Using Inclusive Design to Improve the Accessibility of Informal STEM Education, for Children with Visual Impairment

by
Stephen Murgaski

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Abstract

In this research paper, STEM workshops are designed to provide experiences for twenty-five blind and visually impaired children at a summer camp, with STEM activities that are engaging and fun as well as educational. The aspiration is that the participants should have equitable experiences to their peers without visual impairment, so that they may get the same enjoyment from the STEM workshops as any other participants. Another research goal is to investigate the accessibility features of various commercially available robots, and consider the stability of accessibility features as robots are updated and replaced over time. An analytical autoethnographic approach and an Inclusive Design Model are used, which employ the researcher’s experience as a blind person and children’s feedback to inform ongoing design revisions to the Informal STEM Education activities. Children experimented with playing with and programming robotic toys such as a Bee-bot, Cubetto, Cubelets and Lego Mindstorm EV3, using modified mats and building materials. Video recording, group interviews and direct observation were the data collection tools used. Although all of the STEM education tools used in this study required at least some modification to make them more accessible for the participants, the amount of modification needed varied widely. Some tools were nearly accessible out of the box, while others could not easily be made accessible at all. This suggests many avenues for future research into the accessibility of tools for STEM education, especially robots. The inclusive design of some potential STEM education activities which were not tested, for lack of time, are also described.

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Chapter 1: Introduction

1.1 The Researcher and the Research Problem

In February, 2019, I began talking to administrators at the Canadian National Institute for the Blind (CNIB) about the possibility of running some workshops at the summer camps they organize for blind and visually impaired children. The purpose of the workshops would be to introduce some concepts related to coding and robotics in a way that would be fun for the children to engage. Such workshops have become very popular in recent years as the importance of learning about technology becomes increasingly clear. I was interning at a company, STEM Minds, which runs many such workshops for children, and we wanted to try to design versions of their workshops which would be accessible to children with limited or no vision, to try and give them the same experience as their peers with sight.

I was approaching the project as a student of Inclusive Design, but also as a person who is completely blind myself. This made it easier for me to arrange the workshops with CNIB, since I have been a client of theirs for many years. I knew the staff there from other events, so it was not as though I were cold calling them out of the blue.

I found, too, that there was no difficulty in convincing the organizers of CNIB's camps that learning about coding and robotics could be valuable for the children. Particularly because STEM Minds had generously agreed to run the workshops at no cost to CNIB, it was an easy sell. CNIB's main concern was whether or not we could succeed in running workshops that would be accessible and interactive for their campers. As one organizer explained to me, in the past an organization had visited one of her camps to present an activity about science, but the activities had been presented to the children as a series of demonstrations. She had received angry feedback from a seven year old girl who did not want adults to do science activities for her, because she wanted to do them herself. There was concern that we might fall into the same trap. I assured them that our goal was absolutely to run workshops in which the children would be able to participate, and that as a student of inclusive design and a completely blind person myself I was confident we could make that happen.

While my own visual impairment gave me some insights into designing STEM workshops to be inclusive of this group of users, in cases where the children were legally blind but had some vision, I was less well-equipped to intuit what sorts of designs would work for them. I also had no experience running STEM workshops for children. Fortunately, the staff at STEM Minds were available to answer my questions, and there is extensive academic literature about these topics, from which I could draw for guidance.

My role in the project, then, became to research and help design workshops that could engage children with visual impairments in learning about STEM, and to collect and analyze data about our effort. I also did a lot of liaising with various groups around the project. I didn't facilitate the workshops myself, although on two occasions I worked with small groups of campers on specific activities. But the primary facilitator of the workshops was always a member of the STEM Minds staff, which was a huge benefit because with a novice facilitator it would have been much more difficult to assess the effectiveness of the activities.

1.2 An Overview of STEM Education

STEM is an acronym which stands for science, technology, engineering, and mathematics. It is an acronym which has gained a great deal of popularity in education in recent years; perhaps as a consequence of that, educators understand it to mean a wide variety of things (Breiner et al., 2012). Further muddying the terminological waters, sometimes, terms such as **science education** or **technology education** are used interchangeably with STEM education (English, 2016; Williams, 2011). Finally, some have argued for using the acronym STEAM instead of STEM, in order to include Arts among the traditional STEM subjects (Bequette & Bequette, 2011). Simply for the sake of consistency, I will use the acronym STEM throughout this paper.

In general, the goal of STEM education is to remove the silos that have traditionally been placed around the subjects of science, technology, engineering, and mathematics, allowing students to understand and apply STEM knowledge as an integrated whole (Zollman, 2012; English, 2016). A popular method for achieving this kind of education is known as problem-based learning, or project-based learning, both represented by the acronym PBL. Students are challenged to solve a real-world problem, such as what sort of bridge should be built across a particular river (English, 2016), or how to program a robot to perform a particular task (Kabátová, 2012). This PBL approach has even been used to introduce STEM to preschool children as young as 3, who were given challenges such as helping a stuffed animal named Problem Panda to extract a ring that is trapped in a block of ice (John, 2018). In all these examples students worked in groups to apply concepts from the

STEM disciplines to solve a problem. For example, rather than calculating the cost of different types of bridges in a math class and the structural characteristics of different types of bridges in an engineering class, students were challenged to balance those considerations as a real-world planner would have to do.

While this kind of education has much to recommend it, it has proven difficult to implement in classroom settings. The reasons given for this are many, but the difficulty might be most succinctly stated by John Williams (2011) when he writes that "The rigidity and resilience of the school curriculum structure should not be underestimated when proposing reform" (p. 37). Partly in order to fill this gap, many organizations outside of the traditional school system are offering educational experiences in STEM topics such as coding and robotics. This field is often referred to as **informal STEM education**, or **informal science education** (ISE), and it has a vibrant community of practitioners and researchers participating in it (National Research Council, 2009; https://www.informalscience.org/). The workshops for children offered by STEM Minds Corp., where I was a research intern while preparing this paper, could be classified as informal STEM education (ISE).

ISE experiences, like the robotics workshops I helped design at STEM Minds, are different from the formal education experiences usually provided by schools in a few important respects. ISE is generally voluntary for the participants, so it needs to be engaging. In fact, awakening curiosity about and interest in STEM is often a primary goal of ISE projects (Allen & Peterman, 2019). This makes the effectiveness of ISE projects notoriously difficult to evaluate, since the outcomes being sought are often very individualised (National Research Council, 2009, p. 11). This does not mean that the outcomes being pursued are less valuable, but simply that they are less easily measured (Allen & Peterman, 2019). As a consequence of this difficulty, I will rely heavily on quantitative data to support conclusions in this study.

1.3 Technology and Disabilities

While most people benefit, personally and professionally, from understanding how technology works, this is likely to be even more true for people with disabilities. There are a wide range of "assistive technologies" available to help people with disabilities overcome specific challenges, such as electric wheelchairs, screen reading software, and hearing aids. Learning to use these technologies effectively, however, is rarely a straight forward process. It can require life-long learning on the part of the person with the disability, as new advancements in assistive technologies are constantly changing the available options. The potential of these tools is also more likely to be realized if the person with the disability has a level of comfort and familiarity with technology, and a willingness to engage with it on a fundamental level.

As informal science education projects are increasingly used to introduce children to the STEM disciplines, it is really essential that they not exclude the people who are likely to rely on technology even more than the general population relies on it. Knowing this gave extra impetus to our work of designing inclusive activities for children who are blind and visually impaired to engage with STEM topics. If we can discover any general principles which could aid similar organisations and corporations in designing such activities, that would be a valuable contribution to the endeavour of STEM education.

Chapter 2: Literature Review

2.1 STEM Education

It is not a new idea to suggest that the way science-related topics are taught in schools, as separate disciplines, obscures the many ways in which they overlap in practice. Back in 1903, the retiring president of the American Mathematical Society, Eli Moore, delivered this passionate complaint in his farewell address:

> *Engineers tell us that in the schools algebra is taught in one water-tight component, geometry in another, and physics in another, and that the student to appreciate (if ever) only very late the absolutely close connection between these different subjects, and then, if he credits the fraternity of teachers with knowing the closeness of this relation, he blames them most heartily for their unaccountably stupid way of teaching him. (P. 415)*

Rather than teach science and mathematics in these separated, “water-tight components,” Moore proposed a program of teaching he called a “Laboratory method.” (1903, P. 417) His proposal sounds very much like what is now called problem-based learning, or sometimes project-based learning (PBL), and the arguments he used to justify his proposal are remarkably similar to those given by many STEM advocates over a century later.

Writing in 2012, Alan Zollman gives a modern version of Moore's position, using the term STEM to refer to science, technology, engineering, and mathematics. "the STEM areas cannot be viewed as independent silos of content. For example, there cannot be a separate engineering curriculum and a technology curriculum. STEM should be viewed as a metadiscipline, the creation of a discipline based on the integration of other disciplines" (P. 15) Similar positions in favour of teaching STEM in integrated ways are given by many other contemporary researchers. (English, 2016; Singer, 2011; Stohlmann, 2012)

Even those who are more cautious about the benefits of teaching STEM subjects as an integrated whole tend to agree that the idea has merit. Nasr and Ramadan (2008) compared a group of engineering students who were taught using problem-based learning to a control group taught using more traditional subject-based learning, and found that students using PBL scored higher on the final exam and said that they preferred the PBL method. However, they did note that the problem-based learning took more class time and required more student-teacher interaction. (2008)

In another project, Barak and Assal (2018) used robotics activities to teach STEM concepts to underprivileged junior high school students in a village in Israel. Although they found that all students came away from their course highly motivated to learn STEM, they emphasized the need to scaffold the experience with more traditional, less engaging, explanations of fundamental concepts. Otherwise, they warn, instead of learning by doing, students may be "doing without learning". (P. 122) They also found that about half of the students needed what they called "extensive assistance" from teachers to complete the robotics projects comprising their course. (P. 141) But despite these cautions, they note that when students successfully programmed a robot to drive through a maze and blow up a balloon at the end of it, "One could see that the sound of the balloon blowing up in the class was worth more than a thousand words of praise from the teacher or a good grade in the course." (p. 133)

In these above-mentioned projects, the researchers had access to the same group of students over a number of weeks, and the education they provided was quite structured. Nasr and Ramadan (2008) describes a STEM course that was run in a school, which may be considered a formal education environment. In the project described by Barak and Assal (2018) student participation may have been more voluntary than in formal schooling, but their project could likely be categorized as what Bilandzic (2016) refers to as "nonformal education." In nonformal education, he explains, "the learner implicitly controls the learning goals, but the means to how these goals are achieved are controlled by the institution, e.g. through a predefined learning agenda or milestones" (P. 160). At the end of both of these projects the students were given a formal exam to evaluate their learning, and in Barak and

Assal’s project it was possible to compel students to learn concepts via formal teaching methods in order to scaffold the robotics activities in which they participated.

A third style of STEM education, distinct from both formal and nonformal, is referred to as informal STEM education (ISE). ISE includes things such as afterschool STEM activities, community and youth groups, exhibits about STEM at museums, and websites and documentaries about STEM. ISE can overlap with and complement formal STEM education, for example when school students go on a field trip to a zoo. But it is designed to be a voluntary learning experience. As explained by Crane et al. (1994), the “distinguishing characteristic [of ISE activities] is that they were developed for out-of-school learning in competition with other less challenging uses of time” (as cited in Hofstein & Rosenfeld, 1996, P. 90).

Although these approaches to teaching STEM have many goals in common, the necessity for informal teaching methods to be attractive to students sets it apart from the other approaches in some important respects. Since the workshops I set out to design were taking place at summer camps for children, they had to rely on informal education methods. Therefore, I will review some more literature relating specifically to these types of projects.

2.2 Informal STEM Education

In fiscal year 2017, the Canadian government allocated $50 million for a new program called CanCode, which provides government funding to not-for-profit organisations which teach STEM. In 2019, it announced an additional $60 million for the CanCode program, bringing the total to date up to $110 million (“Government of Canada announces,” 2019; Innovation, Science and Economic Development Canada, 2019). This is arguably a new direction for Canada, which had previously done little to teach STEM disciplines in integrated ways (Expert Panel on STEM Skills for the Future, 2015, p. 97; Ding & Lehrer, 2018). Because the new CanCode program allocates funding to not-for-profit organizations whose programs are “designed to complement educational curricula and to promote, encourage and spark awareness and interest in coding and digital skills more broadly,” (“Government of Canada announces,” 2019, section Quick Facts, bullet point 4) the CanCode program is funding informal STEM education.

For a description of a program being funded by CanCode, see as an example the Toronto Star newspaper article entitled “How this University of Toronto STEM camp is inspiring girls to become engineers” (Kwong, 2019). Women are traditionally underrepresented in STEM fields (Expert Panel on STEM Skills for the Future, 2015, p. 32), so this camp sought to ensure that half of the school-aged children participating in it were girls, and included women as facilitators. The article describing it quotes feedback given by two student participants: "The female leaders make it fun when we do crafts and solve problems;" and "I do want to be an engineer when I grow up. I think it's fun to make stuff" (Kwong, 2019, paras. 9 and 15) Seeking to increase engagement and interest in STEM, particularly among groups who are underrepresented in the field, is a frequently expressed goal of ISE projects (Friedman, 2008, p. 20)

In the United States, where STEM education has received much more attention and funding than in Canada (Krug, 2012), there has been persistent controversy around the challenge of how to evaluate informal STEM education projects. This is because learning in ISE projects is typically "self-directed, idiosyncratic, and highly personal," making it difficult to measure by traditional methods (Allen & Peterman, 2019, p. 19). In addition to concerns over the difficulty of doing effective evaluation, there are concerns that even attempting to evaluate ISE projects risks undermining the primary goal of many of them. For example, if learning objectives are clearly defined, as in formal education, ISE project facilitators might feel compelled to "Teach to the test," at the expense of allowing students to pursue and develop their own interests in STEM (Allen & Peterman, 2019, p. 22; Krishnamurthi et al., 2013). Formally testing the knowledge of participants in an ISE project could also cause them anxiety, undermining the goal of creating an engaging STEM experience. (Friedman, 2008, p. 37)

For agencies which fund informal STEM education projects, however, developing concrete measures for evaluating their effectiveness is a priority. In a report on the views of stakeholders in afterschool ISE programs, Krishnamurthi et al. (2013) found that funders of ISE programs were "Much more positive" about the availability of tools for assessing the effectiveness of the programs than were the people providing those programs (p. 23). In particular, the National Science Foundation, which funds many ISE projects in the United States, emphasizes the need for evaluation of ISE project results to "enable others to build upon the results of prior work and further the state-of-the-art," as well as "To help NSF better understand the impacts of its investments" (Friedman, 2008, p. 8). But it is clear that this need for clearly-defined, measurable objectives can cause tension for providers of ISE programs:

> *The truth is that many project teams begin with an idea of what they want to do (create an exhibition, design a community literacy project or produce a giant*

> *screen film) before they think about why and for whom they want to do it. Ideally however, this is not the case and even if it is, . . . NSF guidelines now encourage, in fact, require the backward research design approach. You first think about what you want to accomplish with the target audience you feel you can best reach and then describe how the particular type of project will enable these outcomes (Friedman, 2008, p. 23).*

2.2.1 Evaluation Methods for Informal STEM Education

Work is being done to try and develop methodologies which can achieve a compromise between the competing needs for flexibility in the implementation of ISE projects, and reliable ways of evaluating their outcomes. Fu et al. (2019) consider several tools that are currently being used to collect data about these projects, and draw some useful distinctions between them. They posit that tools can fall on a continuum from “direct” to “indirect,” depending on whether they collect data about participants directly, or collect data which is self-reported by participants. For example, video recordings and tracking systems can measure participant behaviour directly, whereas interviews and surveys collect data which participants report about their experience. Fu et al. (2019) acknowledge that data about some aspects of experience, such as self-concept and identity, may only be possible to measure indirectly; but they argue that self-reporting is prone to effects such as “participants knowingly or unknowingly trying to please the evaluator” (p. 37), and so they caution against relying on it exclusively.

A second useful distinction identified by Fu et al. (2019) is between “obtrusive” and “unobtrusive” data collection methods. They point out that new technologies are making it increasingly possible to gather data about participants in ISE projects without disrupting the flow of their participation. These unobtrusive methods, such as video recording and the use of sensor-based tracking systems, are increasingly being complemented with software tools which can automate the analysis of the copious amounts of data they tend to generate (Fu et al., 2019). Improvements in the ease of use of this software, and reductions in its cost, are making it increasingly available to researchers (Allen & Peterman, 2019, p. 25). Problematically, the use of unobtrusive data collection methods can also create new ethical challenges of privacy and consent. Institutional review boards will need to consider these issues when deciding whether to approve research proposals. (Allen & Peterman, 2019) However, they offer the tantalizing potential to generate data without relying on more intrusive collection methods, such as surveys and examinations, which threaten to undermine the fun factor in ISE projects.

While unobtrusive data collection methods undoubtedly enable the gathering of large amounts of direct observations about the behaviour of participants in ISE projects, the interpretation of this information by researchers remains a significant challenge. As Allen and Peterman (2019) state, “the main challenge of the analysis is to interpret the intentions, understandings, and reasoning that underlie participants’ actions” (p. 24). Some innovative attempts to develop standard methods for evaluating such ambiguous data have been developed. For example, Friedman (2008) proposes a number of behaviours which could be presented as evidence of engagement with, or interest in, an ISE project. These behaviours include: increasing use of emotion-laden words, such as “awesome” or “Cool;” asking more questions; and spending more time doing the project activities (Friedman, 2008, p. 78). If a stated objective of an ISE project were to generate interest/engagement in STEM, as is often the case, then researchers might be able to adduce evidence of success from video recordings of participants by looking for such indicators of engagement.

While these less obtrusive data collection methods may hold promise for the future, Fu et al. (2019) find that at present they are underutilized by ISE project practitioners (p. 37).

2.3 The Value of STEM Education

A frequently expressed justification for emphasizing STEM education is that it will best prepare students to thrive in economies that increasingly require technological skills. For example, one report prepared for members of Congress of the United States asserts that “The jobs of the future are STEM jobs: The demand for professionals in STEM fields[7] is projected to outpace the supply of trained workers and professionals. Additionally, STEM competencies are increasingly required for workers both within and outside specific STEM occupations.” (Committee on STEM Education, 2013, p. VI) In a similar vein, Canada’s Minister for Innovation, Science and Industry, Navdeep Bains, announced funding for Canada’s CanCode program by explaining that “Our government is investing in a program that will equip young Canadians with the skills they need for a future in which every job will require some level of digital ability” (Innovation, Science and Economic Development Canada, 2017, Para 5).

Although this economic justification for STEM education may make intuitive sense, it has proven difficult to establish through quantitative methods. Xue and Larson (2015) analyzed statistics about the labour market in the United States, and found surpluses of qualified applicants in many STEM fields, and shortages in only some. Data about the Canadian labour market is similarly ambiguous, causing a Canadian report to note that

> STEM skills have been advanced as central to innovation and productivity growth, which are in turn necessary for improving standards of living. While the general reasons behind this logic are clear, the Panel had difficulty finding direct and robust evidence that STEM skills are unique in this regard. (Expert Panel on STEM Skills for the Future, 2015, P. 6)

But perhaps these quantitative measures are too narrow to adequately capture the benefits of STEM education. The statistics they rely on measure only those who pursued formal education in a STEM field, which both underestimates the number of people who learn STEM informally, and confines the analysis to the siloed categories of traditional schooling. For example, Xue and Larson note in their study that “In certain cases, it does not even matter whether a candidate has a bachelor’s degree in a specific area: companies[39] are looking for candidates with hands-on experience in software development through “hack-a-thons,” extracurricular projects, and internships” (Section Shortages, para 2). Informal STEM education is often designed to provide exactly those hands-on experiences, and to encourage participants to pursue lifelong learning of STEM (Allen & Peterman, 2019, p. 18). Canada’s Expert Panel on STEM Skills for the Future was also undeterred by the ambiguity of statistical evidence for a shortage of STEM graduates, stating that “After 18 months of study, we are convinced that high-quality investments in STEM skills . . . are critical to Canada’s prosperity” (p. 7).

Beyond the purported economic benefits of STEM education, many have noted potential civic benefits. Rudolph (2020) suggests that anti-science movements in the United States have had detrimental political impacts on issues such as vaccination, climate change, and the spread of covid-19. He suggests a need for science education whose goal is “helping the public see that reliable knowledge exists and to understand the process by which society arrives at that knowledge” (p. 902). This understanding of science as a part of daily life is often referred to as “STEM literacy,” and promoting it is an explicit goal of STEM education (Peterson, 2017; Expert Panel on STEM Skills for the Future, p. 6).

Other authors describe the sense of agency which learning STEM can confer on its students. Eguchi (2017) emphasizes that by gaining a deep understanding of how technologies are constructed and programmed, students of STEM can move beyond being consumers of technology to becoming makers of it. A practical example of this is described by Bilandzic (2016), in his account of a weekly meetup group known as “Hack the Evening” which congregates in a library in Australia. In Bilandzic's account, the group works very collaboratively on do-it-yourself technology projects, and often continues its meetings at a local snack bar after the library closes. It is an example of a culture in which people draw on one another's knowledge to design and build new technologies.

For those of us with disabilities, however, participation in activities designed for the general public is often challenging. This is particularly unfortunate in the case of ISE projects which empower people to build our own technologies to suit our personal needs. Richard Ladner (2015) explains that when people with disabilities participate in the process of designing technologies which are meant to assist us, the resulting products are more effective. This is also a fundamental premise of inclusive design. Additionally, Ladner (2015) gives many examples of technologies which were originally designed to help people with disabilities, but which later proved to have much broader applications than originally intended. For these reasons, and many others, intentionally designing ISE projects to be inclusive of people with disabilities is an important goal.

2.4 Accessibility

In her book Mismatch: How Inclusion Shapes Design, Kat Holmes (2018) advises that "Inclusive design should always start with a solid understanding of accessibility fundamentals" (p. 55). Accessibility may be defined as the "extent to which products, systems, services, environments and facilities can be used by people from a population with the widest range of user needs, characteristics and capabilities to achieve identified goals in identified contexts of use" (International Organization for Standardization [ISO], 2018, p. 1). While this goal of making things usable by people with the widest possible range of user needs is admirable and ambitious, in practice accessibility is often approached by attempting to comply with various accessibility standards, such as those defined in the Web Content Accessibility Guidelines (WCAG). This may be because accessibility is often encountered as a legal issue, despite in fact being a larger human problem which can be more effectively considered in broader contexts (Feingold, 2017).

While complying with accessibility standards is an excellent start for improving the accessibility of products and services, it is only a starting point for creating accessible experiences. The ISO elucidates this clearly, and defines a useful three-level framework for considering accessibility:

1) Technical: At the technical level of accessibility experience, a system meets specified accessibility guidelines and accessibility requirements.
2) Effective and efficient: A system goes beyond a technical level of accessibility experience to ensure that diverse users can effectively and efficiently complete their user tasks. While the effective and efficient level is a necessary prerequisite to satisfaction, it does not consider whether or not a user will be sufficiently satisfied to actually use the system. . . .
3) Satisfying: A system provides satisfaction when it provides equitable experiences to diverse users in diverse contexts. This goes beyond effectiveness and efficiency to ensure that the user's experiences are satisfying/enjoyable. (ISO, 2019, pp. 12-13)

For this particular project, using inclusive design to create accessible experiences of informal science education for children at summer camps, it would be necessary to achieve the highest level of accessibility. The experiences must be not only doable for the children, but also equitable to the point where they could derive as much enjoyment from them as children without visual impairment. In order to reach this level of accessibility where satisfying experiences are possible, however, it might first help to consider the technical standards which are often used to achieve prerequisite levels of fundamental accessibility.

2.4.1 Web Content Accessibility Guidelines

One of the most influential standards for determining accessibility has been the Web Content Accessibility Guidelines (WCAG), now at version 2.1. Although designed for improving the accessibility of websites, WCAG has been found to be more broadly applicable than originally intended (White, 2019). While its specific advice is certainly tailored to web design, it also defines high-level accessibility principles which may be broadly useful for considering accessibility in unrelated contexts.

The organisation of WCAG is very hierarchical. At the top level are the four general principles which need to be met, in order to improve the accessibility of websites for people with a wide range of disabilities. Beneath those top-level principles are a total of twelve more specific guidelines, and each guideline also has a very specific set of “Success criteria” associated with it (Web accessibility initiative, n.d., Layers of guidance section). Each success criterion is testable, as pass/fail, and examples of how to fix common causes of failure are given for each success criterion. All of this enables web pages to be tested very precisely to check their conformance with WCAG, and the degree of conformance can be expressed as a sort of grade: A, AA, or AAA.

It’s worth reiterating that even in the case of webpages, technical compliance with the WCAG standard is not enough to ensure an equitable experience of the page for people with disabilities. But checking for compliance with standards is an important step in the process of becoming accessible. Although the specific success criteria defined by WCAG would be difficult, or impossible, to apply to things other than webpages, the four top-level principles of accessibility that it defines may be worth considering in more detail. The four principles are perceivable, operable, understandable, and robust, and they can be explained as follows:

1. Perceivable - Information and user interface components must be presentable to users in ways they can perceive.

◦ This means that users must be able to perceive the information being presented (it can't be invisible to all of their senses)

2. Operable - User interface components and navigation must be operable.

◦ This means that users must be able to operate the interface (the interface cannot require interaction that a user cannot perform)

3. Understandable - Information and the operation of user interface must be understandable.

◦ This means that users must be able to understand the information as well as the operation of the user interface (the content or operation cannot be beyond their understanding)

4. Robust - Content must be robust enough that it can be interpreted reliably by a wide variety of user agents, including assistive technologies.

This means that users must be able to access the content as technologies advance (as technologies and user agents evolve, the content should remain accessible) (Web Accessibility Initiative, n.d., Understanding the four principles of accessibility section)

White (2019) discusses how the WCAG principles have been applied to electronic media other than websites, and argues “That such alterations were feasible without substantially revising the standard is indicative of the universality inherent in WCAG” (p. 2). I would like to push this argument beyond electronic media entirely, and consider whether the universality of WCAG’s accessibility principles makes them applicable even to physical objects such as toy robots.

2.5 Robotics for Students with Visual Impairment

Along with the proliferation of informal STEM education initiatives has come a growing number of robotic toys designed to teach STEM concepts to children. Through the partnership with STEM Minds Corp., I had access to several of these toys for use in inclusively designing ISE activities for the CNIB camp workshops. A few of the toys that were available to us had been used previously in research studies involving students with visual impairment, so those studies were a rich source of ideas. As well, sometimes studies which used different robotic toys from those we had available could still provide valuable insights into designing activities for this group of users.

In one such study, Milne and Ladner (2018) described how they introduced STEM to children with visual impairment using a robotic toy called Dash, to which we did not have access. They wanted to provide audible feedback to their participants when the Dash robot completed a programmed task successfully. Therefore, they designed an activity in which the goal was to program Dash to knock over a series of towers made out of wooden blocks. The noise of the falling towers would provide feedback that the program had been executed successfully. Milne and Ladner (2018) reported that “All of the children thought this was quite fun” (p. 6).

Some other studies with visually impaired participants used robotic toys which were also available to us, and so their findings were potentially even more applicable to our project. Below are summaries of findings from some of these studies, categorized by the particular robotic toy that they used in their activities.

2.5.1 Bee-Bots

Bee-Bots are small plastic robotic toys, 12.5 x 10 x 7.5 cm in size (Génération Robots, 2020) manufactured and distributed by TTS and Brault & Bouthillier. They are very approximately bee-shaped, and colorful. There is no screen on the Bee-Bot. To program them, children can press buttons on top of the toy in a sequence which the Bee-Bot stores in memory, and then the sequence of commands is executed when the Go button is pressed. Bee-Bots are designed to work with a clear plastic matt which has colored grid-lines on it; each time the Bee-Bot drives forward, it advances a distance equivalent to one square on the plastic matt. See Figure 1: Bee-Bot

Figure 1: Bee-Bot

Kabátová et al. (2012) describe using Bee-Bots to teach informatics at a school for visually impaired children, in Slovakia. They found the Bee-Bot to be very accessible for children with visual impairment, in part because of the design of its buttons (Kabátová et al., 2012, p. 24). They note that in addition to being different colors, the buttons which control Bee-Bots are embossed with raised symbols, and they are also different shapes. This makes the control buttons tactilely distinguishable. Although the lines on the plastic matts were not raised, so impossible to perceive by touch, they modified them by placing tape and cardboard over the lines.

Finally, Kabátová et al. (2012) placed high-contrast picture cards under the clear plastic squares of the Bee-Bot matt, and used these pictures to create activities such as “collect the flowers, visit friends” (p. 24). This would require children to enter a correct sequence of commands into the Bee-Bots, to make them drive first to the square with the picture of flowers, and then to the square with a picture of friends. However, they found that some children with visual impairment had difficulty seeing these pictures, and the large size of the mats made it difficult for some of them to perceive enough of the squares at once. For children who are completely blind, of course the pictures on cards would not have been perceivable at all.

2.5.2 Cubetto

Although the Cubetto robot looks very different from the Bee-Bot, functionally they have some striking similarities. Cubetto is a wooden cube with an engraved face on the front of it. This cube drives along a path defined by a sequence of commands, input by the user, and it is designed to drive on a clear plastic matt with grid-lines (Solid Labs LTD., 2020). Like the plastic mat used by Bee-Bot, the squares on Cubetto’s plastic matt are 15 X 15 cm in size; and Cubetto also has no screen, which negates many accessibility concerns for users with visual impairment.

One appealing feature of Cubetto is that the sequence of commands, which controls what path the robot will drive, is constructed by placing wooden blocks onto a “Control board.” Cubetto comes with four different kinds of wooden “Action blocks:” go forward, turn left, turn right, and execute function (Solid Labs Ltd., 2020). One part of the control board is designated for defining a function, which is a sequence of commands that can be triggered at any point in the main program by inserting an Execute Function block at that point.

The manufacturer of Cubetto, Primo Toys, has posted a case study of one visually impaired child using Cubetto on their website (Primo Toys, 2016). Some positive features of Cubetto for this user, they state, were that the robot makes an audible chime when turning on, and that the interface for programming it is a large wooden board with tangible blocks. In their case study, an instructor was working with the visually impaired student one-on-one, helping him build programs on the control board. But they state that “after initial support from the facilitator, [the student] indicated his excitement with his success in programming Cubetto, ”by myself!””.

2.5.3 Lego Mindstorms

Unlike the previously described robotic toys, Lego Mindstorms are kits which can be used to construct numerous different programmable robots. A major difficulty I encountered, when researching these kits, is that the Lego Mindstorms NXT kits are substantially different from Lego’s more recent version of the product, Mindstorms EV3. At STEM Minds, I had access to only the more modern EV3 kits, but most of the studies I found described using the NXT kits with visually impaired students. The STEM Minds staff and I were hopeful that the approaches used with those older kits would still work with our equipment, but this was often not the case.

Despite these difficulties, Lego Mindstorms kits offer many tantalizing potential benefits. Because they allow for both the building and programming of robots, they enable exploration of engineering and coding concepts at a more sophisticated level than robots which come preassembled. Lego Mindstorms kits are also used in a wide range of educational and informal education settings, including K-12 classrooms, university courses in computing and engineering, and informal competitions organized by First Lego League (Ludi & Reichlmayr, 2011, p. 25; Böhlmark & Li, 2020). People with visual impairments would typically be excluded from these Lego Mindstorms activities, because the kits are not accessible to us out of the box. But there are examples of the kits being used successfully without vision, such as by a team from a school for the blind which competed in a First Lego League robotics competition using Lego Mindstorms NXT (Texas School for the Blind and Visually Impaired [TSBVI], 2017).

The Lego Mindstorms kits consist of a “Brick,” which controls the robot; a variety of different motors and censors, which connect to the brick via cables; and structural pieces which can be used to build a wide range of robots (Lego Group, 2015). The brick has a small screen and a number of buttons, which can be used to navigate through menus and set various options. See Figure 2: EV3 Lego Robot. The brick can also be programmed, by writing code on a computer or tablet and transferring that code to the brick. In this way robots can be constructed and programmed to behave in almost limitless ways.

Figure 2: EV3 Lego Robot

Ludi and Reichlmayr (2011) ran a series of workshops for visually impaired young adults using Lego Mindstorms NXT robots. Rather than have students build the robots, they focused on getting students to program them. The apps which Lego makes available for programming its Mindstorms robots use very graphical interfaces, which are not accessible without vision, so Ludi and Reichlmayr set out to find a different software package which would meet the accessibility needs of their project. They selected an open-source programming environment, called BricxCC, which now, in 2020, has not been updated in several years.

One striking thing about Ludi and Reichlmayr’s (2011) study is the systematic way in which they defined accessibility requirements for the activities they were designing. Two of their high-level requirements stood out for me particularly: “Regardless of whether a participant has no vision or low vision, the activities must be able to be accomplished by all;” and “Since teams of students would be working together, the auditory and visual presentation must be able to be conducted simultaneously” (p. 25). They then developed a more specific, technical set of requirements which would be needed to achieve these high-level requirements. They assessed the software package they had chosen to see whether it met their technical requirements, and found it adequate (p. 27).

Nevertheless, since the software package they chose was created and maintained by volunteers, it is no longer available. In a later study, Ludi (2014) reports on using a custom-built accessible programming environment to program Lego Mindstorms robots with blind and visually impaired young adults. This environment, developed by Ludi and others, could be used with NXT Mindstorms kits and worked well with screen reader and screen magnification software (Ludi, 2014).

One reason Ludi and Reichlmayr (2011) chose to focus on teaching participants how to program Lego Mindstorms robots, rather than building them, was an absence of building instructions which can be understood without vision (p. 25). Lego's building instructions tend to be heavily dependent on readers being able to interpret pictures. This problem was to some extent overcome by Lindsay (2020), in a study which allowed young adults with a variety of disabilities to build Lego Mindstorms robots. Lindsay (2020) used strategies such as "one-to-one support with prompts, reminders, and behavioral assistance," so that instructors could help the participants to complete their robots (p. 58). Although feedback on those workshops was generally positive, Lindsay (2020) reports that at least three participants said they would have preferred more flexibility in being able to design and create robots, as opposed to simply following instructions (p. 60).

Despite these challenges, the many opportunities which being able to use Lego Mindstorms kits would make available, makes them a compelling research topic.

Chapter 3: Methodology

In this research, I have followed an analytical autoethnographic approach, as described by Leon Anderson (2006). As a completely blind person attempting to design STEM workshops for other people who are blind and/or visually impaired, I am what Anderson (2006) refers to as a "community member researcher." This makes the analytical autoethnographic approach he describes appropriate, since it allows me to draw on and acknowledge insights that come from my own life while still collecting and analyzing data, in order to "contribute to a spiraling refinement, elaboration, extension, and revision of theoretical understanding" (Anderson, 2006, p. 388). In keeping with analytic autoethnography I will try to be what Anderson (2006) refers to as a "visible and active researcher in the text," (p. 383) while still maintaining a "commitment to an analytic agenda" (p. 386).

McKemmish et al. (2012) have noted that "A key challenge when writing about community partnership research is the difficulty of being open and honest when it comes to reporting the learnings and fumblings along the way, the failings as well as the successes" (p. 1107). They argue that reporting on things which did not work adds value, as well as reporting successes. In this research, I began designing several activities which had to be abandoned for various reasons. While data about them could not therefore be collected, I will still describe what was done in the hope that it may add value for those undertaking similar work in future.

3.1 Inclusive Design

As a student of inclusive design, I came to this project with some particular philosophies and methodologies in mind. I expected the process to be nonlinear, iterative, and at times chaotic. Jutta Treviranus (2018) has referred to the inclusive design process as a "virtuous tornado" (Section Planning Using a Virtuous Tornado). As this metaphor suggests, an ongoing and often chaotic process of design and redesign, in response to user feedback and changing circumstances, was to be expected.

One preferred approach to the virtuous tornado of inclusive design is collaborative design, or co-design, in which users and designers co-create as partners in a collaborative process. As Treviranus (2018) explains, "we need to recruit the most relevant and authentic expertise to the design team, namely the edge users or pioneers themselves. Not as research participants and subjects of study and analysis, but as full-fledged design team members, or co-designers." This approach to designing reflects the understanding that design is not the exclusive province of formally-trained designers, but rather that "The ability to design is innately human, allowing us to imagine, define and plan the transformation of the environment to make it more applicable to the necessities or aspirations of an individual or group of people" (Sarmiento-Pelayo, 2015, p. 150). In collaborative approaches such as this the role of the formally-trained designer would be to facilitate the collaborative design process, but not to control it.

In my case, however, a number of constraints limited the extent to which I could co-design STEM workshops with children who are visually impaired. I didn't have easy access to any such children, and there would have been ethical hurtles to clear even if any had been available to work with me, before the workshop dates.

What I was able to do was to modify the designs of later workshops in response to observations of, and feedback from, the children participating in earlier ones. In the terms defined by Druin (2002), I was able to incorporate children into the design process as "users" and "testers," but not as "informants" or "design partners." Observations of how they participated in the workshops, and the feedback they gave, were used to inform future iterations of the design; but it was not possible to get their feedback on low-fidelity prototypes, or to involve them as design partners throughout the process. (Druin 2002) Fortunately, as a member of the blind community myself, I could draw on my own personal experience, as well as insights from academic literature. I strove to design accessible activities for the children by working with STEM Minds' staff to modify activities they were already using with children who are not visually impaired. I then collected and analyzed observations and feedback from the child participants, as described below. This was used to inform the design of future workshops.

3.2 Demographics of Workshop Participants

Through a partnership with the Canadian National Institute for the Blind (CNIB), STEM Minds' staff and I had arranged to run a series of informal STEM education workshops at CNIB summer camps for children. The campers would all be visually impaired to some extent, including completely blind in some cases, but this can also include a considerable range of other visual impairments. (CNIB, n.d.)

The campers would range in age from six to nineteen-years-old, and would be attending 3 different camps. Two approximately three-hour-long workshops were run at each camp, for a total of six workshops. At each camp, two workshops were presented in the same week, always in the afternoon.

The first two workshops we ran were at a camp where children ranged in age from five to twelve-years-old. This was by far the largest group of children, with fifteen campers participating in the activities. The gender breakdown was approximately even, seven boys and eight girls.

The second camp we attended had only four campers, who ranged in age from fourteen to nineteen-years-old. All four of those campers were female.

Finally, the fifth and sixth workshops we ran were at a CNIB camp with five girls and one boy. Their ages ranged from twelve to sixteen-years-old.

In total, then, we ran six workshops with 25 campers, who ranged in age from five to nineteen-years-old. Seventeen of the campers were female. None of the camps were specifically focused on technology, although they may have involved a few other technology-related activities. In general, they were summer camps in which the participants did activities such as baking cookies, going on hikes, and taking field trips to museums.

In addition to myself and a workshop facilitator from STEM Minds Corp., each camp also had significant numbers of volunteer helpers available to assist the children during camp activities. At a minimum, there was one volunteer helper per two campers, but in some cases the ratio was one to one. There was also at least one member of CNIB staff attending each camp. Finally, at two of the camps I had a fellow student from my program assisting me with data collection. All of the volunteers who were working with the children had been with them for the duration of the camp, so they were comfortable working together during our workshops.

3.3 Data Collection

In making a plan to collect data I was determined to be as unobtrusive as possible, to try to avoid making the experience feel onerous for the campers. After all, we would not be spending much time with them, and many of them were children as young as seven. In keeping with the suggestions of Fu et al. (2018), I decided to video the campers as they engaged in the activities which had been designed for them, and to consider this directly observed data in conjunction with more indirect, self-reported data from the campers themselves. I obtained approval to video the campers from the Research Ethics Board of OCAD University, and CNIB staff distributed parental consent forms and child assent forms to the campers and their families, since I did not have contact information for any of them. In addition to video recordings of the ISE activities, semi-structured group interviews were scheduled at the end of each workshop. Interviewees were the campers who had participated, and where possible the volunteers who had assisted them. These group interviews were also video recorded to enable later analysis.

In formulating a plan to use video recordings to collect data, I was mindful of the many technical issues raised by Heath, Hindmarsh, and Luff (2010). I felt that fixed cameras would be adequate for recording the STEM workshops. As Heath et al. explain, “Certain activities and settings lend themselves to using a fixed position and a single viewpoint. . . These include more formal environments where a small number of participants largely remain in a set position" (2010, p. 40). CNIB staff had informed me that we would have tables available for the campers to work at in groups, and I did not intend to design activities which would cause them to move from their tables. In cases where we did need to move, I could ask someone to capture video for me on a cellphone.

Heath et al. (2010) also state that "Prior to filming it is critical to become familiar with the setting – to scout it out. . . it is helpful in developing a sense of where to place the camera to capture the action" (p. 43). By scheduling all of our workshops in the afternoon, we were able to arrive while the campers were having lunch and so get a few minutes for camera set-up. It was by no means ideal, but given that there were three different camps in three different locations, and the scheduling of rooms could not always be known in advance, it was the best compromise that could be achieved.

For the semi-structured group interviews, at the end of each workshop, I had three questions to put to the campers.

1) What did you think about the activities today?
2) Can you think of any way for us to make it more fun or interesting?
3) What was your favourite part of the activities today?

I would pose the first question to the group, and each member would be asked if they wanted to answer it before I proceeded to the next question. In this way interactions between group members would be minimized. While the answers of earlier responders could still influence those of later ones, the questions were designed to invite both positive feedback and suggestions for improvement, so that space for expressing a range of opinions was intentionally preserved. The goal was to make the interviews as nonthreatening and unobtrusive as possible.

3.4 Analysis of Data

I wanted to assess the extent to which the activities we had designed for campers with visual impairments succeeded in meeting the highest level of accessibility, as defined by the ISO. Recall that this would mean their experiences could be equitable with those of children without visual impairment. They should be able not only to complete the activities, but to enjoy doing them. Only in that way could the goal of generating engagement with STEM be achieved.

My intention was to code and analyze the video recordings of the camp activities, using grounded theory. Based on Friedman (2008), I hoped to find evidence of engagement with the activities in behaviours such as increasing use of emotive words, large amounts of time doing the activities, and asking questions (p. 78). But other evidence might emerge as well, so I chose to take an open coding approach to the videos. I was encouraged by the observation of Heath et al. (2010) that video allows experiences to be reanalysed in light of new information, so that “As a study develops, certain phenomena, or aspects of social organisation, are revealed and one can return to the original corpus of data to find further examples or variations of those practices” (p. 62).

Besides the direct observations of campers engaging in the designed activities, I would have their spoken answers to the survey questions. By combining these data sources, I hoped to get an accurate picture of how well the activities achieved their purpose of getting the campers interested in and thinking about STEM.

Since the inclusive design process is iterative, feedback from earlier camps would be incorporated into our designs for later ones.

3.5 Design Phase

In setting out to design informal STEM education activities for children with visual impairments, there were a number of initial questions which needed to be answered.

- What equipment would be available at the camps?
- What activities would be age-appropriate for each set of campers?
- What aspects of STEM did we want to introduce?
- How could we make the activities accessible and fun?

We were constrained by the fact that the camps were taking place in three different locations, none of them on the CNIB site. Therefore, equipment had to be transportable. In addition to the equipment for the workshops, camera equipment needed to be brought in and quickly set up to record the video data. So, heavy equipment like 3D printers could not be available on site.

Having never run workshops for children before, I was reliant on STEM Minds staff and the CNIB camp organisers for insights into what activities might be appropriate for them. My focus was on the STEM content of activities, and ensuring that they would be as accessible for the participants as we could make them. Our belief was that accessibility was a necessary, but not a sufficient, condition for the activities to be fun and engaging. We needed to combine our skills, and to create new iterations of designs in response to feedback from the campers.

As a completely blind designer, I began by exploring the equipment available at STEM Minds Corp. to see which things I could use myself. There were a number of different toy robots, 3D printers and other fabrication equipment, iPads, wooden puzzles, laptop PCs, and a large number of models which could be assembled out of laser-cut wooden pieces. Although we could not transport the fabrication equipment, it might still be possible to get them to design things which could be fabricated off site and brought back at a later date for them to touch.

I observed one day of workshops run by STEM Minds staff as part of their ordinary job, to see what the experience is like for children who are not visually impaired. I didn’t collect any formal data at that point, as it was just informal observation to collect ideas. I also spoke frequently with staff from CNIB and STEM Minds about what activities might fit the camp programs and be workable. A large number of my initial ideas had to be discarded for one reason or another, but I believe that they could have worked under different circumstances. So, I will first list those research and design efforts below, as possible projects for future work, and in the next section describe the designed activities which were actually used in summer camps at CNIB.

3.6 Unused Ideas for ISE Activities

3.6.1 Space Exploration

One of the first pieces of equipment at STEM Minds Corp. that I was excited to try to use was the 3D printer. As someone who cannot see photographs, the idea of being able to generate 3D models of objects accurately and quickly is a potential game-changer. I began looking online for things which I would like to have accurate models of, supposing that visually impaired young adults might be curious about the same things as myself. The first thing I wanted to print was a model of the moon. See Figure 3: 3D Printed Moon Surface

Figure 3: 3D Printed Moon Surface

I found a moon model, in the stereolithography file format, I.E. with the file extension, stl, which can be printed by most 3D printers. The model was programmatically generated by a Wikipedia user, based on laser altimeter data collected by NASA's Lunar Reconnaissance Orbiter space craft (User: Cmglee, 2020). It exaggerates real elevations by a factor of ten, to accentuate the moon's surface features.

The first time we 3D printed this model it came out only about the size of a golf ball, and the surface features were not well differentiated tactilely. Next, we enlarged it to a diameter of about six inches. Printing it was very time-consuming however, and took more than one attempt to print correctly. Several print jobs stalled part way through and those attempts had to be discarded. From my conversations with people who do 3D printing regularly, I understand that this is typical of commercially-available 3D printers at present. Although we did, in the end, generate one wonderfully detailed hard plastic model of the moon, it was such a time-consuming process that I didn't try to find and print models of other celestial objects, or of space crafts. I had no interactive activities in mind for them other than to pass them around and discuss them, and the camp staff at CNIB suggested that focusing on other activities might be more fruitful. But I did bring the one moon model with me as a backup activity, to several of the camps. At one point, I did show it to a group of campers who seemed disengaged from the activity of the moment.

3.6.2 3D Printing with OpenSCAD

As mentioned earlier, I am very intrigued by the possibilities offered by 3D printing for visually impaired people, and this excitement is shared by some other researchers (Jafri &

Ali, 2015). Unfortunately, there were many reasons to be cautious about trying to run activities involving 3D printing in a large group setting. The printers are large and heavy, so moving them to the camp locations would not have been feasible. Some researchers have described getting visually impaired high school students to create virtual objects in a workshop. The researchers then printed overnight using a 3D printer and brought the items back so that the participants could feel how their creations turned out (Kane & Bigham, 2014). But due to the slowness of 3D printing, the objects they produced in this way were only about the size of credit cards, and were somewhat brittle.

Nevertheless, the prospect of programming a computer to create a virtual object and then having that object 3D printed in reality was too enticing to ignore. So, I began learning to use a piece of software called OpenSCAD, which can be freely downloaded from the OpenSCAD homepage (OpenSCAD, n.d.).

Unlike most CAD modelling software, OpenSCAD can create 3D models using a text-based interface which is similar to programming. This makes it far more accessible for nonvisual users than software which requires manipulating objects on screen using a mouse. In the terms defined by the Web Content Accessibility Guidelines (WCAG), OpenSCAD provides text alternatives for visual information, and is operable using a keyboard (Accessibility Working Group, 2020-b, Understanding pages section, Guidelines 1.1 & 2.1). Because screen reader software can read aloud text using synthetic speech, the text-based instructions OpenSCAD uses to generate objects are perceivable without vision; and since these instructions can be input using a keyboard, the software is also operable by users who cannot use a mouse. After quite a bit of research, and trial and error, I was able to instruct OpenSCAD to generate a 3D virtual object.

From the standpoint of teaching STEM concepts, OpenSCAD is an almost ideal tool. The script-based instructions that it uses to create objects are a kind of programming language, and the content of them is very mathematical. It performs operations on geometric shapes whose dimensions need to be precisely defined, and in conjunction with the technology of 3D printers it can be used to create physical objects. It relies on skills such as coding and mathematics to create real-world objects, when coupled with appropriate technology. Because it allows for the construction of precisely-defined parts, it would also be ideal for engineering projects in which pieces need to fit together in order to make a working whole.

For the purposes of these 3-hour workshops, however, OpenSCAD, and 3D printing in general, had important limitations. The learning curve for OpenSCAD is quite high, and like many programming languages, its syntax can be frustrating. Coupled with the uncertainty of being able to successfully 3D print the creations of campers in the required time frame, it seemed like an excessively risky project to undertake. The object I created using OpenSCAD, pictured above, was quite simple, and yet it took multiple tries to print successfully. Had we been working with campers for a week, as in the study described by Kane and Bigham (2014), it might have worked. But under the circumstances we chose not to attempt it.

3.6.3 Biology

A great deal of the content in biology tends to be represented through purely visual pictures and diagrams, or to rely on observation through microscopes. I had initially considered using the 3D printers to create tactile models of organs such as the human heart, but given the hardware limitations of 3D printers it seemed worth purchasing a few of these models instead. So, I ordered a life-sized plastic model of the human heart which I found online, made by Walter Products Inc., for about $30 CAD, (Life-size heart model, 2010). See Figure 4: Walter Products Heart Model.

Figure 4: Walter Products Heart Model

The model, when it arrived, was a shock to me. I have read descriptions of hearts in textbooks, and received “heart-shaped” cards on Valentine’s day; from those experiences, I had formed a mental model of what the human heart is shaped like. It was nothing like the shape of this actual model.

I did a small test of whether this misconception was unique to me, among people who have never seen. I showed the Walter Products model to two adult blind friends without telling them what it was a model of, and asked whether they could identify it. Neither could. (The best guess I received was that it might be a turtle.) Yet people who could see invariably recognized it immediately as a model of a heart.

This convinced me that a unit on biology, with tactile models, could be very valuable for visually impaired children. But it was, perhaps, too controversial for our summer camp setting. At a school, with children who had signed up for a biology course, models of this sort could certainly have worked. But we did not use them.

3.6.4 Video Editing

One of the activities which I observed children without visual impairment doing, at a camp run by STEM Minds Corp., was editing a video on an iPad. The children were given small plastic animals which they could move around to make a story, while an iPad recorded them. They then edited the recording to turn it into a short movie.

Thinking of the importance of video sharing platforms such as YouTube, creating edited videos seemed like an important skill for children to learn. Apple’s iOS devices, such as iPads and iPhones, are very popular with visually impaired users because of their built-in screen reading software, known as VoiceOver (Edwards, 2018, p. 685). Although the accessibility of third-party apps in iOS is often hit or miss, the apps included by Apple with their operating system usually work well with the accessibility features of iOS. I was hopeful that video creation using Apple’s iMovie app, on the iPad, would be accessible for visually impaired users out of the box.

In order to research this, I posted a question in a Facebook group for blind and visually impaired people. I had never attempted video editing myself, but some users of the Facebook group have their own YouTube channels. The question of how to do it effectively was popular enough that one of the YouTube creators there, who is visually impaired, made a series of videos on her channel which explain how she uses iMovie with VoiceOver to do her editing (Monroe, 2019). Although the information was very helpful for me at the time, the accessibility of iOS apps, such as iMovie, is constantly changing as apps and iOS itself are updated. So far as I know, the information provided in her video is still accurate at the time of writing.

What I learned was that using iMovie to create and edit videos without vision is not a straight-forward task. Although people are doing it successfully, they are using work-arounds because many parts of the app do not work with VoiceOver in predictable ways. I was disappointed because there are many sound effects, and pieces of music, which the app allows users to add to their videos, so designing fun activities which do not rely on sight should be possible. But I found the procedure frustrating enough myself, when I tried making a video, that it did not seem feasible to get a group of young people to learn it in a short period. Hopefully, the accessibility of the iMovie app will be improved in future updates.

3.7 Fully implemented ISE activity designs

3.7.1 Bee-Bot Activities

Recall that Kabátová et al. (2012) had found Bee-Bots to be very accessible toys out of the box, noting that their control buttons have embossed symbols on them and are different shapes, in addition to being color-coded (p. 24). This assists in tactilely determining the functions of the different buttons. I would go further and note that the buttons are arranged in a conventional way, making their functions intuitive for many users, and that they are raised high enough above the plastic housing of the Bee-Bot to make their shapes easily distinguishable by touch. Essentially, the direction buttons on Bee-Bots resemble raised arrows which point in the direction which they will cause the bot to drive or turn. Additionally, Bee-Bots are quite noisy when driving. This provides good audible feedback indicating that the toy is in motion. Because they pause after executing each command, and beep when they have executed the final command in their memories, the whole sequence of a Bee-Bot executing its program can be perceived audibly, although the location of the bot may be difficult to track audibly in a noisy environment.

Finally, the shape of Bee-Bots helps in determining their orientation. They have heads and bodies, and a small hook on the back resembling a trailer hitch. For those with at least some vision, the eyes of Bee-Bots flash. Orientation is important for understanding what command a Bee-Bot is executing, since predicting the result of a “go forward” command depends on knowing the bot’s orientation.

Similar to Kabátová et al. (2012), we did modify the plastic mat on which Bee-Bots drive, in order to make the grid-lines raised (see figure 5). Rather than tape and cardboard, I purchased a package of foam sheets with backing which could be peeled off, similar to stickers. We cut these sheets into thin strips and attached them to the plastic matts, forming raised grid-lines. It was hoped that this would be more flexible than cardboard, but thicker than lines made of tape alone. The height of the raised grid-lines was 2 mm, and their width was 10.5 mm. Testing confirmed that Bee-Bots were able to drive over these lines without appreciably diminishing the distance that they travelled across the mat.

Figure 5: Bee-Bots traveling on raised mat grids

Before beginning activities with Bee-Bots, the facilitator of the activity would describe the functions of their various buttons in a systematic way. Descriptions such as “Press the green button to make the Bee-Bot start driving” would not be helpful for campers unable to distinguish colors, so more detailed descriptions would be provided. A facilitator might say, “If you trace your hand back from the front of the Bee-Bot, where its eyes and head are, the first button you should come to is a forward button. After that is a round button, which is green. This round button makes the Bee-Bot start driving…” After such explanations, the activities could start.

3.7.2 Activities with Wooden Blocks

In order to make Bee-Bot activities which would be accessible with any amount of visual impairment, including complete blindness, we did not want to design activities which relied on being able to perceive pictures. Following Milne and Ladner (2018), we decided to use wooden blocks which would make noise when the Bee-Bots knocked them over, and design activities around those. Two kinds of activities seemed possible: ones in which the objective was to knock over one or more towers of blocks; or activities in which Bee-Bot would drive through a maze of blocks without knocking any over.

The first set of wooden blocks that I purchased turned out not to be very appropriate for these activities. They were small, and came in a wide variety of shapes. Building sturdy towers which would make loud noise when knocked over by a Bee-Bot would not have been easy with those blocks.

We settled on purchasing two Jenga games, since they are wooden blocks specifically designed for building towers that fall over in a dramatically noisy fashion. The plan was then to have the volunteers at the camps build towers and/or mazes on the plastic matts, and children would use the raised grid-lines to plan a path for the Bee-Bots to follow. Entering the correct sequence of commands would result in the bots negotiating these paths successfully, which would teach algorithmic thinking and basic coding.

3.7.3 Cubetto Activities

As noted earlier, the Cubetto robot performs many of the same functions as Bee-Bots, although having a separate control board for programming allows the program itself to be tangible. The addition of a function segment of the board, and blocks which can call the function in the main program, also allow it to teach an important additional aspect of programming.

We had only one Cubetto robot available, so our plan was to use it in the same wooden block activities as above, on the same plastic sheets with raised grid-lines. We tested that Cubetto was also able to drive over the raised lines without getting stuck, which it was. Cubetto could, therefore, demonstrate how the same tasks could be achieved using some more advanced programming concepts, such as calling functions.

Here I was remiss in that I did not try programming Cubetto to knock over towers myself. I felt that the wooden blocks which fit into its control board, to create programs, were approximately arrow-shaped, and assumed that their orientation on the board would determine what direction they would instruct the robot to move. Actually however, the wooden action blocks have embossed arrows on them which indicate which direction they represent. These embossed arrows are not easily felt. Unfortunately, the easiest way to distinguish the different command blocks is by their color.

Had I realised this I could have labelled the command blocks, either with raised arrows or with braille labels conveying text, or perhaps both.

3.7.4 Cubelets Activities

Cubelets are described by their manufacturer as “Modular robots” (Modular Robots Incorporated, n.d.). Unlike the other robotic toys described here, when a robot is constructed out of Cubelets it does not have a separate program controlling it. Instead, the function of a Cubelet robot is determined by which cubes compose it, and how they are connected. Each cube has a different function, such as a distance-sensing cube, a battery cube, or a cube with wheels, which can be called a “drive cube.” The cubes snap together magnetically, and begin to function as soon as the battery cube is turned on.

Cubelets were not mentioned in the Literature Review section because, as far as I am aware, they have not been studied for use with children with visual impairment. This does not seem surprising to me, given their design. While some of the cubes can be distinguished tactilely, many are distinguishable only by their color. This made it impossible for me to guess the function of several of the cubes. I didn’t want to put any campers in the position of feeling excluded by the STEM activities, and I couldn’t think of a way to modify this toy to make it more accessible for visually impaired people in the time available to us, so I didn’t plan any activities involving Cubelets.

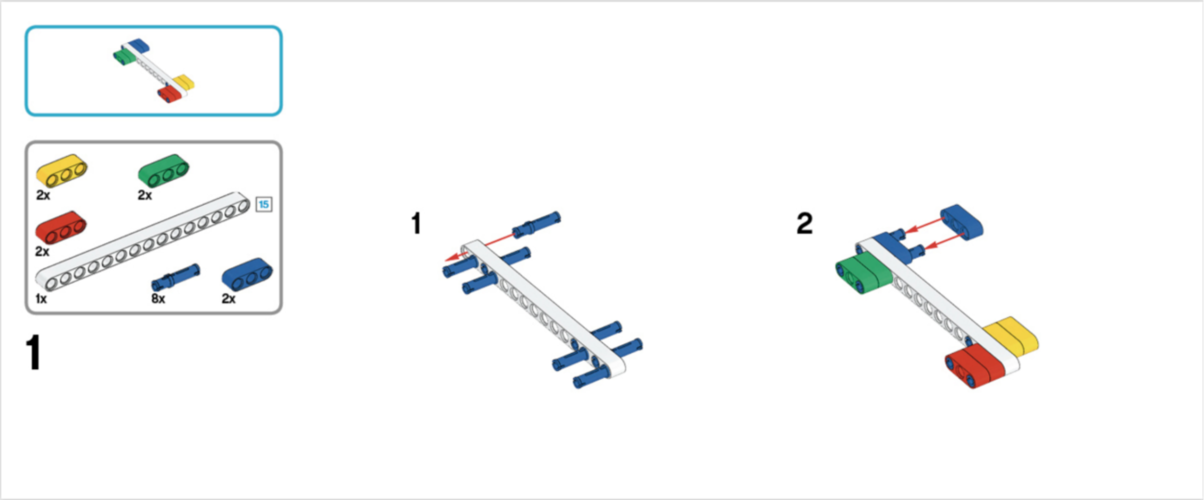
Fortunately, circumstances did cause us to use Cubelets at the last two camps, with positive results. We used some of the building activities described on the Modular Robotics Incorporated website (n.d.), and campers also created their own robots out of Cubelets. There were a large number of volunteer helpers available at the last two camps, relative to the number of campers, and the campers themselves turned out to be very creative problem-solvers. The Cubelets toy also snaps together with much less effort than, for example, building a robot out of Lego Mindstorms Ev3, and not having to program it means that the behavior of the constructed robots can be observed simply by flipping the power switch to “On.”

3.7.5 Lego Mindstorms EV3 Activities

As mentioned earlier, Lego’s Mindstorms EV3 kits allow for the construction and programming of more sophisticated robots than any of the others that were available to us, and they are used in a wide variety of formal and informal STEM education settings. So inclusively designing ways for visually impaired young adults to work with them enjoyably was a priority for the STEM Minds Inc. staff and myself.

As mentioned by Ludi and Reichlmayr (2011), there seem to be two distinct sets of problems involved in making this robot accessible for blind and visually impaired users. First, the building of the robots is often done using instructions which are picture-based as displayed in Figure 6: Sample Lego Robotic Instructions, below.

Figure 6: Sample Lego Robotic Instructions



Secondly, the apps which are usually used to program Mindstorms robots use block-based programming interfaces, which also rely on interpreting and manipulating pictures in order to create programs for the robots to execute. Ideally, in order to make the kits fully usable and enjoyable by visually impaired users, both sets of problems should be entirely solved. But it is also possible to design activities which focus either on building robots or on programming them, without requiring both.

3.7.5.1 Accessible Programming of Mindstorms EV3

I began by simply connecting a Mindstorms EV3 brick to a Windows PC with the screen reading software JAWS for Windows installed on it. My hope was to be able to replicate the kinds of programming activities described by Ludi and Reichlmayr (2011), and/or by Ludi (2014). But this was not successful. I found that the BricxCC programming environment, described in Ludi and Reichlmayr (2011) had not been updated since 2011, and that nothing about the second JBrick environment had been published since Ludi (2014). It turned out that neither project was still being maintained, and I learned from Stephanie Ludi that the JBrick environment of her 2014 article would not be compatible with the new Lego Mindstorms EV3 kits, but only with the older NXT ones (personal communication). Since we did not have any NXT kits available, these software options were closed off.

I also contacted Gerry Cocco, a professional computer programmer who helped to coach a team of blind and visually impaired students to compete in two First Lego League competitions (TSBVI, 2017). He had written some code of his own, and loaded it onto the NXT brick in order to make the brick more accessible for the team. I understood from talking to him that the approach their team was using might not be appropriate for general users, in the short three-hour time slots we had available at our camps. He suggested that building something out of the EV3 pieces could be a more engaging activity than trying to teach programming, in the case of such brief workshops.

I learned, however, that the Lego Mindstorms EV3 bricks can be controlled by an iPad app called Swift Playgrounds, which works with VoiceOver, the screen reading feature of iOS. I tested it, and found that it enabled a few programming activities with the Lego control bricks which might work even in our short timeframe.

Controlling a Lego Mindstorms EV3 brick with Swift Playgrounds is relatively complicated to set up. It requires installing the Swift Playgrounds app on an iPad, installing additional EV3 playgrounds from within the Swift Playgrounds app, and connecting the iPad to the EV3 brick via Bluetooth (Seshan & Seshan, 2017). But once accomplished, Swift Playgrounds can quickly enable some simple interactions with the EV3 brick.

3.7.5.2 Censor Readouts

When a distance censor is plugged into one of the input ports on an EV3 brick, and the brick is communicating with an iPad, the readout from the distance censor is continuously updated and displayed in the EV3 Template of Swift Playgrounds. When the VoiceOver feature is turned on, it can be made to focus on the part of the iPad screen where this readout is displayed. This causes VoiceOver to announce the distance to any object placed in front of the distance censor.

This activity does not require any programming. As long as the brick and iPad are communicating, the EV3 Template displays the readout of censors connected to the brick. Particularly as a person with a visual impairment, I found it enjoyable to point the censor at things and have the distance to them measured and spoken aloud. As a STEM education activity, it demonstrates how the censor works, making it possible to imagine how the distance censor could be used in robotics applications. It also suggests the mathematical nature of robots.

3.7.5.3 Sample Code

The EV3 template opens with a sample activity which has interesting possibilities. It instructs users to connect a motor and a touch censor to the EV3 brick, and to run some sample code which is displayed in a window. When the code is executed, pressing the button causes the motor to run.

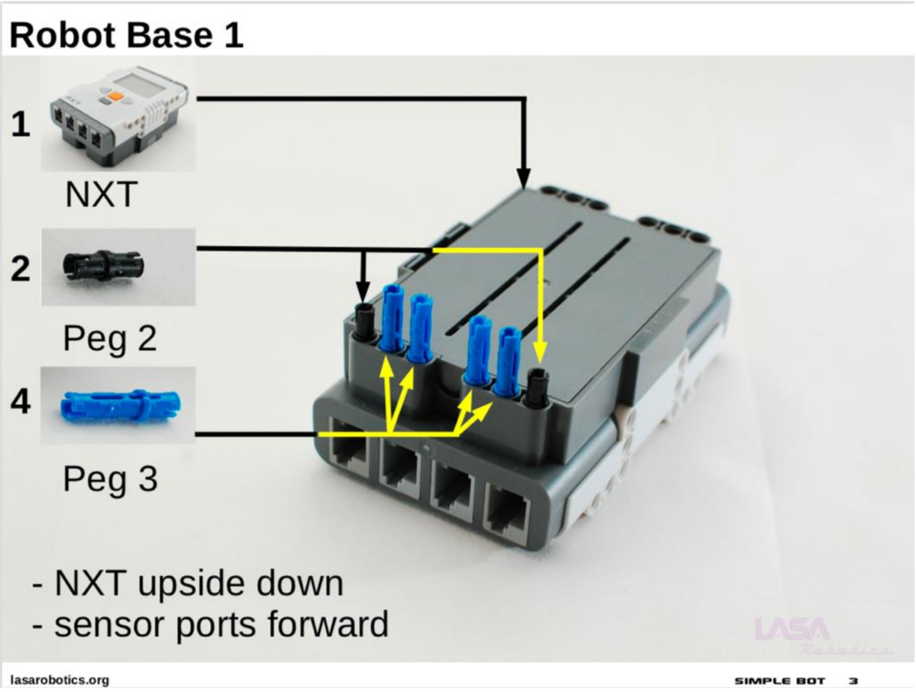
This code can be read aloud with VoiceOver. It would be possible to edit some of the parameters in it, such as the power of the motor, and to run it a second time with the modifications. If the motor power is reduced from 100% to 10%, for example, the sound it makes is noticeably softer. This is a good introduction to coding.

We can add other EV3 pieces to the motor, to demonstrate how it could be used to control a robot.

3.7.5.4 Accessible Instructions

Gerry Cocco showed me some instructions which a colleague of his had created, by working with visually impaired students at TSBVI. The instructions are designed to be easier to read than typical Lego instructions, by using arrows and higher contrast (see Figure 7: Accessible EV3 Instructions)

Figure 7: Accessible EV3 Instructions



- NXT upside down
- sensor ports forward

Unfortunately, these instructions were developed for the older Lego Mindstorms NXT robotics kits. They could work as a template for designing updated instructions for EV3 robots, but were not directly usable with EV3 kits. They would also not be accessible for students like myself, who are completely blind.

Another possibility for creating instructions might be to translate them into text. Although Lego normally uses only pictures for its instructions, it does provide lists of parts, which it calls an "Elements survey." These surveys differ slightly from kit to kit, since not every piece is in every kit, but they could be named and included in text based instructions.

3.7.5.5 Improvised Building Activities

Given the lack of available instructions, we created an activity where children could build a trailer out of EV3 pieces which could be connected to the Bee-Bots. The idea may have been inspired by the name of one of the EV3 Swift Playgrounds, "Animal Rescue." We would provide children with a Bee-Bot, a small plastic animal, and some EV3 pieces they could use to build a trailer. The trailer should attach to the hook on the back of the Bee-Bot, and be used to carry the small plastic animal.

3.7.5.6 Swift Playgrounds: Learn to Code

Recall that iPads have a wide range of accessibility features built-in, including features for those with visual impairment. When we began exploring the Swift Playgrounds app, we found that the Learn to Code activities were well-designed to work with the VoiceOver screen reader. Learn to Code is a set of maze activities similar in concept to the physical mazes we were building out of blocks. A robotic character needs to be coded to navigate its way through the virtual maze, but it can also perform more sophisticated virtual activities as the player advances in levels. The language in which instructions are given to the virtual character in Learn to Code is the Swift language, which can be used to program apps for Apple's iOS devices.

Although the VoiceOver feature can speak aloud all aspects of the mazes in Learn to Code, understanding the maze in this way requires holding it in memory. In a sense, VoiceOver gives users with no vision the ability to perceive all aspects of the maze, but in order to navigate it we need to understand how the many squares of it fit together. Fortunately, Apple has partnered with an organisation called Lighthouse for the Blind to make available braille and large print versions of the mazes in Learn to Code (Brauner, 2019). We acquired a few copies of both the braille and large print maze books. This enabled feeling the mazes tactilely, perceiving them enlarged on a printed page, and/or hearing or enlarging them using the iPad accessibility features. We decided to test these, by trying Apple’s Learn to Code activities in the Swift Playgrounds app.

Chapter 4: Results

The data generated by capturing video of the various activities was often more ambiguous, and hence difficult to interpret, than I had anticipated. For example, in one instance there was a subtle flirtation taking place between two participants throughout an entire workshop. It was nothing more or less than to be expected at a summer camp, but it greatly complicated the task of deciding whether engagement or disengagement with an activity were due to its design. I was looking for evidence of engagement with the activities to assess how effective they had been at generating interest in STEM topics, but separating the impact of the activities from the larger environmental context was always a questionable task.

Other challenges with the video data included technical difficulties in collecting it, and that children, at play, seem to verbalise less than I had expected. We knew from the cautions of Heath et al. (2010) that setting up cameras quickly in an unfamiliar location was going to be difficult, but there were also some equipment failures that caused data to be lost. In one instance, a video file became corrupted in the course of recording, and it could not be recovered. In another case, a child tipped over a camera while playing, and it took some time for this to be noticed and the camera turned upright again.

As a more general complication, I was surprised by how little the children expressed verbally while engaging in the activities. In my experience of being in groups of visually impaired adults, we tend to communicate much of what we are doing through language, and I had assumed the same would be true of visually impaired children. But this was not borne out.

Despite these complications, the combination of video data and group interviews with the campers generated many interesting insights into the effectiveness of the ISE activities which we had designed. Even more importantly, the video was able to capture the process whereby the campers often redesigned our activities to suit their own interests. It captured some small bits of the virtuous tornado of inclusively designing, and redesigning, with the full involvement of participants in the process of creating new solutions. Therefore, I felt that the effort of collecting and analyzing the video was ultimately worthwhile.

Following the same framework as in the previous section, I will categorise the results by the type of robot, or other equipment, which was used in each activity.

4.1 Bee-Bots

We used Bee-Bots primarily in the first camp, for children aged 7 to 12. These toy robots were so initially engaging that once they were distributed, the facilitator found it difficult to put the brakes on the children’s enthusiasm long enough to explain how they worked, or what activities we intended for them. Almost all of the campers clearly wanted to turn the Bee-Bots on and start pushing buttons immediately. However, with effort, the facilitator did manage to describe the functions of the various buttons, and the idea of programming it to knock over towers of wooden blocks on the plastic mats (see Figure 5: Bee Bots Travelling on Raised Mat Grid).

Like Milne and Ladner (2018) we found that the activity of getting Bee-Bot to knock over towers of wooden blocks was very engaging for the campers. They did not always approach it as a programming activity, however. Although the idea was for them to place Bee-Bot on a starting square and program it to drive to the square with the tower on it, in practice it was tempting to simply place the Bee-Bot against the tower and instruct it to go forward. With encouragement from the volunteers, programming was being practiced perhaps half of the time.

The results of the activity in which campers would program Bee-Bot to drive through a maze were unexpected. While sometimes children did the activity as planned, they did not like to rebuild their maze when the Bee-Bot failed to navigate it successfully, causing part of it to be knocked over. (Sometimes we referred to the mazes as “Obstacle courses,” since the mats were not large enough to build very intricate mazes). Volunteers would reconstruct the campers’ mazes when that happened, but it was a less compelling activity for them.

In some cases, though, the small differently-shaped blocks which I had purchased by mistake became ways to decorate the mazes (see Figure 8: Improvised Building Activities). Some children became more engaged in building intricate structures out of blocks than in getting a Bee-Bot to drive through them successfully. I began to understand the value of STEAM (STEM plus Art), as opposed to activities with an exclusive focus on STEM.

After about 45 minutes of using Bee-Bots, campers seemed to become less engaged by them. This was also reflected in some of the group interview comments at the end of the workshops. Although all twelve of the campers described the experience positively, five also mentioned that the robots were easy to use, and one said explicitly that they should have been harder. A quite representative comment was “When you said coding I thought you meant like computer coding. But it was really simple, and sparked some good conversation.”

One positive aspect of the Bee-Bots was how their design seemed to capture the imagination of children. When asked how the activities might have been improved, one younger participant answered “If the Bee-Bots could be controlled from a distance, and buzz, and have wings, and kind of fly.” We heard later, from one of the volunteers, that several kids had said playing with BEE-Bots was their favorite part of the camp. Since the only way to make Bee-Bots work is to press a sequence of buttons and then tell it to execute the program, all of the children were learning a fundamental programming concept while using them.

4.2 Cubetto

Since only one of these robots was available to us, it wasn’t possible to collect as much data about it as had been the case for Bee-Bots. We used it primarily with older campers, because programming it is more abstract than for Bee-Bots. But recall that we had planned the same activities for Cubetto as for Bee-Bots.

An unanticipated problem was that Cubetto did not always knock over towers of wooden blocks, because of its cubical shape. Instead it would sometimes push the towers along with it. A volunteer could, of course, still report to the camper that their code had worked successfully, but it was less dramatic feedback.

The wooden action blocks used to program Cubetto were also difficult for some campers to identify. This could have been solved by labelling the blocks with something tactile. The embossed arrows on them are difficult to feel, and it was clear that some campers did not perceive what the action blocks signified. One commented “If you just put random stuff in, [the cube] just moves.” At other times, campers were not sure how the board should be oriented, so using a tactile marker to indicate the top of it might have aided understanding. The “Function” section of the Cubetto control board was a welcome addition, however. One camper attempting to program it to knock over a tower did not have enough action blocks to achieve the goal, until she realized that it could be done by including a function in her program. This alone was an important conceptual realisation.

Over all, it seemed that campers liked the idea of Cubetto, but they had trouble using it effectively. As one said, “I felt like it was like a puzzle. You had to sort of put it together in a way and I really like things like that.”

4.3 Cubelets

At least one camper, aged 15, really loved using the Cubelets. She had enough vision to distinguish them by color, so she was able to say things to the facilitator such as “I wonder what the red one does.” Campers with less vision were less engaged by the Cubelets, although they could construct things out of them with help. The audible feedback provided by Cubelets is minimal, which prompted the facilitator to ask some campers “Do you want to feel what it’s doing?”

The robots described at Modular Robotics Inc. (n.d.) were popular activity ideas. The cubes click together very easily because of their magnetic connectors, and many campers seemed to really enjoy the chance to build with them.

At one point the campers designed an exciting inclusive activity with Cubelets by themselves. They built what they called a “Stage” out of them, building a flat surface out of the cubes and placing some of the flashlight cubes on top of vertical columns. A camper who was not able to see enough to distinguish colors, and who had been disengaged from the activity thus far, then “performed” on the Cubelet stage. He sang along to a song on his cellphone, and the stage-builders became the audience. It was a fantastic STEAM activity for them.

The Cubelets seemed to introduce a different set of ideas from our other robots, which was very welcome. Campers needed to understand the idea of a circuit, and that without a battery cube in their creations there would be no action. So, although Cubelets were not programmable in a traditional sense, they introduced some engineering concepts which the pre-assembled robots had not suggested.

4.4 Lego Mindstorms EV3

4.4.1 Building with EV3 Pieces

We only once used the activity designed to get campers to build something out of EV3 pieces. It was at the first camp, for younger children. Recall that our idea was for them to build trailers which would connect to the Bee-Bots, and which could carry a small plastic animal across the grid. It was a hybrid activity of practicing programming a Bee-Bot, and also learning to construct an object out of EV3 pieces which could satisfy a specific requirement.

The children found it difficult to manipulate the small, complex EV3 pieces. They often needed help from volunteers. But they seemed to enjoy the story aspect of the activity, which was the Bee-Bots trying to help an animal in trouble. Multiple volunteers said that having a new, more challenging robotics kit to work with in conjunction with the BEE-Bots was good for engaging the children. One volunteer added that getting to build something "Made them understand it more – like what they're doing."

In retrospect, it would have been good to collect data on how many children were working on this activity, and whether or not they completed it as designed. However, this was not accomplished in this setting.

4.4.2 Programming EV3 with Swift Playgrounds

Both times that we attempted this activity, there were significant problems with getting the EV3 bricks to connect to the iPads via Bluetooth, and then for the Swift Playgrounds app to recognize that a brick was connected. Since configuring the bricks can require selecting menu options on the brick's small screen, and the bricks have no built-in screen reading functionality, it would not have been possible for some campers to troubleshoot all issues independently. Even the adult volunteers, whose vision was not impaired, found the task of setting up the connection between the iPads and EV3 bricks difficult. The video recordings show quite long stretches of time in which adults were troubleshooting the connection while campers waited to start the activity.

In cases where campers were able to solve the iPad to brick connection problems, the activity with the distance censor yielded good results. A camper pointed it at several different objects and was intrigued by the distance measurements displayed on the iPad screen. That particular camper did not need the screen read aloud, but the activity would still have worked if he had. The camper expressed that a censor like that could be used to make a robot vacuum cleaner which doesn't bump into things.

Getting the motor to power on when the touch censor is activated, as described in the example activity of the Swift Playgrounds EV3 Template, was more prone to errors. Part of the difficulty with this interface is that the number of possible problems makes it time-consuming to troubleshoot when it doesn't work. Even after one camper successfully got the motor to power on when the touch censor was pressed, it stopped working soon after. This could have been caused by an error being accidentally introduced into the code on the iPad, or another connection issue between the iPad and brick, or a physical problem with the cables connecting the motor and censors to the brick, or something else.

Unsurprisingly, feedback from campers was generally that they found the EV3s to be frustrating. They remained positive in their spoken feedback, but said things like “I was confused. . . It wasn’t that hard, it was just annoying coz it wouldn’t get connected. But it was fun.” The video recordings show some more overtly negative reactions, such as one camper striking the table and yelling “Come on!” after about twenty minutes of unsuccessfully troubleshooting the activity with the motor.

4.5 Swift Playgrounds Learn to Code

We used this activity only once, since it took some time to discover the large print and tactile materials available from the Lighthouse for the Blind and Visually Impaired (Lighthouse Staff, 2019). Preparing the materials also took time. The video recordings of the activity were incomplete, due to some technical glitches, but fortunately I made an audio recording as a backup. The data I was able to collect doesn’t adequately show whether or not the large print booklets were useful for the campers doing the Learn to Code activities. Two campers used the braille booklets, however, and those were helpful in improving the accessibility of Learn to Code. One of them enjoyed the activities enough to ask whether he could keep the braille booklet so that he could continue using it with Learn to Code on his iPad at home. He said that he had done Swift Playgrounds: Learn to Code activities previously, at school, but that “it was harder that time because I didn't have like a 3d grid, and no one really could help me.”

Some campers, who were able to see the iPad screens reported that they found the Bite character too small for them, and that “A lot of the colors are really similar, so it’s kind of hard for me to see.” I don’t know enough about the accessibility features of iPads, for low-vision users, to say whether this could have been improved by adjusting options under Accessibility settings. The large print booklets were available, but no one mentioned using them. Possibly they preferred the immediacy of working on the screen. If a video recording had survived it might have helped resolve the question.

Campers who could see the screen definitely enjoyed how the Bite character reacts when the code incorrectly tells it to move onto a square with water. In general, this was a very engaging way to learn programming.

Chapter 5 Discussion, and Ideas for future work

In striving to design ISE activities which would be accessible for people with visual impairment, I was struck by how many previous attempts to do this had become unusable over time, as a result of changes in technology. Stephanie Ludi had described using two different programming environments for Lego Mindstorms NXT kits (Ludi & Reichlmayr, 2011; Ludi, 2014), but neither of those could be used with the newer Lego Mindstorms EV3. Similarly, software written by Gerry Cocco to make the menus on the NXT bricks speak would not have worked on EV3 bricks (personal communication). Although we worked with several different educational robots and reported on how they might be used in more accessible ways, new robots are replacing old ones at a dizzying rate. With technology in a constant state of evolution, how could accessible solutions for teaching STEM be developed which would not so quickly become obsolete?

The low-tech modifications that we made, such as attaching sticky foam onto plastic sheets to make raised grid-lines, and getting robots to knock over towers of wooden blocks to provide audible feedback, should remain applicable for the foreseeable future. We found, as well, that the ability of children and young adults to design new inclusive activities to meet their own needs should not be discounted. But not all of the problems we encountered were amenable to these kinds of solutions. We also heard from multiple campers that they had attempted things like coding activities in their schools, and found themselves excluded by various barriers. Given the amount of work we did to design these activities more inclusively, and that we were not always successful, it is hardly surprising that in the setting of a large school they could encounter this exclusion.

As mentioned above, one of the most successful examples of an effort to improve accessibility for users on a large scale has been WCAG. Although these guidelines are usually applied to pages on the World Wide Web, they have been found to be general enough to be applied to other electronic resources as well (White, 2019). The highly structured nature of WCAG is one thing which sets it apart. It defines three layers of accessibility: a set of four very general principles; thirteen more specific guidelines; and down to an even larger number of very specific success criteria. In this way, it provides guidance for creating more accessible webpages which are simultaneously very general and very specific.

Could a similar framework be developed for assessing the accessibility of educational robots? If such a thing could be standardised, it might provide guidance to manufacturers wishing to ensure that their products were usable by the widest range of potential students. It could also provide a way for those attempting to create inclusive educational experiences, for their students, to know which products might be a good starting point.

Even if such guidelines could be developed, the earlier discussion of accessibility made clear that compliance with technical accessibility guidelines is only the first step on a path to providing equitably satisfying experiences for all users. There remains a messy process of inclusive design, because even the clearest standards cannot anticipate the incredible diversity of users and contexts of use. But nevertheless, a first step towards greater accessibility would be better than no step. We should do whatever we can to avoid becoming Sisyphus: inclusively designing solutions for use with one technology, only to have our work undone by the next iteration of the technology which comes to market.

Another recurring problem in the inclusive design of these ISE activities has been the lack of instructions which were accessible without vision. Although the team at TSBVI created build instructions for Lego's Mindstorms NXT robots which were better for low-vision users than the standard Lego ones, I am not aware of tactile build instructions having been created by anyone. This same difficulty of producing tactile instructions also prevented us from using several wooden models, which STEM Minds staff often have students assemble in order to practice constructing things. The almost exclusive use of pictures in these instructions is a persistent challenge to making the information available in other formats.

This problem highlights one of the shortcomings of WCAG. Those guidelines do provide advice on how to make pictures accessible in alternate formats, but the advice is to provide a short description of the picture in text, often called "Alternative text." For example, a picture showing how to assemble a robot out of Lego pieces could satisfy the accessibility requirements of WCAG as long as it had a short piece of alternative text associated with it, such as "Build instructions for a Lego robot." While this label is clearly better than no label, and for some purposes it would be an adequate description of the image, it would be no help at all to a person wanting to use the picture to build a robot. Yet it is a step in the right direction, as long as people recognize that for some users in some contexts, it does not go nearly far enough.

Acknowledging, then, that WCAG has many limitations, the high-level principles which it defines still appeal to me as ways of thinking about the accessibility of even real-world objects, such as educational robots. "Perceivable, operable, understandable, and robust" might have helped me to assess the activities that I was attempting to design. For example, although the Lego EV3 bricks seemed to be accessible once they were connected to an iPad running Swift Playgrounds, the solution was far from robust. It made the bricks operable by users with little or no vision, but the information on the small screen of the bricks was still impossible to perceive without sight. I enhanced what could be perceived about them by labelling the connection ports of the bricks with braille, but was enough information being provided to the users for them to understand the activities I had planned?

These might have been useful questions to ask about other robots as well, such as Cubetto and Cubelets. Certain information needed to be perceivable by users in order to understand how they worked, and in order to operate them. That information could be provided in a variety of ways. Particularly in noisy chaotic environments such as some of the camps, any accessibility solutions we come up with should be robust.

Yet I don't mean to suggest that these considerations, suggested by the WCAG principles, are the correct ones. To begin thinking about how they might be improved, I tried a thought experiment in which I considered the accessibility of driving a car. It seemed like an interesting example because I know that I cannot drive a car, being unable to see anything through the windows. Could these WCAG principles explain why driving is not currently accessible for me?

Certainly, I find that the controls of a car are operable for me. I can manipulate steering wheels, gas pedals, keys. I understand what I need to know about the car. There is the problem of perceiving things through the windows, but what if that information were made available to me in alternative text? I could have a person describing the view through the windshield, as I drove. Why could that not work to make driving accessible for me?

Maybe, the reason that this doesn't work is that what I need to perceive in order to drive a car, at any reasonable speed, cannot be communicated to me through language. Although people who are blind have been known to drive cars, under very controlled circumstances, they do it by having someone tell them which way to turn. This is not the same as perceiving what is around the car and making an independent decision to turn. It is not accessibility, it is obeying instructions.

Perhaps "Perception," as imagined by WCAG, is too limited. Its idea of alternative text does not anticipate the need to perceive the complexity of building instructions, in the case of robots. In some real-world instances, such as driving a car, information needs to be perceived immediately, and it may also need to be in a more concrete form than the abstractions of language can provide. WCAG's assumption that all information can be expressed in language might need some revision.

None of which negates the idea that guidelines for the design of more accessible educational robots would be useful, or that WCAG could be a good basis for the beginning of such a project. In fact, it may be our best hope for incorporating more inclusive design into the creation of these products.

Chapter 6: Conclusion

In partnership with the staff at STEM Minds Corp., I sought to design and run informal STEM education activities for children and young adults who are visually impaired. Our goal was to achieve the most complete accessibility possible, so that the participants could have the same opportunity to be satisfied by the experiences as their peers without visual impairment. In this way, we hoped to introduce STEM concepts to them in a format with which they could fully engage.

Although the general feedback we received from participants was unanimously positive, it also helped us to identify a number of specific areas where we could improve. Most strikingly, the activities involving Lego Mindstorms EV3 were disappointingly frustrating for participants. Activities with other robots varied in the degree to which they were able to engage participants, with Bee-Bots being by far the easiest to use with impaired vision. We designed activities to be performed with these robots which did not require any sight.

In many instances the children and young adults who participated in these activities redesigned them to better suit their own needs. Often, they added artistic elements which I had not considered, since I came to the project with a goal of STEM education in mind. For example, the wooden blocks which I had considered only as objects to be knocked over, or not knocked over, by robots, became building materials for much more intricate and interesting structures. This design on the part of the participants greatly enhanced the inclusiveness of the activities. I was also fortunate that almost all of the activities were facilitated by a member of the STEM Minds Corp. staff, from whom I could learn a great deal about remaining calm and focused in the midst of chaos.

As is typical of informal STEM education projects, it was not possible for us to systematically assess the extent to which participants may have learned new things. The design of the robots themselves, however, required users to think computationally in order to operate them. We enhanced this by providing tools such as mats with raised grid-lines on them, so that campers could more easily instruct the robots in terms of a coordinate system. Although these concepts were not explicitly expressed by us, they were implicit in the design of the activities, and it was clear that the robots were successfully causing participants to think in new ways. An interesting piece of evidence for this is that when they were asked how the activities could be made more fun, multiple children suggested that the robots could have remote controls. Of course, that would have negated the need to program them, and to think in terms of coordinate systems, but it was a very understandable suggestion. I take it to mean that some challenging new ideas were being explored.

It was strikingly clear from our study that the extent to which educational robots are accessible with visual impairment varies widely, from robot to robot. In the case of the Bee-Bot we needed only low-tech modifications to the standard activities. Other robots presented different challenges, such as pieces that are distinguishable only by color, or by embossed symbols which are very difficult to distinguish tactilely. In the case of Lego Mindstorms EV3 the difficulties were more complex, and yet solutions do not seem out of reach even there. But there is clearly a great deal more work to be done to improve the accessibility of these educational toys.

Besides robots, Swift Playgrounds Learn to Code is a promising app for teaching coding, especially with the addition of tactile braille mazes. Many more potential activities were described, but were not tested by us for lack of time. The breadth of options for STEM education activities is truly inspiring, and the chance to include more students in them must not be missed.

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