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Blind and visually impaired people have intimate relationships with the digital assistive technologies that they rely on for carrying out their everyday tasks, but have no tools for designing and creating their own such devices. This paper documents the adaptation and extension of an existing computational construction kit, enabling visually impaired learners to write programs to control a Programmable Brick – a microcomputer that can then interact with the world via sensors, speech synthesis and numerous other actuators. Using an initial technology implementation, a series of activities were carried out with a small group of visually impaired teenagers. A case study is presented to highlight specific domains of knowledge that were discovered to be especially relevant for this community. Reflections from this initial study are presented in hopes of changing how visually impaired children are encouraged to relate to digital assistive technologies.

New tools for new explorations

In recent years, computers have become established elements of many types of learning settings, used in different ways for various learning activities. Unfortunately, the power of the computer as a flexible medium for designing and creating has often been ignored. Tools that are designed to let users create their own constructions empower learners to engage computation as a creative material. The process of creating these artefacts opens the door to a myriad of learning opportunities, many in fields that are otherwise difficult to approach. More specifically, in the process of creating computational objects, many of the underlying ideas of computation itself can be explored.

Blind and visually impaired people often interact with more computational devices in learning settings than their sighted counterparts, but have even fewer opportunities to create with computation itself. Visually impaired people use tools such as adjustable magnifiers, text scanners, personal computers and speech-synthesis devices to access curricular materials that are otherwise inaccessible, and use computers to do word processing, send email and surf the web, among other things. Unfortunately, none of these tools takes advantage of the opportunity to engage learners in explorations of how these computational tools can be used to create their own artefacts. This growing reliance on 'black-box' devices in learning settings can be inherently disempowering to learners, denying them not only an understanding of their functionality, but also the chance to explore the rationale behind their design. Moving this agency and creative power to the learner can create opportunities for rich learning experiences with a new creative medium. Even more importantly, it can fundamentally change relationships with the tools they use.

Building with computational construction kits can allow people to create in new ways and engage new fields of knowledge. A computational construction kit can be described as a set of tools or objects that allow one to create a computational artefact. They build on the tradition of existing children's construction kits, such as LEGO bricks and Erector sets, by giving children a set of digital building blocks. The Programmable Brick is a computational construction kit that allows users to create behaviours for their constructions in the physical world (Resnick, 1993). It is a small micro-controller that can be programmed to interact with the world around it using a wide range of sensors and actuators. These extensions, in addition to the 'brain' that is the Brick itself, are the components of the kit[1].

The Bricket

In order to address some of the issues presented, I created a Programmable Brick for the visually impaired, called the Bricket[2]. Users create a program for the Bricket in a variant of the LOGO programming language, with an application called BricketLogo (running on a Windows desktop PC). Accessibility is built in for visually impaired users via screen reading software, which reads out text as the users type, in addition to speaking out interface items. To transfer the program to the Bricket, the code is downloaded to an Interface that is attached to a serial port of the desktop PC. The Interface transfers the program to the Bricket through infrared communication (much like a TV remote control). The Bricket can then run the user's program and can output via speech synthesis, or a built-in pager motor. Inputs are drawn from two analog sensor ports (for things such as light, temperature and touch) and an extensible 'bus' port (which expands the Bricket's capabilities). The latest Programmable Brick, the Cricket, is the basis for the majority of the Bricket's technology (for more technical details, please refer to Martin, Mikhak & Silverman, 2000).

Theoretical foundations

This research draws on a number of approaches to learning. This theoretical basis helped define the learning experiences created and domains of knowledge introduced to the learners. The concrete application of these theories can lead to new relationships to learning tools.

Existing practice

While many special schools for the visually impaired do exist in the United States, they usually focus on offering services for those with multiple disabilities. Unfortunately, those who do integrate into standard school settings encounter many difficulties. These students usually are engaged in after-school activities to learn braille reading and mobility skills. Efforts must be made to make other students more aware of the visually impaired student's needs (Krebs, 2000). However, visually impaired students have been shown to be able to move through school-sanctioned curricula at the same rate as their sighted peers (further discussion of these issues can be found in Holbrook & Koenig, 2000).

The approach of Universal Design for Learning (UDL), proposed by the Center for Applied Special Technology (CAST), in part seeks to address the problems of disabled students in public schools. Much of the UDL philosophy resonates with the theoretical foundations I will present. Like CAST, I find it is crucial to make a concrete differentiation between tools that allow the visually impaired to access information and tools that the visually impaired can learn with (Rose & Meyer, 2000). I also agree that each learner is an individual, with unique learning styles, needs and interests.

However, I am not presenting an argument aimed at curriculum designers, as UDL does. This project involved laying out a set of ideas to explore, building new technologies to support these explorations, and guided a set of learners through that space. The goal is to provide a new community with interesting entry points to the approaches to learning and skills to learn discussed in the following sections.

Theories of learning

At the core, this project builds on the ideas of constructivism and constructionism. Crafted by Jean Piaget, constructivism is a theory of a child's psychological development proposing primarily that children are active constructors of their own knowledge and understanding (Piaget, 1963). Seymour Papert, who worked with Piaget, built on Piaget's approach to propose a philosophy towards learning called 'constructionism'. Constructionism values the act of creating and reflecting on personally meaningful artifacts as a rich learning process (Papert, 1994).

The idea of 'authentic experience' also provided a rationale for the contexts worked in. The term has been used by many to describe their work, but at its core lie three central ideas. One is John Dewey's notion of 'continuity of experience' – the idea that what is learnt should be valuable to the learner's current line of interest or inquiry (Dewey, 1938). Another base is Donald Schön's criticism of the laboratory environment as a dishonest setting for learners (Schön, 1987). Common threads can also be found in descriptions of 'situated learning', which proposes that learners build understanding through concrete experiences in situations (Lave & Wenger, 1991).

The process and content of learning

The set of ideas and skills to introduce to the learners can be roughly divided into two categories – approaches to learning, and things to learn. However, this distinction is not made to ascribe to the traditional 'know how' vs. 'know what' paradigm of schooling. Building on the pedagogy best expressed by those who write about 'situated learning', I do not believe that learning what something is and learning how something can be used are necessarily distinct entities (Brown, Collins & Duguid, 1989). In fact, they coexist and should thus be explored together. One often best learns the 'how' by doing the 'what'.

While constructing these digital devices, the participants often take an iterative approach to the design and become reflective about and critical of the designs around them. This process is inherent to building with the Programmable Brick – one mode of programming is specifically designed to be highly iterative in nature (Martin et al., 2000). The medium of computation provides magnificent opportunities for iterative design because of its highly flexible nature. Building on the realities of the participants' daily lives enabled us to design contextualised learning experiences. Here Schön's 'reflection-in-action' approach to design education was quite informative (Schön, 1987). For instance, while constructing their own assistive devices, participants were not only exploring technical skills, but were also building critical analysis abilities.

Using these approaches to learning, a number of specific skills to learn were emphasised. Programming, for instance, leads to process-oriented ways of thinking. Working with electronic sensors gives learners an opportunity to engage in discussions of their own senses. In addition, working with sensors and variables requires knowledge of traditional mathematical operations (such as averaging and thresholding). For this population, that is particularly powerful because of the permutations that can be made on digital information to represent it in an accessible and meaningful manner. Following the pedagogy laid out earlier, these skills were encountered while 'doing' in real situations rather than constructed or artificial settings. These issues led to interesting discussions about the nature of the information gathered, or how the sensor works, or why one representation might be more intuitive than another.

Bricket activities

This study consisted of a small set of activities to test out the technology and activity ideas. Based on interpretations of the theoretical foundations explained earlier, the study was conducted as a series of themed sessions with individual children in their homes. The participants kept the Bricket between sessions, continuing to build and explore. The study was carried out over five sessions of three to four hours each, totalling roughly 15 to 20 hours of time with each study participant.

Session plans

The initial Bricket activity was designed to immediately suggest assistive uses for the technology, but at the same time honestly expose some of its limitations. We began with the interactive Command Center area of the interface, where any command typed can be immediately executed on the Bricket (in a highly interactive manner). Thus if we typed, say, 'hello', the Bricket would speak the word 'hello' with its speech synthesis module. We would then plug in the distance sensor module and use a command such as say-number distance to have the Bricket speak the distance it sensed. At this point we had a distance-sensing device that was useful and relevant to the visually impaired community, and simple to create. The session ended with leaving the user with the goal of getting more comfortable with the BricketLogo language syntax by creating other simple programs around the say command.

The second activity was designed to introduce the idea of having the Bricket on and around for prolonged periods of time, and to use basic constructs not discussed in the first session. These included the loop and repeat commands, and the idea of recursion. This centred on using the real-time clock module, which reports back the date and time to the Bricket. The overall goal was to try and cultivate an attitude towards the Bricket like that towards a toy.

After two sessions, and the time in between, a sufficient level of familiarity with the programming language and environment was established, and issues of sensing the world were engaged. Valuing what the learner brings to the experience, this was wrapped in explorations around the theme of recreating assistive devices that the participants already used, or new ones that did not yet exist. Examples included:

- a device that alerts the user when a glass is full
- a distance sensing cane
- a device to leave voice messages for others (an audible Post-it note)
- a speaking weather station

The underlying goal of this session was to begin to engage the participants in a discussion about how they felt about the design of the tools they use every day. These discussions led to reflections on their own designs in comparison to existing products. After the introductory session, we moved on to a larger final project which was driven by their own interests and ideas.

The digital cane

In order to provide a more thorough picture of what the learners did, the following is a story of the experiences of one of the children (a pseudonym is used). Jim is a 14 year-old boy, born completely blind. Jim's father is an engineer by trade, and it turned out that they would often work on Bricket projects together. The effects of this kind of parental support and involvement cannot be overestimated.

After the introductory sessions, Jim decided that he liked the idea of redesigning the cane, his most important assistive device. The cane is introduced to some visually impaired children as soon as they begin to walk, and rapidly becomes their most necessary assistive device. Educators for the visually impaired who focus on mobility training speak to the importance of the cane by noting how its early use establishes an attitude of independence, rather than one of reliance.

Jim's initial idea for his digital cane was to simply duplicate the project we did in the first session. We were able to mount the distance sensor three-quarters of the way down one of his canes, run the wires up the cane and plug them into the Bricket (which he was wearing on his belt with an attachable belt-clip). We soon found that the simple program for thresholding we had used earlier proved unreliable for actual navigation. The distance sensor returned both false positives and false negatives quite often. This dilemma set up the major focus of Jim's digital cane – strategies to deal with inaccurate sensor data. This, in fact, led us to a major area of study in robotics, known as sensor fusion. Sensor fusion is the idea that a number of disparate sensors can be combined to create a unified view of the world.

Jim was able to understand the ideas of sensor fusion by comparing them to how he used his own senses together. For instance, he sometimes uses both his cane and his hands to help guide him down a corridor he is unfamiliar with. At its most basic level, sensor fusion suggested a number of techniques for dealing with erratic sensor data. We drew on these in our attempts to discover a good way to get more reliable data out of the sensors.

One of these ideas, redundancy, suggests duplicating the uncooperative sensor, in hopes that two are better than one. At first this seemed silly to Jim, who presented the reasonable argument that 'If one doesn't work good, why would two?' His theory was that 'if you have one sensor giving me bad distances, and add another, I'll just have two sensors giving me bad distances'. To find out if his inclination was correct, we designed a test. We created a construction that, when actuated by a touch switch, spoke out the distance returned by two distance sensors mounted just above one another. We pointed at objects that we knew the distance to, and counted how many times each sensor reported a bad number. As it turned out, it was almost never the case that both sensors were wrong. This was enough to convince Jim that he should try using two, because often the two values were close to each other and an average could thus be relied on to eliminate most bad readings.

This kind of mini-experimentation was a marked departure from the earlier way Jim had been building. He often decided on one way of doing things, and then simply did that way until it worked, or until it did not. Jim liked attempting to implement his whole idea at once, rather than creating a small part, trying it out and trying it again. The iterative approach we were taking to make the digital cane was influencing the models he had for approaching unforeseen problems.

Programming simple algorithms was the main method we used to process the sensor data. One of the behaviors that Jim noticed in our little test was that 'bad stuff comes out of nowhere' – that bad readings are often unpredictable and unrepeatable. He wondered why it 'can't just remember what it saw before'. That being the spark, we created a simple averaging algorithm to remember the last ten sensor readings, and use an average of them to monitor for objects in his path. This did not seem to work, because it would take a noticeable amount of time for the average to purge itself of clear readings when something new entered in front of it. After changing it to average only three samples, it worked quite a bit better. Used in conjunction with an average of two distance sensors mounted in the same direction, this proved quite effective at reporting accurate distance readings.

Comparing his digital cane to other ones that are commercially available, Jim was quite excited by his own design. He was able to tailor its design and customise its features. In fact, he changed the behaviour to speak the distance every few seconds, rather than only speaking when an object was near. In creating his own digital cane, Jim established metrics for the design, finding his own 'more useful', and more 'like using a regular cane'. His critiques of commercial devices showed an understanding of the design decisions that went into their construction.

Reflections

The activities and technologies developed in conjunction with these learners demonstrate that the visually impaired community is able to create assistive devices, among other computational devices, with the appropriate digital building blocks. These children were familiar with computers and screen-reading software, but did not have programming experience. They began with a tool that they used primarily for communicating, and quickly made it a tool for creating and building.

Concepts and approaches

The objects created by the study participants raised the question of whether there are sets of concepts and approaches that are more likely to be familiar to a visually impaired learner. This community's daily interactions already develop certain senses more than others (most sighted people are impressed by visually impaired people's developed senses of touch and hearing). In particular, this study singled out the concept of negative feedback as one such idea. Unlike open loop control systems, negative feedback allows for self-correcting mechanisms (much like a thermostat regulates temperature in a room). Previous work demonstrated that, even after being introduced to the idea of negative feedback as an important control system for mobile robot navigation, sighted students continued to rely on inaccurate dead-reckoning position data (Martin et al., 2000).

In marked contrast to Martin's examples, the learners in this small study immediately embraced negative feedback systems as a natural way to implement control systems. This suggests to me that because of their visual impairment, negative feedback systems became part of their everyday lives. A concrete example of this can be found in their use of the cane. As a visually impaired person sweeps a cane back and forth, their arc and position changes based on what they find. If they encounter some object, their gait and sweep changes to discover the range of the obstacle, and adjustments are made to bypass it. This is a negative feedback control system, but the key difference is that they are part of it – using some device to sense, and then acting on that data to correct for some goal. This close relationship to the concept leads me to propose that the idea of negative feedback is more likely to be developed in visually impaired learners. It also presents another model of introducing sighted students to the idea of feedback – one that might place them in the control loop by replacing one of their senses with an electronic sensor.

Feedback is just one example of a concept that seemed to be developed by the visually impaired learners worked with here. Further research into these issues could shed light on how to design better learning tools for the visually impaired and new entry points to fields for sighted learners.

Future plans

This initial study led to many concrete and theoretical results. On the physical side, the Bricket case had many usability problems and requires a redesign. The software, which relies on the JAWS screen reader, is being adapted to be independent of that expensive commercial software. Additionally, the BricketLogo application is being generalised to work with the LEGO Mindstorms product, another Programmable Bricket that came out of the Epistemology and Learning Group's longstanding collaboration with the LEGO Company. Once these changes are made, the Bricket would be ready for a larger trial. The overall goal of this research is that embracing these new creative technologies will engender new attitudes towards learning, in addition to changing how visually impaired learners relate to the assistive technologies they use every day.

For more detailed discussions of all the issues presented herein, please refer to Bhargava (2002). This work was supported in part by the LEGO Company, the National Science Foundation, Media Lab Asia, Learning Lab Denmark, and the Things That Think and Digital Life Consortia at the MIT Media Lab. Many thanks to Mitchel Resnick, Bakhtiar Mikhak and Sile O'Modhrain for their comments on various parts of this text.

Footnotes

[1] The Programmable Brick has been developed and iterated upon for the past 15 years in the MIT Media Lab's Epistemology and Learning Group (http://el.www.media.mit.edu/).

[2] The inspiration for this project came from discussions between Sile O'Modhrain (who is visually impaired), when she was at the MIT Media Lab as a visiting researcher, and Rahul Bhargava, a graduate student there with no experience of working with visually impaired children. Conversations led to the idea that this could be an interesting community to work with. From a theoretical point of view, working with this community presented an opportunity to take the research in a new direction.

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