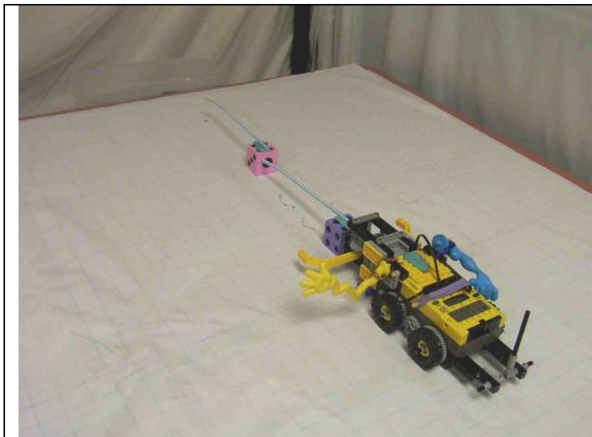
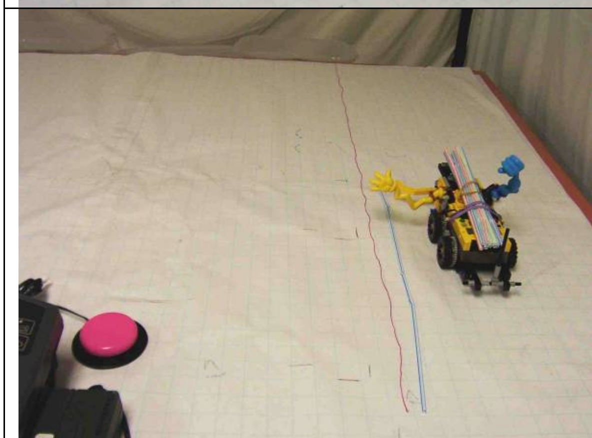
- Complete the worksheet and refer to it
- 'Can you order your measurements?'
- 'Who is the tallest?'

Adapted with permission from Math Makes Sense 2 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2008, Page 26-29

- "How do you know that they are the tallest?" ('*It is the biggest number*')
- 'Who is the shortest?'
- 'How do you know?' ('*It is the smallest number*')

Giant Gingerbread man	**Student**	**Volunteer**
 The Gingerbread man is ______ straws tall.	[Insert picture here] I am ______ straws tall.	[Insert picture here] ______________ is ______ straws tall.

Adapted with permission from Math Makes Sense 2 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2008, Page 26-29

	Method1: Measuring with robot with gripper
	Method2: Measuring with robot and asking teacher to take straw off.
	Gingerbread man used for the first measurement.

LEVEL TWO: Lesson 4

ESTIMATING LENGTH AND CHOOSING UNITS: Giant/Baby steps game

Curriculum Focus:

"Estimate, measure, and compare lengths, selecting appropriate non-standard units, and relate the size of unit used to the number of units needed."

Materials:

- Robot + gripper
- Non-standard units (**magnet rods, magnet toothpicks**) mounted on blocks
- String, scissors
- Worksheet on tablet computer (see end of lesson)

Introduction to Lesson:

Play the Robot Game

- Student must choose the appropriate size of steps to go from start to finish (from one end of the table to the other) without falling off the table.

Giant step = (Robot program 2) = 45 cm forward movement →
Baby step = (Robot program 3) = 8 cm forward movement →

Start____**Finish**

The teacher made a string the length of the giant step and the baby step for the next part of the lesson.

Main Activity:

Measure your own Giant Step

- 'Which non-standard unit (straw, rod or toothpick) is more appropriate for measuring the lengths of a Giant robot step?' (*'straws'*)
- 'Why?' (*'Because they are bigger than the other units', 'You don't have to use as many'*)

Even though straws were most appropriate to use, rods were recommended because they had magnets which snapped together, making them easier to line up tip to tip.

- Estimate: 'How many **rods** it would take to measure the Giant step?'
- Measure the giant step using **rods**

The participant used the robot with the gripper to hold each unit and measure the string as in Robot with gripper (Method 2) in Level 2 Lesson 3 (L2L3) (e.g. Grasped unit, released at far end, released subsequent units tip-to-tip with each unit, and stopped adding units at the end of string)

- **COUNT the units & RECORD** on the worksheet

Measure your own Baby Step

- 'Which non-standard unit (straw, rod or toothpick) is more appropriate for measuring the lengths of a Baby robot step?' (*'toothpicks'*)

- 'Why?' (*'Because they are smaller than the other units', 'You can get a more accurate measurement'*).

There were magnets taped to the blocks affixed to the toothpicks

- Estimate: "How many **toothpicks** it would take to measure the Baby step?"
- Measure the baby step using **toothpicks**

The participant used the robot with the gripper to hold each unit and measure the string as in Method 2 in L2L3.

- **COUNT the units & RECORD** on the worksheet

Compare the length of the Robot's Giant step to the Giant step of another student

In the original lesson, children compare their measurements to each other, but discover that they did not all use the same unit to measure with. So secretly the teacher measured her own step in straws.

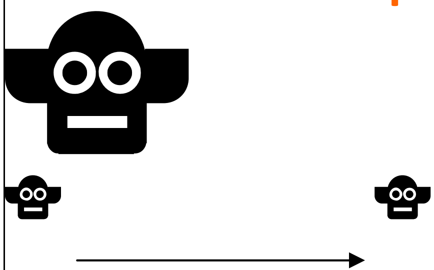
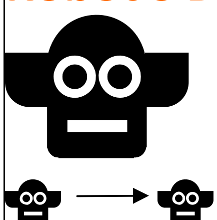
- Tell the student you secretly measured the other step with straws.
- Record the measurement in the worksheet
- If I told you that your robot giant step was 9 rods long, and the other step was 4 straws long, can you say for sure who had the bigger step? (*'no'*)
- 'Why not?' (*'The units are not the same'*)
- 'What do we have to do to compare these measurements?' (*'Do the second measurement again with the same unit as the first one')*
- After establishing which measurement should be changed and what unit to use, measure the remaining items.

> - The teacher and the participant measured the remaining steps in the appropriate unit so the measurements could be compared and ordered. Either:
>   - The teacher demonstrated, or
>   - The participant used the robot + gripper as describe above.

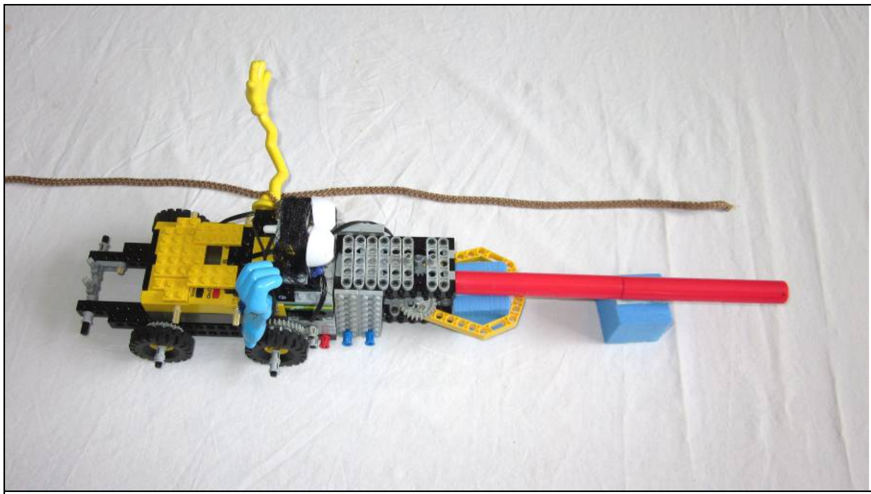
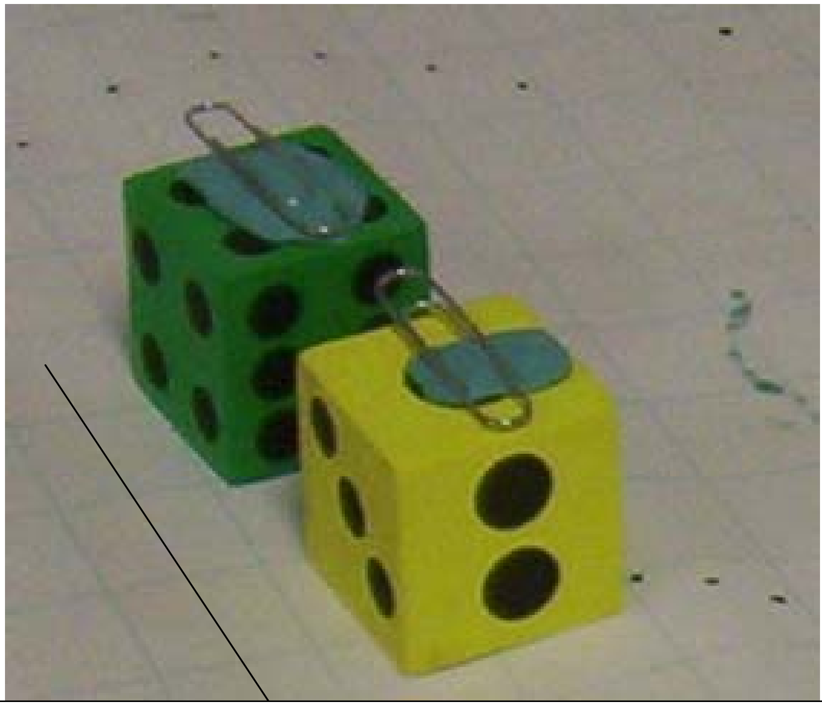
- **COUNT the units & RECORD** on the worksheet

<u>Closing:</u>

- 'Looking at the worksheet, can you order the lengths of the steps?'
- 'How do you know that's the longest one?' ('*The bigger number means that it is a bigger step'*)

GIANT STEPS	UNIT Number of **Rods**	UNIT Number of **Straws**	UNIT Number of **Toothpicks**
Robot's Giant Step 			
Friend's Giant Step 			
Robot's Baby Step 			
Friend's Baby Step 			

Adapted with permission from Math Makes Sense 2 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2008,Page 30-34

	Magnetic rod unit used to measure the Giant Step
	Paperclip unit used to measure the Baby Step

LEVEL TWO: Lesson 5

USING A SINGLE COPY OF A UNIT: Slithering Snakes

Curriculum Focus:

"Measure length by using a single copy of a non-standard unit, estimate and measure a length that is not a straight line, and show that orientation does not affect length."

Materials:

- Robot + pen
- Robot + gripper
- Non-standard unit placed on top of robot (toothpicks, paperclips)
- Non-standard units (toothpicks, paperclips) mounted on blocks
- Pipe cleaner
- Blank paper, tape
- Worksheet on tablet computer (see end of lesson)

Introduction to Lesson:

Choose a random object from the classroom. Ask the student 'which non-standard unit is best to measure the object?' (paperclips, rods, toothpicks, straws, etc.)

- Ask the student to estimate the length in those units.
- Demonstrate measuring the item using multiple copies of the unit.
- Ask (from P.36-38 of the Math Makes Sense 2 Teacher Guide 2008):
  - "What if I only had 1 copy of this unit? How could I measure the length?" ("You could use the same copy over and over.")
- Demonstrate measuring the item using only one copy of the unit, and mark where the units end each time.
  - "Should the measurements with multiple and single copies be the same?" ("Yes")
  - "Why?" ("We measured using the same unit both times.")
  - If the two measurements are different, ask why. ("there were gaps with the multiple units")

Main Activity:

- 'Today we are going to be measuring objects that are both wavy and straight. With these pipe cleaners, we are going to form them into slithering snakes!'
- Tell the student that most snakes move along in a wavy, or S-shape, but some snakes, such as boas, sometimes travel with their bodies straight. (P.36-38)

Measure the straight snake

- Provide the student with a **straight** pipe cleaner.
- Ask the student to estimate how many units the straight snake might be.

Adapted with permission from Math Makes Sense 2 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2008, Page 36-39

- 'You have to measure the straight snake twice, once with one copy of a unit and the robot and pen, and the other using multiple copies of a unit with the robot and gripper.'
- Using single copy of a unit: The participant used the robot and pen to mark off single units. They were expected to drive the robot to the closest end of the pipe cleaner and make a pen mark by putting the pen down and then up again, then move forward one unit length by selecting the appropriate program, make a mark and repeat until they reached the end of the pipe cleaner.
- Using multiple copies of a unit: The participant used the robot and gripper to place multiple units as in lessons L2L3 and L2L4 (e.g. grasp unit, release at far end, release subsequent units tip-to-tip with each unit, and stop adding units at end of pipe-cleaner)
- **COUNT the units & RECORD** results onto the worksheet.

Measure the wavy snake

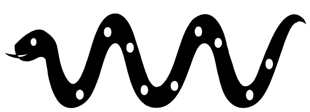
- Bend the straight pipe cleaner into a **wavy** snake in front of the participant (a C-shape).
- Ask the student to estimate how many units the wavy snake might be.
- Measure the wavy snake twice. Once using one copy of a unit, and the other using multiple copies of a unit.
- Same robot tasks as above for single and multiple copies for the straight snake, except to mark single units along a curve, the participant had to turn the robot slightly before selecting the program command.
- **COUNT the units & RECORD** results onto the worksheet.

Closing: Ask (from P.36-38 of the Math Makes Sense 2 Teacher Guide 2008):

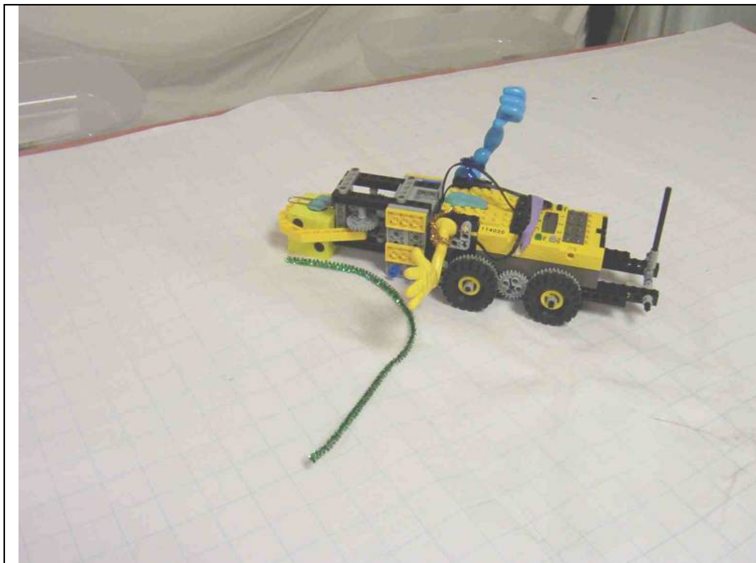
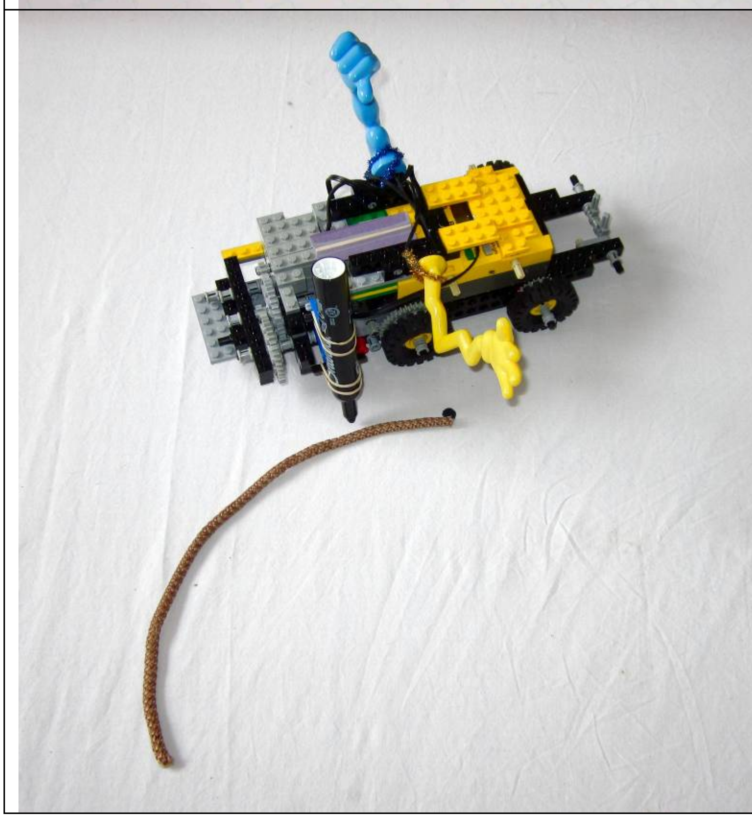
- "What did you notice about our measurements?" ("The wavy snake and the straight snake are the same length.")
- "Was it easier to estimate the length of the straight or wavy line?" ("straight")
- "Was it easier to measure with 1 copy of a unit or more than one copy?" ("1 copy")
- "Does the measurement stay the same when the snake changes direction?" ("Yes")

Adapted with permission from Math Makes Sense 2 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2008, Page 36-39

Slithering Snakes

Snake	Copies of the unit	My estimate	My measurement
 Straight	one	____	____
	more than one	____	____
 Wavy	one	____	____
	more than one	____	____

Adapted from Line Master 12: 2008 Pearson Education Canada

	Measuring the Wavy Snake with multiple units
	Measuring the Wavy Snake with single copy of a unit (see toothpick on top of robot)

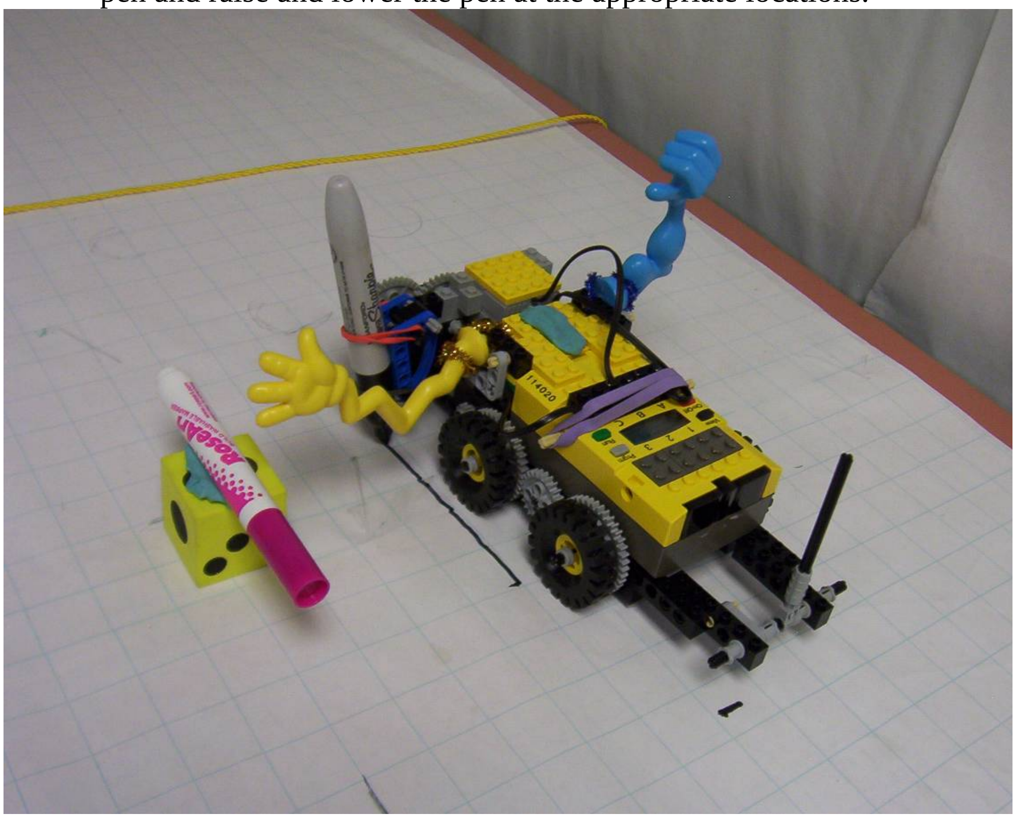
7.3 Appendix C - Revised lesson plans for practice activities

M01 Practice Activities

L1L1 **Drawing lines**

Practice Although M01 performed well on L1L1, this activity to draw lines which were shorter than, the same as, and longer than a referent item was trialed with her since she liked to draw with the robot.

- <u>Observation</u>: First the teacher manipulated the marker by moving it parallel to the foot print and M01 was expected to indicate to the teacher when to put the pen on the paper and when to stop moving it.
- <u>Robot:</u> Then the participant was expected to use the robot with the pen and raise and lower the pen at the appropriate locations.



Lesson adapted with permission from Math Makes Sense 1 Teacher Guide Unit 4 Measurement, Activity Bank Comparing Lengths, Pearson Education Canada 2007, Page 15

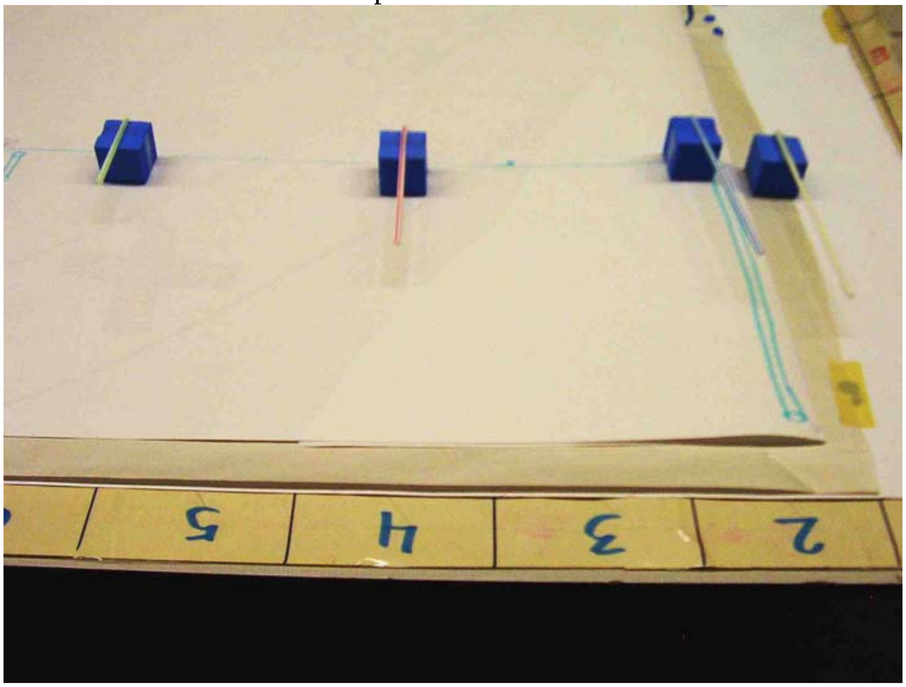
L1L2 **Ordering straws**

Practice2

- Two short activities with straws were done on previous days which were not assessed by the teacher.
  - <u>Observation</u>: First, the teacher manipulated the straws and asked which one was the shortest, the longest, and the middle length, and the participant was expected to answer by gazing at the appropriate straw.
  - <u>Robot:</u> Second, the participant was expected to use the robot to place three straw lengths in order from shortest to longest along a baseline. The "shortest" and "longest" ends of the line were

established with the participant. A block with a straw on it was placed in the gripper of the robot, and the participant was expected to drive the robot to the end of the line where she felt the straw belonged, and place it on the baseline.

- The activity which was assessed by the teacher was to order four straws with a similar procedure as with three straws.



Lesson adapted with permission from Math Makes Sense 1 Teacher Guide Unit 4 Measurement, Unit Centres, Pearson Education Canada 2007, Page 9

M03 Adapted and Practice activities

L2L4 Adapted

Since M03's measurements with straws in L2L3 did not yield values that she could order, the activity was redone in L2L4, but by using smaller units in order to obtain more accurate measurements which could be compared.

- A 10 rod portion of the string was cut off of each string. A line representing the missing 10 rods was drawn on the table. This was done because the strings were so long and to gave the participant the chance to math a question about the total length of the original string (i.e., 10 + 3 = 13).
- Rod units were recommended to the participant (half the size of a straw) because they snapped together due to the magnets. Using the magnets eliminated testing of the concept of leaving gaps, but M03 had previously demonstrated understanding of that concept.
- Robot: The participant then used the robot with the unit in the gripper to measure the strings as in L2L3.
- To examine how to compare measurements made in different units, the teacher found out that the participant's SLP was 8 straws tall (Since M03 was very motivated to find out if she was taller than her SLP).

- The participant was asked if her measurement (in rods) could be compared to the SLP's and what to do to be able to compare the numbers (i.e., change to the same unit).

- Observation: A comparison of the differences in lengths was continued by using even smaller units
  - the participant chose the unit (between rods or toothpicks)
  - the teacher did the manipulation of multiple units.

Lesson adapted with permission from Math Makes Sense 2 Teacher Guide Unit 4 Measurement, Lesson 4, Pearson Education Canada 2008, Page 33-33.

L2L4 Practice

This lesson tested the same concepts as L2L4 Giant/Baby steps:

- The participant was expected to choose between a straw, rod or toothpick unit to measure different body parts on a picture of a giraffe (approximately 1 metre tall).
- Robot: She then measured the body parts using the robot and gripper.
- Observation: Afterwards, she estimated parts of the giraffe using different units and the teacher did the measurements.

Lesson adapted with permission from Math Makes Sense 2 Teacher Guide Unit 4 Measurement, Lesson 4 Practice, Pearson Education Canada 2008, Page 32.

7.4 Appendix D - Measurement rubrics

Level 1

Knowledge/ Skills	**Not yet adequate (needs concept re-explained with no achievement)**	**Adequate (needs concept re-explained and partially achieves concept)**	**Proficient (Prompts- pointing, verbal cues & reminders and achieves concept)**	**Excellent (Achieves concept Independently)**
Conceptual understanding shows understanding by explaining and demonstrating concept of comparing objects ------------------------ shows understanding by explaining and demonstrating concept of ordering (sorting) objects from shortest distances to longest distances	☐ shows very limited understanding that attributes of objects can be compared ------------------------ ☐ shows very limited understanding that attributes of objects can be ordered	☐ shows partial understanding that attributes of objects can be compared ------------------------ ☐ shows partial understanding that attributes of objects can be ordered	☐ shows understanding that attributes of objects can be compared ------------------------ ☐ shows understanding that attributes of objects can be ordered	☐ shows in-depth understanding, in a variety of contexts, that attributes of objects can be compared ------------------------ ☐ shows in-depth understanding, in a variety of contexts, that attributes of objects can be ordered
Procedural knowledge accurately compares by lining up object on a baseline	☐ often makes major errors or omissions in comparing with a baseline ------------------------ ☐ often makes major errors or omissions in ordering	☐ makes frequent minor errors or omissions in comparing with a baseline ------------------------ ☐ makes frequent minor errors or omissions in ordering	☐ makes few errors or omissions in comparing with a baseline ------------------------ ☐ makes few errors or omissions in ordering	☐ rarely makes errors or omissions in comparing with a baseline ------------------------ ☐ rarely makes errors or omissions in ordering
Problem-solving skills uses appropriate strategies to solve measurement problems	☐ needs assistance to use appropriate strategies to solve measurement problems	☐ with limited assistance, uses some appropriate strategies to solve measurement problems	☐ uses appropriate strategies to solve measurement problems	☐ uses appropriate, often innovative, strategies to solve measurement problems

Adapted with permission from Math Makes Sense 1&2 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2007 & 2008

Communication uses appropriate language when comparing (ordering, sorting) ------------------------- uses appropriate language when ordering string lengths	☐ does not use appropriate comparative language ------------------------- ☐ does not use appropriate comparative language when ordering	☐ with prompting, uses some appropriate comparative language; tends to be vague ------------------------- ☐ with prompting, uses some appropriate comparative language; tends to be vague when ordering	☐ uses some appropriate comparative language ------------------------- ☐ uses some appropriate comparative language when ordering	☐ clearly and confidently uses appropriate comparative language ------------------------- ☐ clearly and confidently uses appropriate comparative language when ordering

Additional Comments:

Adapted with permission from Math Makes Sense 1&2 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2007 & 2008

Level 2

Knowledge/ Skills	<u>Not yet adequate</u> **(needs concept re-explained with <u>no achievement</u>)**	<u>Adequate</u> **(needs concept re-explained and <u>partially</u> achieves concept)**	<u>Proficient</u> **(Prompts- pointing, verbal cues & reminders and <u>achieves</u> concept)**	<u>Excellent</u> **(Achieves concept Independently)**
Conceptual understanding shows understanding by explaining and demonstrating:	<u>shows very limited understanding; needs one-to-one assistance to explain/ demonstrate:</u>	<u>shows some understanding; with prompting and support, able to explain/ demonstrate:</u>	<u>shows understanding that attributes of objects can be compared</u>	<u>shows in-depth understanding, in a variety of contexts, that</u> attributes of objects can be compared
• choice of an appropriate unit	☐ choice of an appropriate unit	☐ choice of an appropriate unit	☐ choice of an appropriate unit	☐ choice of an appropriate unit
• how choice of unit affects number needed	☐ how choice of unit affects number needed	☐ how choice of unit affects number needed	☐ how choice of unit affects number needed	☐ how choice of unit affects number needed
• strategies for comparing and ordering	☐ strategies for comparing; ordering	☐ strategies for comparing; ordering	☐ strategies for comparing; ordering	☐ strategies for comparing; ordering
• how overlapping or leaving gaps affects accuracy	☐ how overlapping or leaving gaps affects accuracy	☐ how overlapping or leaving gaps affects accuracy	☐ how overlapping or leaving gaps affects accuracy	☐ how overlapping or leaving gaps affects accuracy
• how changing orientation of object does not alter measurements	☐ how changing orientation does not alter measurements	☐ how changing orientation does not alter measurements	☐ how changing orientation does not alter measurements	☐ how changing orientation does not alter measurements
• estimation strategies	☐ estimation strategies	☐ estimation strategies	☐ estimation strategies	☐ estimation strategies

Adapted with permission from Math Makes Sense 1&2 Teacher Guide Unit 4 Measurement, Pearson Education Canada 2007 & 2008

Procedural knowledge • measures and compares (non standard units	Needs one-to-one help; makes frequent errors in: ☐ measuring and comparing length, height, and distance around objects	Partially accurate; some errors in: ☐ measuring and comparing length, height, and distance around objects	Generally accurate; may make a few minor errors in: ☐ measuring and comparing length, height, and distance around objects	Accurate; very few or no errors in: ☐ measuring and comparing length, height, and distance around objects
• orders length, height, and distance around objects (non standard units)	☐ ordering length, height and distance around objects	☐ ordering length, height and distance around objects	☐ ordering length, height and distance around objects	☐ ordering length, height and distance around objects
• measures length using multiple/ single copies of a unit	☐ measuring length using multiple copies of a unit ☐ measuring length using single copies of a unit	☐ measuring length using multiple copies of a unit ☐ measuring length using single copies of a unit	☐ measuring length using multiple copies of a unit ☐ measuring length using single copies of a unit	☐ measuring length using multiple copies of a unit ☐ measuring length using single copies of a unit
Problem-solving skills Chooses and carries out appropriate strategies including estimation, to solve problems involving measurement.	☐ needs assistance to choose and carry out appropriate problem solving strategies	☐ with limited assistance, chooses and carries out some appropriate problem-solving strategies	☐ chooses and carries out appropriate problem-solving strategies	☐ chooses and carries out appropriate and effective problem-solving strategies in a variety of contexts; may be innovative
Communication uses appropriate language and explains reasoning	☐ unable to explain her reasoning and procedures	☐ partially explains her reasoning and procedures	☐ explains her reasoning and procedures clearly	☐ explains her reasoning and procedures, clearly, confidently, and with some precision

Additional Comments:

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7.5 Appendix E - Summaries of "Doing"

The following summaries of each lesson contain a description of the each manipulation mode used in the lesson (either observation of the teacher or using the robot, and in L1L0, M02 directed the teacher). If the participant performed the manipulative activity as expected, or with no problems, the entry reads "Appropriate". Otherwise, a description of the problem or interesting strategy used is entered.

Legend for all lessons:

Appropriate: The participant performed the activity as expected or with no problems
[]: Additional information is in square brackets
(): Prompts from the teacher are in round brackets
"**bold**": Word in quotes are what the participant said
NA: Not Applicable (participant did not perform that manipulation task in the lesson)

Level 1 Launch (L1L0) - Comparing objects

Manipulative Task	M01	M02 (directing the teacher)	M03
Observe teacher	2 items: the teacher held items vertically on the table	2 items: the teacher lined up the items horizontally on the table	0 items
Place items parallel	• first tried to grab the block under the item • after prompting that she had to compare them first by lining up the ends, she made the tips of the referent and the item touch (i.e., at an angle)	• (Tell us what to do to make sure they are both the same.) "**What do you mean?**" • (We could put it like this)[crooked] "**Move it straighter**."	Appropriate
Line up ends of the items	• hit forward movement so robot was too far ahead • after prompting, backed up to line up ends	• (We could put it here)[with ends not matched up] "**down a little bi**t" • (Tell me when to stop.) nod • (Why stop here?) "**It is in the centre**"	• Did not line up the referent with the end of the item at first [so her reporting was incorrect]. • After prompting to line it up on the baseline, she did and reported correctly

Level 1 Lesson 1 (L1L1) - Comparing lengths and sorting into bins

Manipulative Task	M01	M02	M03
Observe teacher	1 item: the teacher demonstrated the task while holding the robot	1 item (the 9th): o the investigator lined up the items o M02 gazed to the appropriate bin.	1 item: the teacher demonstrated while holding the robot
Place items parallel	Appropriate	Appropriate	Appropriate
Line up ends of items	• first tried to grasp the block under the item • after prompting to match the ends, she moved the robot appropriately	• on the first item, he did not seem to be matching ends o after clarification, he confirmed that he was matching the back end of the referent, rather than the front	• needed prompting to remember to line up the ends
Grasp item	Appropriate	Appropriate	• Had difficulty approaching the items so that the robot's grippers could grasp the blocks under the items
Put item in appropriate bin (teacher re-measured at end of session)	Appropriate: 0 mistakes out of 4 items in total	Appropriate: 1 mistake out of 10 items total Good strategy: opened grippers early and pushed item until it fell into bin	Appropriate: 1 mistake out of 6 items total
Compare items using the strategy that if they could judge just by looking, they didn't have to line up the ends:	After being told she could use the strategy she did two more items: • put both directly into the bin • both items were noticeably shorter than the referent	After being told he could use the strategy he did 6 more items: o put 1 directly into the bin o matched ends for 5 items, two of which were noticeably different lengths from the referent	She was immediately told she could use the strategy: o put 2 directly into the bin o matched ends for four items, two of which were visibly different from referent

Level 1 Lesson 2 (L1L2) - Ordering lengths in car and ramp activity

Manipulative task	M01	M02	M03
Release car	Appropriate	Appropriate	Appropriate
Unwind string as drive robot	• Instead of going from the bottom of the ramp, she wanted to go from the first car's tape mark to the second car	Appropriate	Appropriate
Pull strings parallel - Start position	• Facing away from the participant. • Robot placed at the same start location each time o hence, she had to turn for subsequent strings to make sure she did not drive overtop of the first string. o she did this appropriately	• Facing away from the participant. • The teacher placed the robot a few inches away from previous strings for each start o hence, he did not have to turn to avoid driving overtop of the other strings	• Facing parallel to the participant (because she moved the robot before the teacher was ready). • The same position was used for subsequent strings o hence, M03 had to turn the robot to travel away from her and avoid the other strings. o she did this appropriately
Pull strings parallel - Driving the robot	Appropriate	Because of the start position, the strings were already parallel.	Appropriate
Line up ends of strings	• Did not line up the end of the 2nd string to the 1st o teacher suggested she might be trying to line them up, and M01 nodded, so the teacher did it for her. • Did not line up the end of the 3rd string to the others o Since it was noticeably shorter, the teacher did not tell her to fix it	Appropriate	• Did not line up the end of the 3rd string to the others. o After prompting, she chose the appropriate string to fix. o The string was reattached to the robot and M03 moved it backwards (with the teacher keeping the string tight) o she was asked to clarify which end of the strings she was lining up ("**bottom**")

Level 1 Lesson 3 (L1L3) - Challenge activity - Who went the farthest pathways

Manipulative tasks	M01	M02	M03
Unwind string as drive robot • determine start position • drive along path • ask for tape to keep string on the path • stop at appropriate position	• Appropriate start position • Appropriate driving along each pathway • Appropriate amount of tape to keep string on pathway (9 times) • Appropriate stop position	For both the 2 and 3-path worksheets: • Appropriate start position • Excellent driving along each pathway • Appropriate amount of tape to keep string on pathway (12 times) • Appropriate stop position	• Had difficulty understanding that the string would be taped below the spool. • Appropriate driving along the S-curve path, but difficulty on the V-shaped pathway especially when she got off the path and tried to back up to get back on the path. • Asked for more tape than was necessary (29 times) and once did not ask and the string went off the path • Did not stop at the correct location on the first path
Pull strings parallel	Appropriate	Appropriate	Appropriate
Line up ends of strings • NA for 2-paths worksheet since the strings were taped to the baseline	• Additional activity: Pulled both strings up to a baseline drawn on the table. o Appropriately lined up ends of strings	• For the 3-paths worksheet he pulled each string parallel and lined them up o Appropriately lined up ends of strings	NA
Extension activity: Draw your own "Who went the farthest" pathways worksheet	• first pathway was inappropriate since it had several forward and backwards movements in it. • after instructions to make simpler pathways, the second and third paths were appropriate	• all pathways appropriate for someone to solve o as though characters went around a race track.	• all pathways were appropriate (though somewhat long) o asked for each path to be labeled with a friend's picture and the destination to be a mall

Level 2 Lesson 3 (L2L3) - Measuring and comparing lengths with non-standard units

Manipulation task	**M01**	**M02**	**M03**
Observation with teacher guided questions	Teacher measured gingerbread man	Teacher measured gingerbread man and Friend1	Teacher measured gingerbread man
• start position for unit • no gaps/overlap with units • end position for unit	Appropriate responses	Appropriate responses for both	• Appropriate start position • At first said gaps were okay, after three prompts, she gazed at the straws for the teacher to fix them. The teacher put the units crooked and M03 needed a hint that something was still wrong. M03 said, "**fix / **" • Allowed teacher to put a straw past the end position.
Manipulation method: Straws on robot, say "off"	This was the **1st** manipulation method she tried	The **2nd** method he tried	The **2nd** manipulation method she tried
• move robot to first end of string and ask for straw "off"	• she went ½ way up the gingerbread man before stopping • after instructions, she stopped close to the bottom and when asked where she was heading she said, **"foot"**	Appropriate • He went to the far end of the string rather than the closest	• did not put straw at end of string, she had trouble understanding where the straw would be placed with respect to where the straws were laying on the robot
• move robot so unit tip to tip with previous unit then ask for straw "off" (repeat) o Teacher placed the straw down directly below its position on top of the robot	• straw 2: left gap. The teacher placed the straw tip to tip and said, "because you told me to do it that way before" • straw 3: hit the forward movement (Fwd) accidentally • on straws 5, 6, and 7, if the teacher indicated there was going to be a gap or overlap, M01 moved the robot to the appropriate location	Appropriate • He had to travel from start position (at close end of string) to the other units each time (inefficient)	• straw 2: left gap between straws • straw 3: beginning to get it • straws 4...: appropriate
• stop placing units at second end of string	Appropriate	Appropriate	Appropriate

Manipulation method: Straws in "Gripper" of robot	This is the **3rd** method she tried (she had prior practice where she needed prompting to use little forward movements (L-fwd) for straw 1 to line up to baseline, and not to overlap for straw 2	This is the **1st** method he tried.	This is the **1st** method she tried.
• grasp unit	Appropriate	Appropriate	Appropriate
• release unit at first end	Appropriate	Appropriate	• did not understand where to stop the robot until got concrete demonstration
• move robot so unit tip to tip with previous unit and release (repeat)	• straw 2: moved forward accidentally • straw 3...: Appropriate, with occasional Fwd accidents	Appropriate	• straw 2: she placed it side by side with first straw at the baseline. • straw 3: needed prompts, overlapped (3 tries) • straw 4: starting to get it • straw 5...: appropriate
• stop placing units at end of string*	Appropriate • Teacher guided her to round up	Appropriate • reported using fractions	• she placed an eighth straw (but it was only slightly more than 7) o teacher explained rounding down
Manipulation method: Participant choice	"Off" method - This is the **2nd** method she tried, but she did not have a choice	"Gripper" method - This is the **3rd** method he tried	"Gripper" method - This is the **3rd** method she tried
• start position for unit • no gaps/overlap with units • end position for unit	• appropriate start position • no gaps/overlap, but needed prompts to use L-fwd • appropriate end position	• appropriate start position • no gaps/overlap • appropriate end position	• appropriate start position • no gaps/overlap • appropriate end position

Level 2 Lesson 4 (L2L4) - Estimate and choose units for M02 and Level 2 Lesson 4 Practice 1 for M03

Manipulation task	**M02 - Giant & Baby steps**		**M03 - Giraffe body parts**	
Part1 Game:	Race from one end of the table to the other		NA	
• select robot programs to move ahead	Appropriate			
• end as close to edge of table as possible	• first time, drove the robot off the table • second time, stopped exactly on the edge of the table			
Part 2: Measure using "Gripper" method	placed rods for his and the teacher's giant steps	placed toothpicks for his, teacher's, investigator's baby steps	placed straws for total height, torso, and face	placed toothpicks for ear to ear
• grasp unit	Appropriate	Appropriate	Appropriate	Appropriate
• release unit at first end	Appropriate	Appropriate	• height straw 1: went too far, but fixed it	Appropriate
• move robot so unit is tip to tip with previous unit and release (repeat)	Not Applicable because magnetic rod units used Note: He discovered a strategy on his own for going long distances.*		• height straw 2: overlapped, but fixed it • torso straw 2: overlapped, but fixed it	Appropriate
• stop placing units at end of string	Appropriate, except for: • one rounding issue (he said 11 when it was closer to 10)	Appropriate	Appropriate	Appropriate
Observation of teacher with guidance	The teacher used straws to measure the giant steps • appropriate responses		Participant made estimates and teacher manipulated rods and toothpicks to check them • appropriate responses	

* M02's strategy for going long distances: He set the robot in motion by selecting the giant step program and when he was close to the target location, he selected the Stop command. This strategy worked well for him, and if he pressed Stop too late, he simply backed up the robot and all of the rods came with the robot because they were attached by magnets.

Level 2 Lesson 5 (L2L5) - Using one copy of a unit in measuring snakes

Manipulative task	**M02**		**M03**	
Observation	Demonstration of measuring robot with single paper clip		Demonstration of measuring toothpick and toy rake	
Robot and pen practice				
• place mark at end • select robot program to move one unit (repeat) • place last pen mark at appropriate location	NA		Practice measuring shoe cut-out with single paper clip: • Appropriate mark at end • Problems remembering to use the paperclip program, she kept using little forwards (L-Fwds) • Put last dot at end of shoe instead of at end of unit	
Single copies of a unit with robot and pen	**2nd: Straight snake ***	**3rd: Wavy snake**	**1st: Straight snake**	**4th: Wavy snake**
• place mark at beginning of pipe cleaner	Appropriate	Appropriate	Appropriate	Appropriate
• select robot program to move ahead one unit and repeat	Appropriate	Appropriate: • He used robot unit program first and then turned, so some marks were closer together than one unit **	• Problems remembering to use the paperclip program, she kept using little forwards (L-Fwds)	• Problems remembering to use the paperclip program, she kept using little forwards (L-Fwds) *** • She turned first, then adjusted with L-fwd, then made a mark to see if her dots lined up
• place last pen mark at appropriate location	Appropriate	Appropriate	• Put last dot at end of pipe cleaner instead of at end of unit length	• Put last dot at end of pipe cleaner instead of at end of unit length
Multiple copies of a unit with robot and gripper	**1st: Straight snake** • teacher demo with guidance	**4th: Wavy snake**	**2nd: Straight snake**	**3rd: Wavy snake**
• release unit at first end	Appropriate responses	Declined to do this because he said it	Appropriate	Appropriate

• move robot to end of unit and release (repeat)	Appropriate responses	was **"too hard"**.	Appropriate • Used interesting strategy of selecting the unit program while carrying the unit forward.	• Had difficulty managing the angle from which to approach the curvy snake to place the units. The teacher facilitated by spinning the unit so that they were tip-to-tip ****.
• stop placing units at end of string	Appropriate responses		Appropriate	Appropriate

*Afterwards teacher re-did measurements with multiple units because the multiple and single unit measurements did not work out to be the same. They had a discussion that the numbers were different because the magnets left gaps between the units.
** After he fixed the marks to be one full unit, the teacher crossed out the erroneous marks
*** She liked for the teacher to make the marks bigger with a felt pen
**** The difficulties arose because she decided to go pick up the next unit from a pile instead of letting the teacher lift the robot and place the unit in the griper. Therefore, her angle of approach to come to the pipe cleaner was awkward.

M01 Practice Lessons

Level 1 Lesson 1 Practice - Drawing lines shorter than, same as, and longer than

Manipulative task	**Description**
Observe teacher and indicate when to stop	Appropriate responses
With robot and pen	
• Bring pen to end of item	• Needed prompting on the first one
• put pen down	Appropriate
• draw line	Appropriate length lines • hit the forward movement button on the third line (same as) but backed up to the appropriate end position (teacher scribbled out extra portion)
• lift pen	Appropriate

Level 1 Lesson 2 Practice 1 (L1L2 P1) - Ordering lengths from fake car race

Manipulative task	**Description** * Orientation changed from previous lesson. In L1L2 she drove the short way across the table. In this practice she drove the long way.
Draw a baseline	Appropriate
Pull strings parallel	• On the first string, she placed it at an angle to the baseline ▪ After prompting about the baseline, she placed it parallel to the baseline. [The teacher placed the string perpendicular to the baseline to demonstrate how it should be placed]. • On the second string, she pulled the string beyond the baseline and then turned the robot parallel to the baseline. [The teacher placed the string perpendicular to the baseline again] • On the third string, M01 placed the string appropriately.
Line up ends of string along baseline	• When M01 looked up at the teacher to indicate she was done she hit the forward movement accidentally.

Level 1 Lesson 2 Practice 2 (L1L2 P2) - Ordering straws

Manipulative Task	**Description**
Part 1 - Observing the teacher and answering which straw was the shortest, longest, and middle	Appropriate
Part 2 - Order 3 straws with robot	
• Grasp straw and bring to appropriate location along baseline (i.e., in order)	Appropriate
• place straw on baseline	• Did not put the items exactly along the baseline, but close
Part 3: Ordering 4 straws	
• Draw a baseline	Appropriate
• Grasp straw and bring to appropriate location along baseline	• Appropriate for first three straws • On 4th straw, she said **"I don't get it"**. After prompting about where the straw did not belong, she was able to place the straw appropriately.
• place straw on baseline	• Needed prompting to put them along baseline.

Level 2 Lesson 3 Practices (L2L3 P1, P2, P3)

	Manipulative task	
Practice 1: Robot with gripper	• Release unit at first end • Move robot to end of unit and release (repeat) •Stop placing units at end of item	• Appropriate • Appropriate • Appropriate
Practice 2: Robot with gripper	• Release unit at first end • Move robot to end of unit and release (repeat) •Stop placing units at end of item	• Appropriate • Appropriate • Appropriate
Practice 3: Robot with pen	• Lower pen at beginning of string • Select robot program to move ahead one unit and repeat • Raise pen at end of string	• Appropriate • Appropriate • Appropriate

M03 Level 2 Lesson 4 (L2L4 Adapted)

Manipulative task	**Description - Choose appropriate units to measure self , gingerbread man and mother**		
Draw baseline	The teacher drew a line with a green marker on the table to represent 10 rods which were cut off of each string.		
Pull strings taped to back of robot	**1st: String 1 (self)**	**2nd: String 2 (Gingerbread man)**	**3rd: String 3 (mother)**
• parallel	Appropriate	Appropriate	Appropriate
• lined up on baseline	• not on the line	• not on the line	Appropriate
Measure in rods using robot and gripper	String 1 (self)	String 2 (Gingerbread man)	String 3 (mother)
• Release unit at first end	Appropriate	• not on the green line	Appropriate
• Move robot so unit tip to tip with previous unit and release (repeat)	Appropriate • overshoots, but fixed it	Appropriate	Appropriate
• Stop placing units at end of string	Appropriate	Appropriate	Appropriate
Measure difference in height between self and SLP and Mom	The teacher did the manipulation while the participant observed: • difference between SLP and self in paperclips • difference between her mother and self in toothpicks		

7.6 Appendix F Summaries of "Talking"

The following summaries of each lesson contain a description of the communication made by the participants in each portion of the lesson (either before, during and after observation of the teacher or during or after using the robot). If neither mode is applicable, the question asked is shown.

Legend for all lessons:

[]: Additional information is in square brackets.

(): Prompts from the teacher are in round brackets.

"bold": words that the participant said using their SGD

NA: Not Applicable (participant did not perform that part of the activity)

In this summary, the communication during the introduction portion is only listed for the first lesson.

Level 1 Launch (L1L0) - Comparing objects

	M01	M02	M03
Do you know any measurement words?	[Did not generate words independently. With prompts:] **"shortest, shorter, longer, same, match up"**	[Independently generated:] **"small, large, medium, little, tiny".**	[Tried to spell:] "**measure**" [looked at the ruler on the table and the teacher guessed she meant:] "**centimetre**"
During observation	Item 1: - "**maybe**" [incorrect, the item was longer] Item 2: - "**shorter**" [correct]	"**One is bigger than the other one.**" **"The stick is longer than the other one"** (How can you tell?) **"I looked at the thing and I looked at the pencil so I came with my answer."**	NA
During robot use - For M02, it was during directing the teacher	Item 3: - "**shorter**" [correct] Item 4: - "**long**" [correct]	[During directing the teacher to manipulate] "**They are both the same with longer."**	Item 1: - **"s-a-m-e"** [incorrect] - "**It** (the referent) **is longer**" [correct] Item 2: - "**Book is 2 i-n-**(guess inch)**-c-h-s**" (two inches what?) "**shorter**" [shorter correct, but only 2 mm shorter] Item 3: - "**Longer**" (which one is longer?) "**garden thing**" (rake) [correct]

Level 1 Lesson 1 (L1L1) - Comparing lengths and sorting into bins

There was no reporting during the activity, except for M03's extension activity to make a math sentence.

	M03
Can you make a math sentence about the activity that you just finished?	(some prompting) **"3*2=6** [using the calculator on her SGD] (explaination that dividing the six items into three bins was a division equation) (some prompting) **"6 / 3 = 2"**.

Level 1 Lesson 2 (L1L2) - Ordering lengths in car and ramp activity

	M01	M02	M03
During robot use	(What can you tell us about the race?) - No response. (The yellow car travelled the...) - "**farthest**" (What about the pink truck?) - "**Middle"** [incorrect, it was not the middle length string, but it was placed in between the other two] (Does that mean that the green car travelled the shortest distance?) - No response. (Do you think this [pink&short] travelled shorter than this one [green&long]?) - Nod (Which colour travelled the shortest distance?) - "**Green**" [incorrect]	Race 1: (What can you tell us about your race characters?) **"That yoshi went the farthest."** **"He (Bowser) is in 2nd place."** **"He (Mario) is in shortest place."** Race 2: **"Yoshi is the longest string."** (Do you know what that would mean then?) **- "He is the fastest"** (Can you use farthest in a sentence?) - **"He** (Yoshi) **is the farthest and long string."** **"He** (Bowser) **went the middle distance."**	[Before pulling strings] Gazed at the Tyra mark "**long**" [After pulling strings] "**The blue went the furthest**." (How do you know that Tyra went the farthest?) **- "10 inches"** (It's something to do with the length of the string. Because it was the shortest, middle, longest?) - nods on longest. **"The red went in medium** (middle?)" (It's the middle string length or placed in the middle?) - Gazed at placed in the middle. [incorrect, it was placed on one of the sides, but it was the middle length]
During observation	[The teacher placed the pink and green strings closer to M01 and along a baseline and explained which one was shorter.] - Nod		[The teacher moved two strings closer to M03 and in perpendicular direction, matched up along the baseline.] **- "The green is the shortest"**.

Level 1 Lesson 3 (L1L3) - Challenge activity - Who went the farthest pathways

		M01	M02	M03
Estimate who went the farthest?		"**Yellow**" (S-shaped path) [some confusion over this] [But, she changed her prediction after spooling out string] "**Blue**" (V-shaped path)	2-paths: Eye gazed at the V-curve path "**it looks longer**" 3-paths: Eye gazed to fox farthest, bunny middle, and wolf shortest	Gazed at S-shaped path [But, she changed her prediction after spooling out string] "**blue longer**" (V-shaped path)
Reporting	During observation	NA	NA	NA
	During robot use	"**Blue longs**" (longest or longer?) -Gazed at longest (can you say it?) "**Longest**" (Can you tell me something about the yellow string?) - "**Short**" (almost there) "**Shorter**" (Can you tell me which person went farther?) **- No response.** (Was it blue that went farther, or yellow?) - "**Blue**"	2-paths: "**B went farther than Y."** (How do you know?) **"I looked at the strings to see which one is farther."** 3 Paths: "**red** (fox) **went the farthest"** (Who went the shortest, wolf?) - Nod	**"The blue went the furthest"** **"The green went seven inches."** (explains about middle) "**The green went the middle"** **"The red is shortest"**

Level 2 Lesson 3 (L2L3) - Measuring and comparing lengths with non-standard units

	Reporting	M01	M02	M03
During Observation	Estimate gingerbread man length in craft sticks. (Actual - 9)	"**100**"	"**30**"	"**30**"
	If the gingerbread man was standing, how tall would he be?	"**100**" [After concrete demonstration]: "**9**"	"**40**" [After concrete demonstration]: "**9**"	[Asked after measuring in straws, so actual is 7]: "**10**" [After three concrete demonstrations]: "**7**"
During robot use	Measurements	See worksheet entries below		
	Can you order your measurements? Start with the shortest	No response	"**6 5 ½ 7 7 1/4**" [After concrete demonstration on white board understood that 5 ½ was less than 6]	"**We are all the same**"
	Reporting on tallest, shortest, and how do you know?	Gazed at EA "**Woman**" (it is something to do with numbers) (Which is the bigger number?) - "**Nine**" [Answered Y/N questions about the shortest incorrectly, but didn't understand that two of the measurements were the same]	Tallest: - Gazed to adult friend Shortest: - Gazed to young friend (How do you know?) **"I looked "** (Because he's an adult?) - Nod*	NA

*After an explanation that the numbers tell him, M02 indicated he understood. He was able to order three numbers with no fractions in a brief activity the next day.

Worksheet entries

	M01	M02	M03
The gingerbread man is ___ straws tall.	**"8"**	Estimate**: "8"** Actual**: "7"**	Estimate**: "10"** Actual**: "7"**
I am ____ straws tall.	**"8"**	Estimate**: "6"** Actual**: "6"**	**“7”**
My friend is ____ straws tall.	**"9"**	Estimate**: "8"** Actual: **"8 1/2"** (not quite, I'll count) **"6 ½"** (actually it's 5 ½)	**“7”**
My other friend is ____ straws tall.	NA	Estimate**: "10"** Actual**: "7 and a quarter"**	NA

Level 2 Lesson 4 (L2L4) - Estimate and choose units for M02 and Level 2 Lesson 4 Practice 1 for M03

		M02 - Giant & Baby steps	M03 - Giraffe body parts
During observation	Best unit to measure the giant step (or table for M03)? Why?	Gazed at the straw "**Straws are longer than the rod"** [straws were correct, but investigator suggested using rods since they have magnets which are easier to line up tip to tip]	Gazed at the straw "**Longer**" [At end of activity, "For which body parts would you use longer units?] "**body**"
	Best unit to measure baby step (or your hand for M03)? Why?	"**Toothpick**" "**Littler**"	Gazed at the toothpick "**Shortest**" [At end of activity, "For which body parts would you use shorter units?] "**head tail**"
During robot use	Measurements	See worksheet entries below	
	Can you order the giant steps?	[At first he did not think he could order them, but he **answered appropriately using yes and no questions.]**	NA
	Can you order the baby steps?	[He said he could not write a sentence about what he just measured, but he said he could order them:] **- "1 1 2"**	NA
	Asking re: comparing measurements made with different units?	[At first he thought that his robot step would be the shortest measurement but then he said that that he could not just compare the numbers because:] - "**Straws are longer than the rod."**	[Indicated that the measurements could not be compared, but did not give a reason.]
	What can we do to be able to compare?	[He needed prompting for the strategy to change the units so the measurements could be compared, but he agreed that it made sense.]	[She needed prompting for the strategy to change one of the units, but M03 chose to change the wrong one]

M02's measurements and ordering

	Rods (Participant with robot)	Toothpicks (Participant with robot)
Giant step - Robot	Estimate **= "11",** Actual **= "9"**	NA
Teacher's step (she measured in straws =5)	Estimate **= "10",** Actual **= "10"**	
Investigator's step	Teacher measured = 7]	
Baby step - Robot	NA	**"1"**
Teacher's step		**"2"**
Investigator's step		**"1"**

M03's measurements and ordering

	Straws	Toothpicks	Estimates done at end of activity
Total height	**"5"**	NA	In rods: **"10" (**actual 9**)** In toothpicks: **"12" (**actual 18)
Torso	**"3"**	NA	NA
Ear to ear	NA	**"4"**	
Face length	**"1"***	Chose not to use this unit	

* When asked why she chose straws to measure the giraffe's face [when toothpicks would be more appropriate], she said because the straws were **"longer",** but the reason why she chose toothpicks for ear to ear was because they were "shorter")

Level 2 Lesson 5 (L2L5) - Using one copy of a unit in measuring snakes

		M02	M03
Teacher demonstration	Do you think the number with single and multiple units will be the same?	- Shake	- Shake
During robot use	Measurements	See worksheet entries below	
	Do you find it easier to estimate straight or curvy?	"**both**"	Gazed at same
	Do you like measuring with single or multiple copies? Why?	Gazed at single	Gazed at multiple - "**easier**"

M02's results (with the order in which he did the measurement in brackets)

Snake	Copies of the unit - toothpick	My estimate	My measurement
Straight	one	"**7**" "**6**"	[2nd with robot]: "**6**"
	more than one		[1st Observed teacher]: "**5**" [Teacher re-did measurement without gaps after M02's 2nd measurement, since this should have been the same size as measurement with single copies of a unit]: "**6**"
Wavy	one	**6**	[3rd with robot]: "**6**"
	more than one	**6**	[4th]: [Chose not do this but he indicated that it would be the same number as the others] "6"

M03's results [with the order in which she did the measurement, all with the robot, in brackets]

Snake	Copies of the unit - paperclip	My estimate	My measurement
Straight	one	"**6**"	[1st]: "**7**"
	more than one	"**7**"	[2nd]: "**7**"
Wavy	one	"**9**"	[4th]: "**7**"
	more than one	"**10**"	[3rd]: "**7**"

M01 Practice Activities

Level 1 Lesson 1 Practice - Drawing lines: No reporting

Level 1 Lesson 2 Practice 1 (L1L2 P1) - Ordering lengths from fake car race

The pink string is...	**"Shortest"**
Did the pink string go the shortest distance, the longest or in the middle?	**"Help"**
This is the shortest string. So did she go the longest distance or the shortest?	Gazes at shortest
The yellow string is...	**"Longs"**
The yellow string is longest so it went the ________ distance. Shortest, middle or farthest?	**"Farther"**
The black string is 'something' than the yellow.	**"Middle"**
Is the black string shorter, longer or the same?	**"Help"**
Is the black string shorter or longer than the yellow?	**"Short** (can you finish?) **er"**
Is the black string shorter or longer than the pink string?	**"Taller"**
Ariel went the shortest distance...What distance did Mulan [black string] go?	**"Middle"**

Level 1 Lesson 2 Practice 2 (L1L2 P2) - Ordering straws

Is the yellow straw longer or shorter than the red straw?	"**Long**" (can you finish that) "**Longing**"
Can you tell me one on your own now?	"**Red**" (what about red?) "**Tall**" (is red longer?) "**Taller**" (what is red longer than?) "**Green**"
Which straw is longest or shortest?	"**Green shorter red"**
Which colour is longest of all?	"**Yellow longs**" (pointing and reading the endings: "ing","s", "er", "est") "**Longest**"
Which straw is the shortest?	"**Green short**" (reading the endings) "**Shortest**"

Level 2 Lesson 3 Practice (L2L3 P1, P2, P3)

Practice 1	- "**Long**" (are you finished?) "**Longer**" (Which one is longer?) "**Fork**" (longer than what?) "**Foot**" - "**Block taller foot**" [not mathematically correct] [She could not use the numbers to determine which item was larger although she could answer which number was the biggest out of 3, 2, or 1.]
Practice 2	She reported which item was shortest and longest correctly and she stated that she knew why: - "**scissors 1**" (and why was the shovel longest?) "**3**"
Practice 3	- Estimated the 4th measurement (9, actual 12) after she had done the other three measurements (7, 8, 8)

	- "**EA M01 middle**" [confusion over her meaning of middle] (Between 12 and 7 or the same?) "**same**" - "**you shorter**” (Shorter than who?) "**EA**" "**Me**" [not mathematically correct, but corrected herself after the teacher's clarification that she was reporting on jumps, not heights.] [She was not able to explain her reasoning from the numbers, but she filled in the blank appropriately:] "**12**" (bigger than) "**8**".

M03 Adapted and Practice activities

Level 2 Lesson 4 (L2L4 Adapted) - Choose appropriate units to measure gingerbread man, self, and mother

Write a word problem	Remember, we took off 10 rods before, how many rods are there all together?	[Self:] 14 [Gingerbread man:] 14
	"If the bottom part of your mom is 10 rods long and she is three rods long on the top. How many rods long is she all together?"	"**10 + 3 = 13**"
During robot use	What can you tell us about your results?	- "**Same**" (Is everyone the same?) "**Mom and me**" (You're the same height as someone else) - "**G**"(gingerbread man?) "**and me**"
	How did you know that you were the same height?	- " **14**" (What about your mom?) - "**mom is the shortest**." (How did you know that your mom was the shortest?) "**Thirteen**" (What about it?) "**Mom**" (and?) "**Two fourteens "** (Was your mom's number bigger or smaller than your number?) - Gazed at smaller.
	Why are rods more accurate than straws?	"**Littler**"
During observation	I found out that your SLP is 8 straws. You're 14 rods. Can you say who's taller?	[Did not demonstrate understanding that measurements with different units could not be compared.]
	Is your mom 1 whole rod shorter than you? Can you think of another unit to be more accurate?	- Shake head "**Toothpick**" [teacher measured the difference with toothpick] (How much shorter is she?) "**one**"
	Is your SLP 1 whole straw taller than you? Can you think of another unit to be more accurate?	- Shake head "Paper clip" [teacher measured the difference with paper clip] (How much taller is he?) "**two**"*

*M03 subsequently told the SLP this result the next time she saw him, "**two paper clip longer**"