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Published citation:
Esquivel, P., McGarvey, L., Phelan, S., & Adams, K. (2022). Exploring environmental factors affecting assistive technology strategies in mathematics learning for students with physical disabilities. In *Disability and Rehabilitation: Assistive Technology*. DOI: 10.1080/17483107.2022.2062465

Exploring environmental factors affecting assistive technology strategies in mathematics learning for students with physical disabilities

Purpose: To explore the environmental facilitators and barriers affecting K-12 students with physical disabilities when using two assistive technology (AT) strategies, LEGO Mindstorms robots and a computer, in mathematics lessons.

Materials and methods: A qualitative multiple case study with three students with physical disabilities was conducted. The participants did five lessons in concepts they were studying in school with each AT strategy in a controlled environment. Observations of the lessons, and parent and teacher interviews after the last session were collected.

Results: The AT strategies acted as facilitators because they were easy to use, participants could participate actively, and parents and school staff wanted to implement them. However, the strategies presented some barriers since the students required more time to complete the lessons with the robot, and some computer programs were not compatible with the students' skills. Also, barriers such as lack of technical knowledge on the part of parents and teachers, distractions in the environment, and funding issues were reported.

Conclusion: This study may be useful for rehabilitation staff and teachers who are considering implementing AT to support the participation of students with disabilities. Personnel needs to be trained to use the AT strategies, and several modifications may be necessary for the satisfactory use of the devices.

Keywords: LEGO® robot; computer; students; physical disability; mathematics; environment.

Introduction

The inclusion of students with disabilities in K-12 education, including those with physical impairments, has been recognized as a priority initiative internationally [1]. Although full participation of students with disabilities in academic activities is promoted [2], students with physical disabilities do not participate to the same extent as their typically developing peers and are often excluded in subjects such as mathematics [3].

Mathematics is one of the most important subjects in school because students need to develop mathematical reasoning that allows them to solve real-life problems and improve their critical thinking [4]. To promote learning of early mathematical concepts, teachers often use hands-on strategies using manipulatives (e.g. Cuisenaire® rods or strings of beads). However, students with physical disabilities may have limited participation in the use of these strategies because they may not be able to manipulate objects with their hands [5]. As a consequence, they may have a lower academic performance compared to their typically developing peers [6] and a delay in the development of more complex mathematical abilities [7].

To facilitate the use of manipulatives in early mathematics learning in students with disabilities, assistive technology (AT) strategies have been implemented [8-14]. One strategy is using alternative access methods such as switches or eye gaze to control LEGO Mindstorms robots to move physical manipulatives [8-10]. LEGO robots have been shown to allow students to demonstrate their understanding of mathematical concepts, as well as to provide teachers with a way to assess student understanding [8]. Another strategy could be to use alternative access methods to control virtual manipulatives in computer programs. Though they did not use alternative access strategies, several studies have found that students with learning disabilities or autism perceived such programs as easy to use, interesting and entertaining, and were willing to continue using the computer for mathematics [11,12]. However, in general there is little research in the use of AT strategies for mathematics learning in children with physical disabilities [13,14].

Although AT has been widely used in the education sector, there is still a high incidence of abandonment of these technologies, in part, because there is a lack of consideration of the environmental factors surrounding students with disabilities [15,16]. School staff and clinicians should consider the child-environment interaction when assessing effectiveness of an AT strategy in a school setting [17,18].

The International Classification of Functioning, Disability, and Health (ICF) describes environmental factors that can influence the level of participation of people with disabilities [19]. According to the ICF, environmental factors can be divided into five domains: products and technology (also called AT); natural environment and human-induced changes in the environment; support and relationships; attitudes; and services, systems, and policies. These ICF domains can be used for identifying environmental facilitators and barriers surrounding the person with disabilities. In the particular case of AT implementation in the classroom, facilitators such as the ease of use of the technology and its compatibility with the student´s needs and abilities can increase the likelihood of adopting it in the student´s learning [20,21]. Furthermore, support from teachers, such as giving assistance and encouragement to use AT could increase the willingness and confidence of the child to use AT [17]. On the other hand, barriers such as lack of portability of technology, incompatibility among hardware and software, and limited adaptability of software for diverse needs are considered barriers to effectively integrate AT in schools [20,22]. Moreover, the limited knowledge of teachers about how to integrate AT strategies in the classroom may be a factor resulting in abandonment of the AT [17,23,24]. Finally, lack of government funding for providing AT to the schools and lack of policies that provide support for teachers who have students with a disability may negatively influence the implementation of AT [20,23].

According to the literature, there is a need for research studies regarding AT and its use in mathematics learning in students with disabilities [25,26]. Furthermore, there is limited research regarding environmental factors that may influence the implementation of AT in mathematics instruction [23]. When implementing AT in a school setting, school staff must not only consider the features and feasibility of the AT devices, but also the environmental factors that surround students [23]. The factors mentioned above from the literature around AT may or may not be applicable to the particular AT being used for mathematics, and there may be other factors of importance. It is relevant to identify facilitators and barriers that may affect the use of an AT for mathematics in the classroom to generate a more accessible environment for the student [19] to achieve classroom goals. Moreover, professionals such as allied health professionals, school staff, and policy makers may have a reference that assist them during AT decision-making when they want to support the mathematics learning of a student with disabilities [27].

This study was part of an overarching project that used a mixed-methods design to examine the experience of students with physical disabilities when using two AT strategies in mathematics lessons, LEGO Mindstorms robots to move physical manipulatives and a computer to move virtual manipulatives. The students' performance, level of prompting and assistance given with each strategy, and students' opinions about the robot and the computer are presented elsewhere (blinded for review). The purpose of the study presented here was to explore the environmental factors surrounding the students when they used the robot and the computer,. The research question that guided this study was: What are the **environmental facilitators and barriers** affecting students with physical disabilities when they use the robot and computer in mathematics learning?

Methods

A qualitative multiple case study methodology [28] was used to examine the research question. Use of case study is ideal when the research covers contextual situations that directly affect the phenomenon under study, the boundaries of the phenomenon and context are not clear, and the data collection relies on multiple sources of evidence [28].

Cases

Each case was comprised of the student, who is central to the case, his participation in mathematics lessons using the LEGO robot or the computer that were tailored for his level of mathematics understanding, his parent or teacher interview about the AT strategies, and observational data from the lessons. The setting for the lessons and person interviewed was chosen depending on what was most convenient for the family and school. A convenience sample [29] of three students with physical disabilities participated in the study. The inclusion criteria for the participants were: a) motor impairment resulting in limitations when manipulating objects, b) taking mathematics lessons at a school in the area or through private lessons, c) ability to answer yes/no questions.

The pseudonyms Dylan, Edward, and Jacob, will be used for the students. All students had difficulty moving their upper and lower limbs, could not manipulate objects with their fingers, and used a manual wheelchair, not self-propelled. None of them had visual impairments, and they all understood English.

Dylan was a 3-year-old boy, homeschooled before entering preschool, who had a diagnosis of cerebral palsy. He was minimally verbal, relying on single words to communicate. He did not require a communication device. He had no functional use of his upper limbs, but at the time of the study, he was beginning to learn to use two Jelly Bean® switches[1] mounted on each side of his manual wheelchair headrest. Dylan's research sessions took place in a rehabilitation hospital in a large room in an AT assessment centre. His mother was present in all the sessions but did not intervene. The concept for Dylan to work on, sorting by colour, shape, or type, was chosen from the preschool mathematics curriculum by a special education teacher on the research team.

Edward was a 6-year-old boy, in kindergarten in a large urban school district. He had a brain stem stroke one year before the study that resulted in no functional movement of his left arm, slight movement in his right hand, and good movement of his head. He was not able to communicate verbally, but he used an Accent 1000 communication device[2], accessed through the built-in head tracker to move the cursor on the screen, and a Jelly Bean switch on his wheelchair lap tray to select items with a small movement of his right hand. Edward's sessions took place in a rehabilitation hospital in a small research lab. One year prior to starting the sessions, Edward participated in a trial where he controlled a LEGO robot. The purpose of the trial was to observe Edward's control of head tracking as an alternative access method. During the research sessions, his mother was always present but did not intervene. The mathematical concept to work on with Edward, counting up to 10, was suggested by his kindergarten teacher.

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1. Manufactured by Ablenet Inc., 2625 Patton Road, Roseville, Minnesota 55113-1137
2. Manufactured by Prentke Romich Company., 1022 Heyl Road, Wooster, Ohio, 44691

Jacob was a 17-year-old boy, in a special education classroom in a high school. His classroom was in a program intended for students of junior to senior high age with severe disabilities. He had a diagnosis of cerebral palsy with spastic quadriplegia. His only functional movement was to use his right arm to target switches, and he could move his head to his left side. He was learning to use a Proloquo2Go[3] communication app on an iPad, with vocabulary customized daily by his teacher, but for this study he did not use it. He was not verbal, but he communicated by shaking his head to signal "no" and moving his right arm to signal "yes." He was learning to do step scanning on the computer with a Jelly Bean switch mounted beside his head to move through the options, and a Jelly Bean switch on the right side of his wheelchair lap tray, which he pressed with his right hand, to select the desired option. Jacob's research sessions took place in a therapy room next to his special education classroom in his school. Jacob's teacher requested that the sessions be conducted there so as not to interrupt the other classroom activities. In the sessions with Jacob, only the researchers were present; however, Jacob's teacher observed the sessions briefly and met with the researchers at the end of each session to discuss the daily lesson. The concept to work on with Jacob, comparing weight (heavy/light) and describing position of objects (in/out), was suggested by his teacher.

Materials

The mathematics lessons were based on the "Maximizing Math K" teacher resource [30]. Lessons were adapted to be accomplished using the AT strategies. Lessons with the robot and the computer were matched to focus on the same concept.

The participants used a LEGO Mindstorms EV3 robot (figure 1) to move concrete manipulatives. The robot had a gripper for grasping and pushing objects and a pointer and robot-

3. Manufactured by AssistiveWare, Laurierstraat 193, 1016 PL Amsterdam, Nederland.

generated voice for counting objects. The robot was able to move forward, backward, left, and right, open and close the gripper, and move the pointer up and down. A robot control program, written in MATLAB[4], sent the commands to the robot via Bluetooth based on keyboard key input.

--- Insert figure 1 about here ---

A laptop computer was used for the virtual mathematics programs. Free virtual mathematics programs were used as much as possible. In the case of sorting for Dylan, and in the in/out lessons for Jacob, the virtual lessons were created using The Grid 2 software[5] and Boardmaker™ [6] (figure 2) respectively, because it was not possible to find free online programs that were accessible through the alternative access methods used by the participants. During the lessons, the programs had the audio on to simulate how the student would normally use the programs. Some of the free programs provided feedback when the participant chose an incorrect answer. For instance, the program would display a message to indicate that the answer chosen was wrong and that the participant needed to choose another one. A list of the virtual lessons used in this study is provided in the Supplemental Materials. Each participant used their usual alternative access method to control the robot or computer. Dylan controlled both AT strategies using his two head switches, which were connected to the computer through a Don Johnston switch

4. Manufactured by MathWorks., 1 Apple Hill Drive, Natick, Massachusetts, 01760-2098
5. Manufactured by Smartbox Assistive Technology, Ysobel House, Enigma Commercial Centre, Sandys Road Malvern, WR14 1JJ
6. Manufactured by Tobii Dynavox, 2100 Wharton Street, Suite 400, Pittsburgh, PA 15203

interface[7]. The switches outputted left or right turn commands to the robot, or selected an item on the left or right of the computer display. Edward controlled the robot using a communication page on his Accent 1000 that outputted keyboard keys for all the robot functions. To control the computer, he used a HeadMouse Nano[8] connected directly to the computer and a switch at his hand to "click." Jacob controlled the robot with three Jelly Bean switches, the two he usually used and another one on his wheelchair lap tray. The switches were connected to the computer through a Don Johnston switch interface, and controlled the robot to turn left and right and go forward. He used his head switch and one lap tray switch to do step scanning on the computer.

--- Insert figure 2 about here ---

Procedure

Ethical approval was received from the Human Research Ethics Board at the <blinded for review>. The participants provided assent and the participant's legal guardian provided consent prior to commencing the study. The research team consisted of a rehabilitation science researcher, a special education teacher specializing in AT, a mathematics education researcher, and two research assistants: a Master of Science Student with a background in occupational therapy, and an undergraduate student in education with a previous degree in engineering.

The participants first received training sessions to learn how to control both AT strategies by performing tasks not related to mathematics. Dylan and Edward had two training sessions with the robot and two with the computer, whereas Jacob had three sessions with each strategy.

7. Manufactured by Don Johnston Incorporated, 26799 West Commerce Drive, Volo, Illinois 60073
8. Manufactured by Origin Instruments Corporation, 854 Greenview Drive, Grand Prairie, Texas, 75050

After training, the participants used the two AT strategies to do the chosen mathematics lessons. The first strategy was chosen at random and then alternated successively between them in each lesson. The participants did five lessons with each AT strategy. Sessions were conducted twice per week and were approximately one hour in length. If a lesson was not completed within a session, it was carried over to the next session. At the end of each session, the participants had an opportunity to free play with the robot or the computer.

The research assistant who was pursuing a Bachelor of Education degree conducted the mathematics lessons, while the other research assistant observed the sessions and collected data. During the lessons, the research assistant read the question, and the participant drove the robot and moved the concrete manipulative to answer it (robot strategy), or moved the computer cursor to select the appropriate option (computer strategy).

For Dylan's lessons with the robot, the research assistant presented the object to sort and then Dylan used his head switches to turn the robot to the right or left to indicate the desired box for the research assistant to put the target object into, then the research assistant let him know if it was correct. In the lessons with the computer, the object to sort appeared at the top-centre of the screen and the participant had to use his head switches to choose the right or the left category to sort the object into (figure 2(A)), and the program let him know if the choice was correct.

In Edward's lessons with the robot, the research assistant gave the instruction (e.g. “the number of blocks you have to bring is…”, while holding a card with a number 5 on it), then Edward used the communication page on his Accent device to select commands to move the robot to grasp a manipulative and then drive the robot to the desired position on a ten frame board. Then he drove the robot to grasp another manipulative and so on until completing the activity. In the lessons with the computer, the numbers were presented by the program and

Edward used his head mouse and switch to move the virtual manipulatives to the target on-screen destination. The virtual programs gave him feedback whether the answer was correct or not.

In Jacob's lessons with the robot, after the research assistant placed the object on top of the robot, Jacob used his three switches to move the robot onto a scale. Then the research assistant placed the object on the scale and asked the participant if the object was heavier or lighter than the comparison object on the scale. To demonstrate in and out, the research assistant gave the instruction (e.g. this object has to be "in" the box), then Jacob moved the robot to put the object in or out of the box. In the lessons with the computer, Jacob used two-switch step scanning with the virtual manipulatives programs, and both the free ones and the ones created in Boardmaker™ let him know if the answer was correct or not. Jacob had three heavy/light lessons and two in/out lessons with each strategy.

Data collection instruments

Observations of all the mathematics lessons were performed to identify environmental facilitators and barriers when participants used the AT strategies during the sessions. A field notes protocol using a Student-Environment-Tasks-Tools (SETT) framework [32] was used to record both descriptive and reflective notes. Participants were observed in person, and the sessions were video recorded. Two video cameras were used where one camera recorded the participant's face and body, and the other camera recorded what was happening with the robot and concrete objects or what was happening on the computer screen when the participant was using virtual manipulatives.

The videos were imported into Morae™ usability software[9] to view and code events. The

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9. Manufactured by TechSmith Corporation, 2405 Woodlake Drive, Okemos, Michigan 48864-5910

events tracked with Morae™ described possible factors that would influence the outcomes when using AT [31], such as device problems, time to set up the robot or computer, time to take them down, and situations within the room that may have affected the use of the AT strategies. The coded events of each video were exported into Microsoft Excel, thus having a spreadsheet for each video. Afterwards, the events were compiled into an Excel document for each participant. Subsequently, each document was analyzed to code environmental facilitators and barriers. For this coding, the ICF manual was considered [19]. If the event had a positive effect on a participant's performance (e.g., the research assistant moved Edward to another position so he could see the blocks better), it was coded as a facilitator. Conversely, if there was a negative effect (e.g., a student and a teacher entered the room. Jacob got distracted looking at them), the event was coded as a barrier.

Immediately after the last session, semi-structured interviews were conducted with Dylan and Edward's mothers and Jacob's teacher. They were interviewed since they were the people who had the most information about how the sessions went with the participants and could give a more complete picture about the use of the robot and the computer. The purpose of the interview was to understand their opinion about the features and use of the AT strategies. The interview contained ten questions. Some of the questions were: What do you think would be the challenges of using the robot/computer? What were some of the positive observations you saw while –name of participant- was using the robot/computer?

We conducted a second interview to seek their perceptions about how the AT strategies may be implemented in the participant's classroom, and the social environment surrounding the students when they use AT. The interview with Jacob's teacher was carried out six months after his last session, and the one with Edward's mother was one year after his last session. Dylan's mother did not participate in the second interview because it was not possible to contact her. This second interview had twelve questions. One question included in this interview was: What kind of barriers do you consider may affect the implementation of the robot/computer in – name of participant - classroom (e.g. funding, support, etc.)? The interviews were audio-recorded with the parents' and teacher's permissions.

Data analysis

The process of data analysis consisted of two phases. In the first phase, a cross-case analysis was conducted using content analysis to code data from interviews and observations. In a case study, a cross-case analysis can be used to identify common elements among the cases, as well as the unique attributes of each case [33]. The interviews, transcribed into a Microsoft Word document, and the observations in Microsoft Excel documents, were imported into NVivo 12 Pro[10] software to be coded. The data were analyzed using a conventional approach to content analysis [34]. This approach is used to classify and summarize descriptive qualitative data [34] and allows the researcher to examine data in a systematic way by reducing the text into fewer categories [35]. In this study, an inductive content analysis was used and the categories emerged as the analysis was carried out [35]. First, the data was coded to create open nodes. Then, the nodes were organized by subcategories, the subcategories were grouped into generic categories, and these were grouped into a main category. Main categories were named using content-characteristic words [35]. In the last phase, data triangulation was carried out to analyze the results according to the research question. From the observations, data on LEGO robot and computer program features, as well as physical setting, were triangulated. From the interviews, data on the use of the AT strategies and social environment while using them, were triangulated.

10. Manufactured by QSR International, 35 Corporate Drive, Burlington, MA 01803

Results

The results were organized by separating them according to the two parts of the research question, environmental facilitators and environmental barriers. Within these two parts, there were two main categories. The first category (A) was the results of the observations, and the second category (B) was the results of the interviews. Within each main category, there were three generic categories: 1) Robot, 2) Computer, and 3) Social environment. A fourth generic category, physical setting, was included when appropriate. Table 1 presents the main categories that emerged during the data analysis.

--- Insert table 1 about here ---

Environmental facilitators

A. Main category from observations: "Ways of using the strategies and modifications"

1) *Robot.* The research assistant implemented several modifications to help the participants to use the robot and thus be able to perform the mathematics tasks. For instance, with all the participants, the research assistant always brought the robot to the initial position when the participants finished completing the question, or when they were driving the robot in the wrong direction. With Edward and Jacob, although they could turn the robot to the left and to the right, it was observed that this action involved a considerable amount of physical effort. Therefore, the research team decided to adapt the use of the robot so the questions could be solved by only driving the robot forward. For instance, the research assistant placed the

manipulative on top of the robot, and the participant only needed to drive the robot forward to the location to place the manipulative, and the research assistant removed it. When this adaptation was implemented, the participants reduced the number of required switch hits, and there was a decrease in their physical effort.

During the sessions, the participants had several opportunities to play, and the robot seemed to be the most motivating. The research assistant created games with the concrete objects used in the lessons (e.g. making a poster), or provided time to play with the AT strategies at the end of each session. Most of the free play activities were performed with the robot, although Edward played with the computer a few times. The participants showed enthusiasm by smiling or providing yes responses when asked if they were excited to play with the strategies.

2) *Computer.* The participants answered the mathematics questions faster using the computer than using the robot. The participants accessed the computer programs through direct selection, except Jacob, who selected the options using switch scanning. With direct selection, the participants were able to directly select the answer on the screen without the need for additional steps, such as with the robot (e.g. driving the robot and opening the gripper). The average time to complete a question with the computer was 38 seconds and with the robot it was 3 minutes and 3 seconds. The lessons with the computer could be carried out in one session. In contrast, some of the lessons with the robot were done in two sessions because the participants could not answer the mathematics questions during the scheduled time.

3) *Social environment.* The research assistant who was conducting the mathematics lessons provided prompting when participants were controlling the AT strategies. For instance, with respect to the mathematics concept, if the participant made an incorrect answer, the research assistant worked through the participant's understanding of the steps to accomplish the

manipulative task. With respect to the control of the AT strategy, if the participant did not attempt to control the robot or computer, the research assistant reminded him what switch he had to press. These sorts of prompts were used in all lessons for all participants. The participants were also given assistance by the research assistant who often acted as “the hands” or “the voice” of the participants. For instance, he counted aloud while Edward pointed at the objects on the computer screen with the HeadMouse, or he pointed to the objects to ask Jacob which object was the heaviest.

The research assistant supported communication in many ways to reduce the cognitive load on the participants while they used the AT strategies. During the sessions, the most frequent communication modalities were gestures for Yes or No, or choice-making, where the research assistant named two choices and used his hands as place holders for each choice, and the participants indicated their choice by looking at one of the hands. In the case of Dylan, although he could speak, the yes and no gestures were frequently used. With Edward, though he was quite proficient with his communication device, the above modalities were used to reduce the cognitive-linguistic load while he was controlling the robot and computer. Jacob primarily communicated through yes or no gestures; therefore, the research assistant asked him closed-ended questions.

4) *Physical setting*. In all three settings where the study was conducted, a large table was present in the rooms upon which the robot, the computer, and the concrete objects were placed. The table had an adequate height so that the participants could see the AT strategies and objects properly. The AT strategies were placed on the table as close as possible to the participants. In the sessions, the research assistant ensured that the participants were able to see the robot by leaning towards the table so that his eyes were at the same height and line of sight as the

student's eyes. The participant indicated whether he could see the objects adequately. If that was not the case, the AT strategies and the objects were moved, or the participants were repositioned (e.g. the wheelchair was moved) until they could see the objects.

B. Main category from interviews: "Use of the strategies to enhance independence and participation"

1) *Robot.* The interviewees expressed as a positive outcome of the robot the opportunity that it offered to the participants to be able to manipulate objects. The parents and the teacher mentioned that they observed that the students had independence with the robot to move the objects according to what they wanted. Dylan's mother said*: "the robot was becoming that extra set of hands which was really neat to see […] he could choose between sorting the stuff with the robot."*

In addition, the parents expressed that the LEGO robot could potentially be a viable tool in the classroom for students with disabilities to do the same type of academic activities as their peers. Edward´s mother expressed enthusiasm for Edward to learn the same mathematical concept as his peers. She said: *"he is learning to do things [with the robot], the same things as everybody else but in a different way."*

2) *Computer.* The interviewees agreed that one of the main features of computer programs was their ease of use, which could promote their implementation in the school. Edward's mother pointed out that before he started the sessions, she thought that the robot was going to be the easiest strategy for Edward to control. However, after the sessions, she realized that Edward was faster completing the lessons with the computer compared to the robot: *"It is faster to use the computer. He does not have to look away from the screen to see and look back. It is always presented to him on the screen."*

Computer programs can also provide opportunities for students with disabilities to participate in the same activities as their peers. Dylan's mother emphasized that the use of the computer can help Dylan to play as a typically developing child while developing cognitive abilities: *"Dylan cannot play like other kids and we always need to find things to challenge him cognitively, and those computer games did that."* Edward's mother mentioned that he used a computer in his classroom along with his classmates and that he participated in the same academic activities. Although Edward was slower than his peers to control the computer, they had a strategy to wait for Edward to nod when he finished giving his answer and then continue with the next activity. Moreover, Jacob's teacher also used computer activities during her teaching instructions with her students with disabilities. Based on her experience, she commented on one of the advantages of using computers in the classroom: *"Students [with disabilities] are so used to living their lives as observers in life and not participants in life. There are so many things they can't engage in. So, it is nice to have something that they can feel they have control over it and participate well."*

3) *Social environment.* After seeing the benefits that the students gained from using the robot, parents considered using this strategy at home for play or for educational activities. Edward's mother contacted the authors to implement the robot at home. When asked about this decision, she mentioned that she would like to use the robot with Edward for play activities initially. She said: *"It would be mostly for play, and then, as time goes on when things like math and spelling become more difficult, or writing […] we would probably use it in different applications."* Furthermore, Dylan's mother was excited to implement the robot at home for learning activities. She said: *"When I'm watching you guys, I'm thinking I could do like*

alphabets and numbers and stuff and help him learn that way, because when you're putting stuff on the table he gets bored so easily and in this way you can keep him interested."

Regarding the use of the AT strategies at school, the interviewees reported that schools had a very supportive staff to assist the students and expressed the collaboration and willingness of school administrators to implement AT in students' learning. Jacob's teacher said: *"I think they [school administrators] will be very open to it [implementing the robot]. It is a really great school and they always want to try something new."* Edward's mother expressed that school administrators would be willing to include technical support or educational aides to facilitate the use of AT strategies in the classroom. She said: *"I know they are always welcome, they are always asking for people to come in and help teaching and to work with the staff, so everybody can become more independent and confident with using the technology."*

Environmental barriers

A. Main category from observations: "Challenging features of the strategies and environmental distractions"

1) *Robot.* It took more time to do the lessons with the robot compared to the lessons with the computer. As mentioned above, the steps needed to drive the robot to move the manipulatives and open and close the gripper took quite a lot of time. Plus, each time a question was answered incorrectly with the robot, the participants spent a great deal of time to re-do an answer in comparison with the computer. With the robot, the concrete objects and the robot had to be repositioned again, and the participants had to drive the robot to manipulate the objects to answer correctly. With the computer, participants could continue moving the cursor to the desired answer. In addition, a greater amount of time was needed to set up the robot and the concrete manipulatives compared to the computer. The average time to set up the robot was 4:27 minutes, and the computer was 00:58 seconds. Furthermore, the participants became fatigued

more easily in the robot sessions; thus, they sometimes requested to end the lesson, in which case, the session was stopped for the day.

Another barrier encountered during the sessions was issues with the robot control program. Often, the robot did not move when the participants pressed their switches or, on the contrary, did not stop when the switch was released. Usually, the research assistant solved these issues by restarting the robot control program. Although this did not affect the lessons in this case, it could be considered a barrier if non-technical teaching staff tries to implement the robot in the classroom. Because the research assistant had technical knowledge, he was able to solve any problems with the robot, but a person without this skill might not be able to implement the robot in academic activities.

2) *Computer.* The free virtual mathematics programs used in this study did not allow changing their configuration to fit the needs of the participants. For example, enlarging the size of target objects in the programs would be easier to point to with the HeadMouse. Also, there was no control over the mathematics questions of the programs. For instance, the computer programs that were used with Edward often repeated the same number, and numbers were usually less than 5. This is a disadvantage compared to the robot, where the research assistant had control over the type of question and asked Edward to do all the numbers from 1 to 10.

Another barrier, reflected in the field notes was identified when trying to find free online programs to use in the study. There were very few that could be controlled using the students' alternative access methods. As mentioned in the Materials section, in the case of Dylan and Jacob, it was not possible to find programs that could be controlled through switches about sorting or the in/out concept, respectively.

3) *Social environment.* The distraction of the participants when people other than the research team were in the room was a challenge. This was most evident with Jacob, where it was common for teachers or students to enter the room where the sessions were conducted because it was a therapy room. When people came into the room, Jacob turned his gaze away from the AT strategies to where the other people were. Therefore, the research assistant had to get Jacob's attention and explain the instructions again. With respect to Dylan and Edward, their levels of attention during the sessions were not affected by the presence of other people (e.g. researchers or mom). However, there was no opportunity to observe if they would have been distracted with some peers around them.

B. Main category from interviews: "Challenges with the strategies in terms of their use and implementation"

1) *Robot.* The only barrier that the interviewees noted about the robot was the amount of additional steps the participants had to carry out to solve a problem, in comparison with the computer. When asked about some challenges in using the robot, Edward's mother said: *"I thought that doing the LEGO robot was easier because it's fun, he enjoys doing it. But there's more he has to think about and manage. Where's he's going to drive it and that stuff."* She added: *"because there are extra steps, there is more cognitive load."*

2) *Computer.* One of the main concerns of the interviewees was that some computer programs may not be compatible with the student's abilities. The interviewees mentioned that it is difficult to find computer programs that students can access through their alternative access methods, or programs that are at a suitable speed for the student (e.g. programs without time limits). These factors could prevent students from showing their mathematics knowledge through the computer. Edward's mother said: *"We are constantly looking for [computer programs], but*

it's hard to find one that only uses point and click. A lot of them need keyboards and use arrows and all kinds of different things and that for Edward is too tiring."

3) *Social environment.* The lack of understanding about how to set-up and troubleshoot the LEGO robot was considered a barrier to implement this AT strategy in students' learning according to the interviewees. Jacob's teacher tried to download the LEGO Mindstorms commander program on her computer in her classroom, but was not successful. She was excited to implement this AT strategy with her students. Yet, due to her failed attempt with the program, she gave up on the idea. She mentioned: *"I tried to use the software on my computer, I can't make it work. So, if I was able to make it work, I would have felt that it would be a good activity for Jacob, but I haven't been able to connect it with my Bluetooth."* In the same way, parents also expressed issues when they tried to download the LEGO Mindstorms program at home. Edward's mother stated: *"We borrowed one [LEGO robot] from a friend and have not had a chance to set up it yet. It is difficult to download software onto Edward's tablet [communication device]."* Also, she pointed out that the main barrier to the implementation of the robot would be the: *"technology glitches. Especially for people who do not have a lot of background knowledge in programming, it could be really challenging for them. If anything goes wrong, they just don't use it."*

Another aspect that was considered a barrier to implement the LEGO robot in mathematics was the difficulty of being able to use it in a full classroom. Jacob's teacher said when asked if she would implement the robot with all of her students: *"It is hard because some of my students have visual problems, so they have to be close enough… So I would do it more as one-on-one or in a very small group activity just because the types of disabilities the students have."* In addition, she added: *"Most of my students would not have the coordination or the* *cognitive abilities to manage turn left, turn right, that sort of thing, using the robot. Jacob was a student who could understand those concepts; the other two students, they would use a switch but not necessarily… [understand how to turn the robot]. So, I would have to choose who are going to be in the robot activities."* Edward's mother mentioned that teachers would have difficulty implementing the robot in the classroom because they would not have enough time to download the program and try to understand how it works and how to incorporate it into their teaching lessons, she pointed out: *"they do not have time to sit and play with it while teaching a whole classroom; it has to work right away."* When interviewees were asked about the implementation of computer programs with the whole classroom, they did not mention any barriers. Teachers generally implement computer programs with most of their students with disabilities or without disabilities. Jacob's teacher said: *"I use computers with all my students and I will continue doing that."*

Finally, the topic of funding was also mentioned as a barrier at the institutional level to implement the robot at school. Jacob´s teacher stated: *"The devices we use with our kids are very cheap and not a lot of places have money for that [to buy a robot]."* In addition, she emphasized that the ability to buy a LEGO robot would depend on the school, she explained that *"the school I will move to has no budget, zero. It will be a very different experience compared to here."*

Discussion

This study aimed to explore the environmental factors surrounding students with physical disabilities when they used two AT strategies, a LEGO Mindstorms robot and a computer, in mathematics lessons. The products and technology, i.e., the AT devices, seem to be a major environmental factor that influenced their use in mathematics by the participants. Both the robot and the computer presented significant facilitators and barriers. Furthermore, the support from parents, school staff, and the research assistant, as well as school services and policies, and the human-made changes to the environment highlighted some facilitators and barriers that may affect the implementation of the AT strategies in the classroom.

Robot as environmental facilitator

An important environmental facilitator regarding the use of the robot was the students' opportunity to actively participate in the mathematics lessons. The robot promoted active participation by allowing independent manipulation of concrete objects. Also, the interviewees concurred that the robot seemed to give the students a sense of independence. Previous studies [8,36] have associated that independent exploration and manipulation of the environment may increase active participation of children with physical disabilities when using the robot in hands-on activities. Moreover, the interviewees mentioned that students could actively participate in the same lessons as their peers through the use of both devices. Similar results showing that AT can provide a means for children with disabilities to participate in the classroom in an active way were reported by Eriksson [3] and Huang, Sugden, and Beveridge [17]. Additionally, it is worth noting that participants were enthusiastic about using the robot as it enabled play actions and was used as a reward at the end of each session. The students' increased interest using the robot during mathematics lessons is consistent with previous studies [8,9]. Thus, the robot may be considered an effective way to enhance students' active participation and interest in mathematics activities, which favours its implementation in the classroom.

Robot as environmental barrier

Although the robot might enhance students' active participation, one environmental barrier was found in this study that may impact its implementation in mathematics. The participants required more time to complete a question using the robot than using the computer. With the robot, participants had to grasp the concrete manipulative, and then drive the distance between the start point and the destination, limited by the speed of the robot. The additional time required to complete a mathematics question with the robot could negatively affect its use in a regular classroom.

Computer as environmental facilitator

Regarding the virtual mathematics programs, an environmental facilitator that was observed and confirmed by the interviewees was that participants could solve the problems faster using the computer than using the robot. Dylan and Edward were able to quickly select the virtual manipulatives through direct selection. Performing mathematics tasks using a computer seems to be more efficient than other techniques commonly used in the classroom, such as worksheets [11,37]. However, although the participants' access methods allowed them to complete the lessons on the computer in an adequate time frame, the scanning technique presented some disadvantages for Jacob. Scanning was very laborious for Jacob due to the demand to press the switches repeatedly; therefore, he easily became fatigued, regardless of whether he was using the computer or robot.

Computer as environmental barrier

Despite the efficiency of using the computer in mathematics, two important barriers could prevent the usefulness of computers with virtual manipulatives in the classroom. The first barrier is that, because many virtual mathematics programs were incompatible with the alternative access methods of the students, teachers would have to design each of their lessons using accessible software. According to Case and Davidson [38], much of the student's success in using a computer will depend on how a program is designed, and programs are often designed without thinking about the needs of people with disabilities. This is one of the reasons why AT devices are abandoned, as there may be a lack of matching between the user's needs and the device features [6]. The second barrier of using the computer is the lack of control over online mathematics programs to configure them according to the academic level of the students. When the programs used with Edward presented small numbers, it was not possible for him to achieve learning of larger numbers. With the robot, the researchers had control of the questions and were able to challenge Edward's understanding of counting numbers from five to ten.

Support and relationships

In addition to the AT strategies themselves, this study also identified that support and relationships might be facilitators for using the robot and the computer for mathematics. The interviewees supported the idea of implementing the robot in the students' learning because they had observed the multiple benefits that this technology might provide in academic activities. Computers already had support from school administrators, teachers, and students to improve learning in the classrooms. Furthermore, the social support through positive reinforcements, prompts, support, modifications of the activity by the research assistant facilitated the participants completing the questions satisfactorily while decreasing the physical and cognitive load in using the strategies. In addition, the social support of the research assistant contributed to an increase in the level of engagement of the participants during the sessions.

The involvement of the school staff and parents about the implementation of the robot and the computer, as well as prompts and support given during the activities, are indicators that the AT strategies could be successfully implemented with students with disabilities in mathematics lessons. These factors have also been identified as positive indicators when implementing AT in classrooms [6,39].

However, a barrier that was presented in relation to support for using the AT strategies, especially the robot, is that teachers may find it challenging to provide specialized support or manage time for the student with disabilities to use the robot to do the same activity as typically developing students, as also identified in Encarnação et al. [10]. In this study, the research assistant gave prompting and assistance so that the participants could solve a question in a more efficient way; however, this implies that an adult would always need to be with the student to provide support while the student uses the robot. Furthermore, it may be difficult to use the robot with all the students at the same time in the classroom since there could be students with different skills or needs, or the teacher may not have time to set up the robot. Therefore, likely the best utilization will be in individualized lessons or small group activities designed for a specific group of students.

Another barrier identified is the lack of technical knowledge of teachers and parents on how to install the robot control program onto a computer and how to connect the program to the robot via Bluetooth. The fact that two interviewees had trouble downloading the program indicates that the people supporting the student may not understand how to solve technical problems with the robot control program that may arise while using it. Teachers who do not have technical experience might not consider the use of this strategy in the classroom. Training and knowledge of technology are important for staff to feel comfortable in supporting the student in the use of AT [27].

Services, systems, and policies

A significant barrier related to the education system that might adversely effect the use of the AT devices, particularly the robot, is the cost. The robot might be considered expensive for some schools or parents, and there may not be enough financial resources to buy it. The interviewees mentioned that the budget in each school varies, and usually the AT devices that are implemented in classrooms are cheaper than the robot. Although the cost of a LEGO Mindstorms robot could be considered low, CAD ~ $400, it could still be too high to be implemented in educational environments with insufficient funds or in a low-income family [40].

Natural environment and human-made changes to environment

Finally, there were factors in the physical environment in this study that were facilitators and barriers to use the AT strategies in mathematics. As environmental facilitators, the rooms where the lessons were conducted had a large table to place all the concrete manipulatives and the AT strategies, and the tables had an adequate height so the participants could see the objects while seated in a wheelchair. Thus, for implementation in classrooms, consideration should be made about if a suitable table can be set up, without causing too much disruption to the classroom layout. Adams and Cook [8] recommended adapting mathematics lessons so they could be accomplished on one or two desks in order to use the robot in a classroom.

A barrier with respect to the physical environment was the distractions presented in the environment. A clear example was the noise and the people present during the sessions, with distraction being more evident in Jacob. Reed, Bowser, and Korsten [41] emphasized that it is essential to identify if there are distractions in the environment when using AT in the classroom, since the students' ability to maintain interest in mathematics lessons or maintain concentration to use alternative access methods may negatively impact students' learning using AT strategies. The distraction in the therapy room may have been a factor that affected Jacob's ability to control the AT strategies.

Limitations and future research

This study has some limitations. One of the major limitations was the settings where the sessions were conducted. Simulated mathematical instruction was created in a controlled environment (e.g., rehabilitation facility, researcher as instructor, quiet space, no other students present);

therefore, it is not possible to establish whether the results will be applicable in a typical classroom setting. In addition, results might have been different if a mathematics teacher with several years of experience in the classroom would have planned and conducted the lessons, rather than the research assistant. Another limitation was the reliance on Yes and No questions by the research assistant for participants to indicate their response. Other modalities could have been implemented, such as a word/phrase board with vocabulary related to the mathematics activity or core words, or an eye gaze board where the student gazes at pictures, words, etc. attached to a transparent frame to make a choice [42]. By using different communication modalities, other comments could have been elicited from the participants. Finally, this study contains a small sample size due to the laborious process of recruitment for people with disabilities.

It is important to note that although there was diversity in the participants in terms of age and mathematics lesson, in qualitative research the use of non-probability sampling with a heterogeneous group allows for a wider picture of the phenomenon [29]. In qualitative research, the results are contextual and subject to individual characteristics and knowledge [33], therefore, it is not the intention to generalize the results of this study. However, the findings present some factors and characteristics that might inform other researchers and clinicians who want to implement the AT strategies used in this study.

Future research is needed to help address the identified barriers and explore other influences on use of the AT strategies. For example, instructions for students and school staff to use the LEGO robot in the class room could be developed, including guidance on handling the technical aspects. In addition, computer programs should follow the principles of universal design, resulting in software that can be used through different alternative access methods.

Future research could explore environmental factors in a classroom while a teacher is giving the mathematics instruction and the student is solving the problems while using the AT strategies. Moreover, future research should include personal factors and perspectives of students about the AT strategies and how that influences outcomes.

Conclusion

Each AT strategy provided different facilitators and barriers affecting their use in mathematics. The LEGO robot allowed manipulation of concrete manipulatives and the students were more engaged during the lessons when they used the robot than the computer. However, teachers may not know how to troubleshoot if problems arise with this strategy, and it may be considered expensive for some schools. The virtual mathematics programs allowed the students to solve the problems quickly in comparison with the robot, which can positively influence the participation of students with physical disabilities in the same activities as their peers. Yet, many of these programs are not designed to be accessible, nor was it possible to change them to match the lessons plans more precisely. Therefore, students with physical disabilities might have difficulties using these programs, and teachers may find it challenging to implement the computer in their mathematics lessons.

Parents and school staff had a positive perception of the use of both AT strategies to improve the academic performance of students with disabilities. However, there is still the need for future research to propose solutions to reduce the limitations that arise with both devices, so students with physical disabilities can use them in their classrooms.

Acknowledgements
To be completed after blind review.

Funding
This work was supported by the Social Sciences and Humanities Research Council of Canada Insight Development under Grant [230-2015-00876].

Disclosure of interest
The authors report no conflict of interest.

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Table 1. Main categories that emerged from the content analysis. The categories were divided into facilitators and barriers. The categories were also divided by data collection instrument (i.e. observations and interviews).

Data collection instruments	**Environmental facilitators**	**Environmental barriers**
Observations	Ways of using the strategies and modifications	Use of the strategies to enhance independence and participation
Interviews	Challenging features of the strategies and environmental distractions	Challenges with the strategies in terms of their use and implementation

Figure 1. Lego Mindstorms robot with a gripper to grasp objects that were placed on top of blocks.

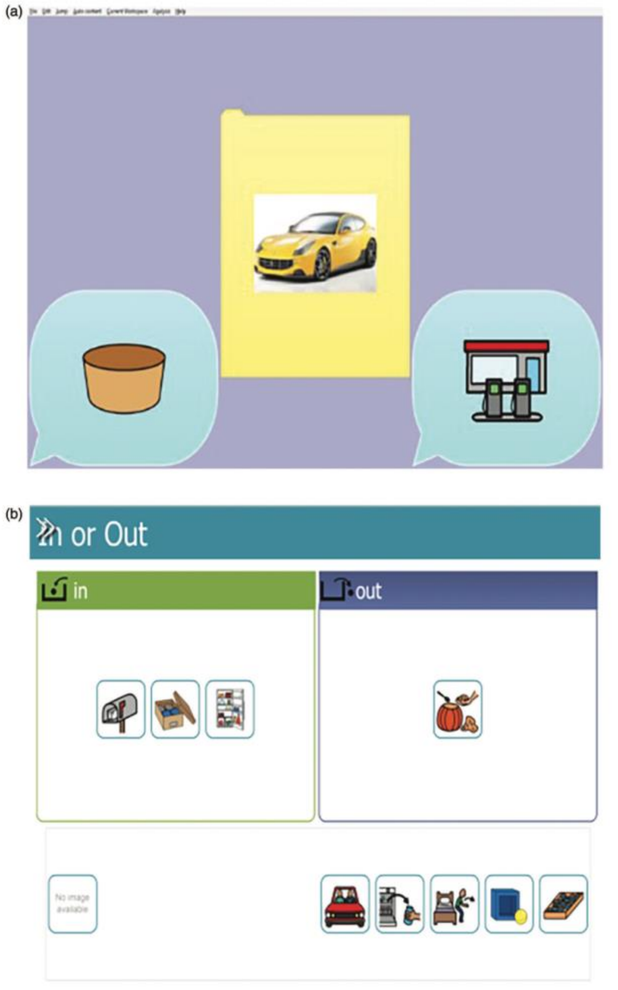

Figure 2. Virtual mathematics programs used with Dylan and Jacob. (A) Dylan's sorting lesson created using The Grid 2 software. The object to be sorted is in the middle, and the two categories are zoo and house, selected by pressing the left or right switch. (B) Jacob's in/out lesson created using Boardmaker™. The objects at the bottom are scanned with a switch and selected with a second switch, the chosen object is highlighted. Then, the in/out areas are scanned, and the desired box is selected. The highlighted object is moved to the area.