MyAccessible Math: Shining Light on Math Concepts for Visually Impaired Students

by

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A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
August 6, 2022

Keywords: Information and Communication Technologies (ICT), Human-Computer Interaction (HCI), Assistive Technologies, Mathematics, Students with Vision Impairment (SVI), Accessibility

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Abstract

Human-Computer Interaction (HCI) research aims to make systems versatile, easy to use, and accessible for most people. While computer technologies have successfully remodeled and improved the learning process, students with vision impairment (SVI) are at a disadvantage due to the lack of accessibility to their learning tools. This research aims to present the tools and studies that promote self-learning in mathematics for students who are blind or have low vision.

First, we present the initial work in MyAccessible Math, an open-source web platform that integrates user-centered design principles for SVIs to learn and practice mathematics. The prototype integrates speech recognition and text-to-speech libraries to provide personalized real-time feedback. We evaluated interaction modalities in the prototype using experimental research designs with visually impaired elementary, middle, and high school students from Alabama Institute for the Deaf and Blind (AIDB) and Alabama School for the Blind (ASB). We recognize the limitations of interaction features in the prototype and propose further improvements.

Then, we transform MyAccessible Math into a fully functional cloud-based system. We introduce the math evaluator that generates step-by-step solutions to math expressions. We incorporate speech recognition libraries with Natural Language Toolkit (NLTK) to answer open-ended questions related to mathematics. Finally, we evaluate improved interaction and motivational techniques in MyAccessible Math with five individuals to assess the system's usability.

Acknowledgments

First, I would like to express my sincere gratitude to my advisor, Dr. Richard Chapman, for his continuous support and mentoring over the last four years. He has always provided honest and supportive advice in my research. It has been a great privilege to have worked under his supervision. I also want to express heartfelt appreciation and gratitude to Dr. Daniela Marghitu. Her guidance, suggestions, and encouragement have helped me throughout my journey here at Auburn University.

I express my sincere gratitude to my advisory committee members, Dr. Dean Hendrix, Dr. Sanjeev Baskiyar, and Dr. Bo Liu, for their guidance during my graduate studies. Their feedback on my work and comments have been very beneficial in improving the quality of this dissertation. I would like to thank Dr. Chih-hsuan Wang for serving on my reading committee.

Finally, I am also grateful to my family and friends back in India for the continuous support and inspiration they provided me over the last six years. I cannot express enough gratitude to my best friend and my life partner, Fatemeh Jamshidi, for her love and support.

We appreciate the students and educators at AIDB and ASB for their support in this study.

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List of Abbreviations

AFB	American Foundation for the Blind
AIDB	Alabama Institute for the Deaf and Blind
API	Application Programming Interface
ASB	Alabama School for the Blind
AST	Abstract Syntax Tree
AWS	Amazon Web Services
CSS	Cascading Style Sheets
CT	Computer Technologies
HCI	Human-Computer Interaction
HTML	HyperText Markup Language
IAPB	International Agency for the Prevention of Blindness
ICT	Information and Communication Technologies
IRB	Institutional Review Board
JSON	JavaScript Object Notation
JSP	Java Server Pages
NHIS	National Health Interview Survey
NLTK	Natural Language ToolKit

NLTS	National Longitudinal Transition Study
NSB	National Science Board
NSF	National Science Foundation
NVDA	NonVisual Desktop Access
OCR	Optical Character Recognition
OS	Operating System
PDF	Portable Document Format
RNIB	Royal National Institute of Blind People
SR	Screen Reader
STEM	Science, Technology, Engineering and Math
SUS	System Usability Scale
SVI	Students with Vision Impairment
TTS	Text-to-Speech
UCD	User Centered Design
UEB	Unified English Braille code
VA	Virtual Assistant
WCAG	Web Content Accessibility Guidelines
XML	eXtensible Markup Language

Chapter 1

Introduction

Recent findings in 2020 from the International Agency for the Prevention of Blindness (IAPB) discovered that 32 million children or adolescents in the world are blind or experience moderate to severe vision impairment [41]. According to the 2018 National Health Interview Survey (NHIS), an estimated 32 million adult Americans (about 13% of all adult Americans) have trouble seeing even when wearing glasses or contact lenses, or they are blind or unable to see at all [17].

Human-Computer Interaction (HCI) is a study of design, implementation, and evaluation of an interactive computing system for human use and studying the major phenomena surrounding them [40, 50]. The abundant information available on the Internet and recent improvements in HCI technologies have improved the way we acquire, share and test our knowledge. With the growing interest in self-directed learning, many developers, researchers, and universities have launched creative, flexible, and easy-to-learn programs to improve students' productivity [44].

The COVID-19 pandemic has affected everyone, but it has been challenging for visually impaired students [7]. While e-learning technologies have paved the way for self-learning during the COVID-19 pandemic, self-learning has not become a reality for visually impaired people. According to the Royal National Institute of Blind People (RNIB) [5], two-thirds of visually impaired individuals have become less independent.

According to the 2013 National Longitudinal Transition Study-2 (NLTS-2) report by the U.S. Department Of Education [14], students without disabilities are approximately three times as likely as students with disabilities to earn high GPAs; 20 percent of students in the general population earned GPAs of 3.35 or above, compared with 6 percent of students with disabilities [14]. The poor performance in their academic courses is a major factor in failing to graduate or acquire the skills desired by employers. The employment data collected by the American Foundation for the Blind (AFB) between May 2016 and April 2017 shows a 70% unemployment rate for people who are blind or have vision impairment [16].

Many initiatives have been undertaken by the United States Congress to identify the reasons for this and to suggest possible solutions [56]. The National Science Board (NSB) Vision 2030 Task Force was established and charged with coordinating the development of a Vision that will help guide the Board and the National Science Foundation (NSF) to increase support for science and engineering research [64]. The latest report shows that the U.S. K-12 mathematics and science scores have stagnated and are well below those of many other nations [66]. In addition, the report states that women and underrepresented minorities remain inadequately represented. The term "underrepresented minorities" is not exclusive to ethnic and racial minority groups. The earlier 2015 report by NSB mentioned individuals with disabilities as the most underrepresented group facing obstacles in STEM (Science, Technology, Engineering, Math) disciplines [69, 65].

Mathematics has been recognized as a formidable roadblock for Students with Vision Impairment (SVI) [38]. High-school mathematics is a baseline for students to learn and persevere in the social and professional worlds. With technological advancements, Information and Communication Technologies (ICT) have provided many resources and educational tools such as graphics calculators, computers equipped with dynamic geography software, and web applications for virtual learning, contributing to an overall better learning experience in mathematics [47]. Many research studies have attempted to address the use of Computer Technologies (CT) in mathematics education in K-12 classrooms, especially for special needs students [52]. Additionally, CT have shown more significant effects on mathematical education for special needs students than general education students. The positive effect was greater when combined with a constructive approach to teaching than a traditional one [52]. These studies facilitate SVIs and provide digital access to math formulae on the web and in Portable Document Format (PDF), use sonification and verbal messages to convey the overall structure of the graph with additional information, and incorporate auditory methods to provide hints when necessary.

1.1 Dissertation Goals

This research focuses on developing MyAccessible Math, a multimodal platform for SVIs to learn and practice math concepts. Specifically, the following features have been implemented as proof-of-concept: (1) an easy-to-learn interaction mechanism for the students for clear communication with the application; (2) an algorithm that solves math problems and provides step-by-step solutions to students; (3) a voice assistant for students to learn math concepts; and (4) a math module for professors to add math questions. These features were implemented in a web application to promote a seamless self-learning experience for SVIs.

MyAcccessible Math uses an iterative development process that involves feedback from students and their educators from the Alabama Institute for the Deaf and Blind (AIDB) and the Alabama School for the Blind (ASB) to ensure usability. A small usability study for proof-of-concept was used to assess the accessibility features of the application. The features mentioned above are improved after careful analysis of user feedback.

The first area of focus, the interaction mechanism, offers "handsfree" interaction and navigation on the web. Custom voice commands are added to explore the content on the application. These commands allow users to navigate within the math questions and ask for hints while practicing math questions. A secondary interaction, using keyboard shortcut keys, is also implemented on the application for users who do not have access to a microphone. These shortcut keys are consistent with the NonVisual Desktop Access (NVDA) Screen Reader (SR).

The second area of focus, the step-by-step solver, allows users to work on math problems one step at a time and ask for help when needed. This solver incorporates compiler-based approaches to scan, parse and evaluate a mathematical expression. This math evaluator has two advantages: First, the delivery and complexity of each step presented to users, and second, the wide range of math concepts it can support. This research supports basic arithmetic operations and solving linear equations.

The third area of focus, the voice-based Virtual Assistant (VA), enables the communication between the application and the user. VAs, such as Apple's Siri, Amazon's Alexa, and Microsoft's Cortana, are primarily used for everyday tasks such as controlling a music player, checking the weather, and setting up reminders [78, 79]. This research investigates using enhanced VA to help users learn math concepts. The VA is trained with over 1000 math questions. This dataset includes questions and answers related to knowing more about the system, learning mathematical concepts, and asking for help. This feature enables responses to open-ended questions and responds to questions as a tutor would.

The fourth area of focus, the math editor, allows instructors to add math questions. The system uses MathML for encoding mathematical expressions. Wiris MathType editor [13] is embedded on the website to convert mathematical expressions to MathML. These questions with other important details such as question points, math topic, description of the math topic, maths question in MathML format, and question description are stored in a secure database.

1.2 Research Questions and Approaches

The work attempts to answer following questions to support dissertation goals:

- RQ1: Can auditory methods allow students who are blind and do not know Braille to practice and learn math concepts?

- RQ2: How effective are voice-based interaction and navigation on the web application? Does this allow students to navigate within the math question?
- RQ3: How can we design the system to respond to open-ended questions?
- RQ4: Can compiler construction theory approaches be used to solve and generate step-by-step solutions for users?

To answer RQ1, we collected, analyzed, and critiqued mathematics learning technologies for SVIs. These apps were categorized by the domain, interactive features, and accessibility approaches to examine the teaching, learning, and assessment. Educators at local blind institutes were also consulted on current technology trends used in their classrooms for math education. These research studies showed that the Braille literacy rate among young children in the U.S. has been decreasing since 1960. The Braille Literacy Statistics by BrailleWorks shows that only 8.5% of students were identified as Braille readers in 2012 compared to over 50% in 1960 [56, 2]. On the other hand, auditory assistive technologies have enabled digital access to math formulae on the web [42, 29, 73] and incorporated with multimodal applications; auditory methods have helped many visually impaired students learn math concepts [26, 54].

Over the years, with the technological advancements, there have been many improvements in how information is presented to students with vision impairment, SRs being the dominant mechanism [43]. The main disadvantage of SRs, as mentioned in [70], is that blind users need to go through an abundance of irrelevant content before finding what they were looking for [43]. To answer RQ2, we designed and developed the prototype of MyAccessible Math. Visually-impaired students from local schools in Alabama participated in the survey to evaluate the voice-based interaction on the web application.

The initial prototype of the web application uses text-to-speech and speech recognition libraries. This approach enables communication with the system but limits the responses to closed-ended questions. To answer RQ3, we improved the human-computer interaction by introducing an intelligent conversational bot.

The initial prototype uses expression parser libraries to parse and evaluate mathematical equations. To answer RQ4, we explored the use of compiler construction theory approaches to generate an abstract syntax tree (AST) for a math expression and provide hints when asked.

1.3 Contributions

The dissertation makes empirical and artifact contributions supporting the research questions mentioned above. The contributions and how they support my thesis are summarized below:

1. Barriers and issues SVIs face while working with math are identified. Through a literature review, we found that there are opportunities to build assistive technology that (1) enables "human-like" interaction with the application and (2) provides step-by-step solutions to math problems. Though similar applications exist, they are far from an average student's reach, too expensive, or not accessible.

2. Design, development, and evaluation of the initial prototype of MyAccessible Math are completed. Students from local schools in Alabama participated in the study to evaluate the application. We showed how students could explore and solve complex mathematical formulae with auditory methods. If auditory methods are not attainable, the alternate keyboard interaction is implemented. We showed how a navigation system could be implemented for students to navigate within math questions. The prototype also allowed instructors to add math questions and create practice quizzes. Additionally, we identified classroom technology trends and further application improvements through semi-structured interviews with educators.

3. Improvements in accessibility features are achieved. We identified limitations in the prototype and improved interaction and communication features. The current version

has two improvements: (1) developing a simple machine learning model to respond to open-ended questions and (2) implementing a math evaluator to add support for more mathematical concepts. This research reports findings based on interviews, survey responses, and System Usability Scale (SUS) questions from five blind or low-vision individuals working with the application.

1.4 Definition of Terms

Blindness: a medical term indicating the state of being sightless; blindness is often also used to describe severe visual impairments in one or both eyes with some residual vision.

Legal blindness: defined by the U.S Social Security Administration as best-corrected visual acuity of 20/200 or less in the better eye; or a visual field limitation such that the widest diameter of the visual field in the better eye subtends an angle no greater than 20 degrees [4, 56]. With 20/200 visual acuity, a person can see at 20 feet what a person with 20/20 vision sees at 200 feet [12].

Assistive Technology: defined by the AccessComputing [11] as "Assistive technology is a technology used by individuals with disabilities in order to perform functions that might otherwise be difficult or impossible. Assistive technology can include mobility devices such as walkers and wheelchairs, as well as hardware, software, and peripherals that assist people with disabilities in accessing computers or other information technologies. For example, people who are blind may use software that reads text on the screen in a computer-generated voice, people with low vision may use software that enlarges screen content or people with speech impairments may use a device that speaks out loud as they enter text via a keyboard."

1.5 Dissertation Overview

In Chapter 2, Related work, we summarize the work done for people who are blind or have low vision, in particular focusing on math education for K-12 students. This includes visual disability, e-learning, and similar design frameworks that investigate the experiences of blind students and assistive technologies that have been developed to help them.

In Chapter 3, Initial Work, we illustrate the prototype of the MyAccessible Math, which describes the iterative design process, the application architecture, methods of data collection, evaluation of application features, and further improvements.

In Chapter 4, MyAccessible Math, we summarize limitations and feedback from students and educators. This is followed by the improvements in interaction and communication features. This includes the design and implementation of a basic chatbot and a math evaluator. The chapter also covers the evaluation of improved accessibility features for people with vision impairment, data analysis, and results from interviews, surveys, and SUS questions.

In Chapter 5, Contributions and Future Work, we summarize the dissertation's contributions, discuss our research's limitations, and highlight areas for future work.

Chapter 2

Related Work

In this chapter, we summarize the background and related work in mathematics education for people who are blind or have low vision. We will describe (1) math accessibility on the Web, available tools, and usability issues for visually impaired people; and (2) assistive technologies for accessing and working with mathematics.

2.1 Math Accessibility on the Web

2.1.1 Accessibility

Accessibility is "the fact of being able to be reached or obtained easily", as defined by the Cambridge English Dictionary [10]. In the current context, accessibility is the practice of making the product or service available to as many people as possible. Accessibility involves two key points: how users with disabilities access digital information and how developers enable digital content through assistive devices by adopting good interface design practices.

Many users of the Web have various types of disabilities. These disabilities include sensory, motor, physical, neurological and cognitive impairments. These users with disabilities use various forms of assistive technologies to allow them to browse websites [51]. These technologies include hardware and software such as SRs, voice recognition, alternative pointing devices, alternate keyboards, and refreshable Braille displays [51, 68]. A website that is flexible to be used by these assistive technologies is called an accessible website [74]. This is what is referred to as "Web Accessibility" or "Design for All." There are guidelines, called the

Web Content Accessibility Guidelines (WCAG) [9], that web developers can follow to help make websites accessible. The United States Government offers similar guidelines, included in the Section 508 initiative [8], to web developers.

E-learning is a term generally used to refer to computer-enhanced learning [75]. Today with e-learning systems, instructional delivery and communication are possible between students and instructors that are geographically dispersed and have conflicting schedules. Several schools and universities have provided courses and degree programs via distance education. However, the benefits of such systems will not be realized if learners fail to use the system. Unfortunately, less than 2% of the world's top one million sites offer full accessibility, according to the study conducted by WebAIM [77]. In a research study, Baule (2019) [28] analyzed 24 special education websites in the U.S. to determine the accessibility for individuals with disabilities. The study found that only 25% of special education sites meet the minimum levels of accessibility criteria.

2.1.2 Practices and Challenges in Math Education for the Blind

In today's educational practices, educators of SVIs play an essential role in evaluating the competencies of continuously evolving products. We interviewed educators on assistive technologies used in their classrooms for mathematics. See interview questions for educators in Appendix A. The results from the study are summarized below in Table 2.1. The study aimed to gain insights into the technologies used at different phases of instruction, delivery, and communication at local schools in Alabama.

Braille is a tactile system used by visually impaired students to read and write by raising dots within Braille cells. While Braille is suitable for the text representation, mathematical equations are multidimensional and may contain fractions, algebra, series, logs, and exponentiation [43]. Also, 6-dot Braille can represent only alphanumeric characters and a small set of special characters with the 64 combinations of possible dot placements. Thus, by extending the 6-dot Braille system to the 8-dot Braille system, 64 possible combinations can

Table 2.1: Assistive technologies used in math classrooms

Purpose	Devices
Devices used in basic math courses	BrailleNote Talking Calculators The Abacus
Devices used in advanced math courses	Math Manipulative Toolbox Tactile devices BrailleNote Refresh-a-Braille
Devices used by educators to prepare math lesson content	Braille Writers Braille Transcriptions
Devices used by students and educators to simultaneously study, work or discuss math problems	Google Docs Printed Braille Docs
Devices used by students to work on math problems independently	iPad iPhone ChromeBooks

be extended to 256 combinations. This is an excellent choice for a specific context. However, by today's digital standards, the use of Braille is not applicable in a tech-driven industry [61].

Another constraint is that mathematical Braille is not universal. The International Council on English Braille developed Unified English Braille (UEB) to unify the Braille codes used among English-speaking countries. UEB codes for math and science differ significantly from the Nemeth code. See UEB and Nemeth code cheat sheet for Mathematics in Appendix B. The U.S. used Nemeth code for working with math and science until 2012, while other English-speaking countries such as South Africa, Canada, Australia, New Zealand and the U.K. used UEB for math and science. The U.S. officially adopted UEB in 2012 and transitioned from Nemeth to UEB in 2016. Even today, some states feel that the Nemeth is superior to the UEB code. Only a few states have adopted UEB for math and science, while others have opted to stick with the Nemeth code. The data [62] shows that only seven states have set UEB for technical materials as the default code. This means that a student attending high school in a state where UEB is taught for math and science might attend college in a state where the Nemeth code is used. That student must learn an entirely new code to complete their studies successfully [62].

Students with disabilities often face access barriers when it comes to mathematics education because of symbolic and nonlinear math expressions. People with vision impairments often rely on SR when working with computers. SRs are software programs allowing blind or visually impaired users to read content on the computer screen and web browsers. SRs work by translating visual content into a format the user can consume and interact with, such as audible speech and Braille.

The audio SR transforms content on a screen into audio using a Text-to-Speech (TTS) engine. Over 15 SRs are available on the market today, with personal computers running Linux, Windows, Mac, IOS, Android, and more. The Operating System (OS) is a set of programs that perform essential tasks necessary for the computer to function. Today most common OS are Microsoft's Windows and Apple's Mac OS. There has been a significant disparity in the accessibility tools for Windows and Mac OS. Some assistive technologies and accessibility features come bundled with all operating systems, but typically these applications provide only a minimal level of accessibility [6]. Some of the most popular SRs are JAWS[1] (Windows), NVDA[2] (Windows), VoiceOver[3] (Mac and iOS), TalkBack[4] (Android), and ChromeVox[5] (Chromebook). When users need to move to a new system, it is challenging to preserve their current settings. This is very sensitive for users with specific needs, especially those who are visually impaired [49].

Despite their importance, SRs have many limitations. The SR only speaks plain text and semantic information about the focused element. Like audiobooks, SRs read from left to right and top to bottom, moving from one element to another, ignoring the page structure. Although their capabilities are robust and convenient, SRs fail when working with mathematical notations, images without *alt* text, and inaccessible PDF documents. SRs are challenging to master and have compatibility issues.

[1] https://www.freedomscientific.com/products/software/jaws/
[2] https://www.nvaccess.org/download/
[3] https://www.apple.com/voiceover/info/guide/_1121.html
[4] https://blog.google/products/android/all-new-talkback/
[5] https://pressbooks.library.ryerson.ca/iwacc/chapter/chromevox-screen-reader/

Accessing math content is also possible through printed Braille documents or refreshable Braille displays. Hard copy or printed Braille documents are large in volume and expensive to print. Refreshable Braille displays enable access to information on a computer screen by electronically raising and lowering different combinations of pins in Braille cells. Compared to speech, refreshable Braille displays are quiet, provide easier access to information, and allow users to check format and spelling. However, the price of Braille displays ranges from $3,500 to $15,000, far from what average users can afford.

In summary, people with visual impairments suffer because of the lack of accessibility to their learning tools, especially in mathematics. Additionally, translation software and electronic devices provide a way to access complex math and technical documents. However, the complexity and cost of these tools and different Braille standards make it difficult for the visually impaired audience while working with mathematics.

2.2 Math Tools for the Blind

With the increased interest in digital learning over the past decade, several authors have conducted systematic literature reviews documenting assistive technologies implemented for visually impaired people. These existing systematic reviews cover the effects of computer technology on school students in mathematics learning [53], ICT applications for visually impaired people [27], or digital learning technology for visually impaired students [48, 18].

In a similar work, Karshmer (2009) [46] divides math accessibility approaches into two types: static and dynamic. Static approaches provide a way to express math content using Braille. On the other hand, dynamic approaches cover technologies that require interaction and engagement with math content [56]. In more recent work, Mejía (2021) [57] divided the applications into tools for accessing mathematics and tools for creating mathematics.

Based on the taxonomies of the previous surveys presented, we discuss math tools in two categories: projects or independent libraries that provide digital access to math content and systems that allow students to learn and practice mathematics. We represent these tools by answering the following questions:

- What are the reported accessibility approaches and outcomes in existing mathematics learning apps?
- What are the domains, interactive mechanisms, and accessibility features of these apps?
- What are the contextual settings in which these applications are scrutinized?

2.2.1 Digital access to Mathematics

Although a digital copy of a text is useful for learning for SVIs, creating a digital copy of complex mathematical formulae is relatively difficult [22, 31]. When a complex mathematical formula, as shown in Equation 2.1, is presented in digital format, many screen readers can interpret it in multiple ways. The digital copy of mathematical formulae often fails to convey the correct information. Sheikh (2018) [73] introduced a non-ambiguous language Math-Speak, that can easily translate STEM materials into high-quality computer-synthesized voice. MathSpeak takes an equation and provides the correct interpretation, thus removing any ambiguity. For Equation 2.1, MathSpeak would read the equation as "3 plus two plus open fraction 1 over x end fraction" [73, 31].

$$3 + 2 + \frac{1}{x} \tag{2.1}$$

Twenty-eight undergraduate students participated in the evaluation to answer if the terminology used in MathSpeak significantly reduces ambiguity relative to the common everyday terminology used to convey mathematical expression. The evaluation results show that using MathSpeak resulted in the correct interpretation of a significantly large number of mathematical expressions compared to the common terminology [73].

Bouck (2014) [31] evaluated the performance of the digital and traditional textbooks while accessing algebra. The results demanded further research on implementing the digital text in mathematics for visually impaired students. The authors in separate studies [33, 24] also showed the advantages of audio-tactile devices and speaking systems. Audio-tactile systems also increased motivation and curiosity for visually-impaired students.

Axessibility (2018) [20] is a LaTeX package that enables math formulae accessibility in PDF documents. The package enables the creation of accessible PDF documents by inserting hidden replacement text for maths formulae using *ActualText* PDF attribute, making it visible to screen readers and braille bars. Through a preliminary evaluation with four blind users, the authors uncover that Axessibility effectively makes mathematical formulae accessible [20]. However, the package is currently incompatible with Adobe Acrobat DC PDF tagging functionality.

Cervone (2019) [32] presented work toward making math accessible by extending personalization features in the MathJax library. MathJax accessibility features are mainly aimed at supporting users with reading disorders. MathJax provides speech and tactile output to support screen-reader users and provides visual aids to maximize accessibility on the Web. MathJax provides aural rendering for mathematical expression, which can be generated on the fly when running in the web browser or precomputed by the author. It also offers various techniques such as highlighting, contrast, formula coloring, and magnification to increase the accessibility of math formulae on the Web. The latest version 3 allows users to combine different accessibility components such as speech and Braille output and magnification with exploration and highlighting.

Dumkasem (2019) [34] introduced a cloud-based mobile application, EyeMath. It allows users to upload images of a page snippet containing math expressions and converts them into sentences for the device's SR program to read aloud. First, the application separates math expressions from plain text. Math expressions are then processed into an AST and parsed into Thai sentences [34]. EyeMath uses Tesseract Optical Character Recognition (OCR) to extract text from images. The usability testing with five visually impaired people confirms the application's potential benefits of reading math expressions aloud from images.

Web-ALAP (2020) [25] is a web-based LaTeX editor that provides speech-based prompts and automatic narration of the error messages. It also offers a "Math Mode" that offers a natural language description of the mathematical content within the document. Web-ALAP offers comprehensive keyboard shortcuts to maximize accessibility and more accessible navigation for math equations. The web-based LaTeX editor is equipped with accessible debugging features for real-time auditory feedback. The user testing with ten students showed that the users appreciated the Math Mode of the web application. All participants recognized the importance of being informed through audio feedback.

While tactile methods fail to accommodate students with graphs and visual cues, sonification is an effective way of conveying them [67]. AudioFunctions.web (2019) [21] is a web application that uses sonification, earcons, and speech synthesis to enable blind people to explore mathematical function graphs [21]. Based on user needs and preferences, AudioFunctions.web allows a global overview and analytical exploration of a given function graph on mobile and traditional devices through different interfaces such as touchpad, mouse, or keyboard. An experimental evaluation with 13 visually impaired participants shows that the proposed interaction methods are highly usable.

2.2.2 Learning and Practicing Mathematics

More recent technologies have attempted to develop multimodal systems for students to learn and practice mathematics. Elkabani (2015) [35] designed a framework that enables visually-impaired students to learn and practice algebra like sighted students. The process is divided into four steps: The teacher provides algebraic expressions using a math editor. The system then converts math expressions to MathML objects. The interactive workspace in the system allows users to interact and navigate within questions using keys. The system provides auditory feedback in English and Arabic using the TTS engine. The workspace generates MathML objects from solutions submitted by students. Finally, teachers can access these solutions in MathML using a MathML editor. The systematic evaluation from a group of visually impaired individuals showed that the system increased their performance. It enables students to solve linear algebra exercises faster than Braille writers and allows them to study linear algebra without needing a sighted tutor.

Ahmetovic (2017) [19] proposed the iPad application Math Melodies for primary school children to teach mathematics. The application enables exploring audio-visual elements on a touchscreen and provides feedback to keep students engaged and entertained. The application has 19 types of exercises organized into ten chapters. These exercises are accessible to students through SRs and an on-screen keyboard to provide answers. Two sighted and three blind primary school students participated in the study. Participants were able to interact with the system and found the application accessible and entertaining [19].

One recent study, AnimalWatch-VI-Beta (2018) [29], a self-voicing computer program, attempts to increase students' performance for pre-algebra word problems [29]. The application has more than 800 word problems for teachers to use with their students. Each word problem includes interactive hints, worked examples, and video lessons that students can access on request to guide them to and through the appropriate steps to a solution [29]. These problems and interactive hints are presented via audio using a self-voicing program. 14 SVIs participated in field-testing the application and provided feedback on their experience using it. The research data showed the potential value of audio features in technology-based learning environments. Students could solve most of the easy and medium-difficulty questions. The results were consistent with other recent studies that suggested that audio materials can be helpful resources for students with visual impairments in learning math [36, 39, 58, 29]. However, the study focuses on word problems. The feedback from students also suggested adding more problem sets. In addition, the program only provided two hints per problem. Sometimes more hints and explanations are required when working on complex math problems.

Grossman (2019) [37] developed an automated text-based tutor to promote online math education. The system is built as a chatbot, presenting the math materials through a simple text-based interface. The chatbot uses informal languages, including emojis, to give a human touch to the application. The prompts include personalized feedback and answers to open-ended questions. In the first study, the authors examined the user preferences of 116 users, comparing MathBot with videos and written tutorials from Khan Academy. 42% of users preferred MathBot over videos from Khan Academy. The study concludes that conversational agents are promising tools in online education. However, the application is not designed considering students with disabilities. It requires users to use the on-screen keyboard to communicate with the chatbot.

Maćkowski (2020) [55] developed a computer-aided method to increase self-confidence and motivate visually-impaired students working on mathematics. The method has the following elements: First, the math exercise is divided into smaller steps. Second, based on users' responses at each step, the system evaluates the user's skills. Third, The system provides a new exercise if the user solves the math exercise. If the user submits incorrect answers, it is assumed that students do not know the concept and the system provides contextual feedback through hints. The motivation of the method among blind people is to provide a tool that can gradually improve the value of factors motivating blind people to learn mathematics [55]. However, as mentioned by the authors, the system may be difficult for users to use independently and may need educators' help.

Nahar (2020) [60] developed a mobile application for students to learn Nemeth Braille to provide an affordable tool. The application includes the basic learning content of math Braille and is designed for beginners. The application provides auditory instructions at every step while using it. It takes input through the phone touch screen and provides feedback to help users make decisions. The application enables users to use the application without anyone's assistance. Teachers, experts, and end-users evaluated the application to identify its usability. The evaluation showed promising results toward the acceptability of the designed application.

2.3 Chapter Summary

The work in this chapter provides insights into different assistive technologies developed to improve the mathematics knowledge of students with vision impairments. However, learning through listening, while continuing to be recognized as part of the expanded core curriculum for educating blind and visually impaired students, receives less attention [42]. There is a need to combine these techniques, such as learning to interact with the system through voice, learning by listening, and self-directed learning to create a barrier-free and accessible system.

The goal of my dissertation work is to address the uncovered gaps in the area of math education for students with disabilities.

Chapter 3

MyAccessible Math Prototype

This chapter presents the development and the empirical investigation of the prototype of MyAccessible Math. We address RQ1: *"Can auditory methods allow students who are blind and do not know Braille to practice and learn math concepts?"*. We addressed this research question for two reasons: (1) Fewer than 10 percent of the 1.3 million people who are legally blind in the United States are Braille readers [76]. (2) Special embossing printers are required to produce documents printed in Braille. These documents consist of raised embossed dots suitable for haptic perception using the fingertips. These printers are expensive - generally starting from two thousand US dollars. To assess the use of auditory methods, we first developed the prototype of MyAccessible Math. The prototype incorporated speech libraries to enable voice-based interaction and navigation. The prototype also uses keyboard interaction using shortcut keys when voice interaction fails.

We also address RQ2: *"How effective are voice-based interaction and navigation on the web application? Does this allow students to navigate within the math question?"*. We evaluated the system with a lab study where ten blind and low vision participants worked on five practice math questions. Participants enjoyed the prototype, and auditory methods helped them practice math questions. Our results showed that student preferences for interaction mechanisms, color themes, and voices varied greatly. Also, keyboard interaction was dominant while navigating within math questions.

3.1 Introduction

According to the U.S. Department of Education, as mentioned in [14], 45% of all students with disabilities had GPAs less than 2.25. Most students aged 5 to 20 years with vision impairment have trouble accessing the content in STEM. Many assistive technologies either focus on reading or speaking mathematics or are limited to descriptions of graphs [30].

In response to this need, we developed MyAccessible Math, a web application that provides auditory hints while solving various math problems. The prototype is designed to free the SVIs from needing the help of an instructor and promote self-learning. Our goal is to enable blind or low-vision people to practice math concepts effectively and independently.

Our work makes several contributions. First, we developed a prototype for blind or low vision people. The prototype can hear, speak, and act as a math instructor. Second, we determined that detailed auditory feedback may improve math performance. Finally, our work can provide general insights for future engineers and scientists on improving the education of SVIs.

3.2 MyAccessible Math Prototype Design

User-Centered Design (UCD) is a robust framework for creating easy-to-use and interactive self-learning platforms, especially for SVIs. As the name suggests, the UCD is built on the idea that the needs and preferences of end-users should drive the design process for new technologies [63]. The UCD approach used in developing MyAccessible Math depended on feedback received during interviews and evaluation with SVIs. We identify three design principles used in developing MyAccessible Math, followed by a technical description of the development process.

3.2.1 Design Principles

MyAccessible Math uses speech synthesizer and speech recognition libraries to provide audio descriptions of math problems and feedback when necessary. We identified these design principles to support the goal of the project: non-visual interaction and navigation, boosting confidence by promoting self-learning, and catering to novice and non-Braille users.

Non-visual Interaction and Navigation

Many SRs are compatible with the websites developed under accessibility standards. However, the main disadvantage of SRs is that in most cases, users must go through the whole page to get the layout overview. Custom voice commands are programmed on MyAccessible Math to support efficient web browsing so users can easily navigate between web pages. When users do not have access to a microphone, keyboard interaction using shortcut keys is also supported. The prototype also allows users to navigate within questions using arrow keys.

Boosting Confidence

In addition to providing a visual representation of math expressions, MyAccessible Math also allows SVIs to learn and practice math concepts. The prototype promotes self-learning, increases the independence of SVIs, and decreases the amount of time required compared to traditional tools. It also reduces students' working memory since users can use arrow keys to navigate within math questions. Overall, SVIs would work with systems as a normal user would, eliminating the need for one-to-one interaction with the instructor and boosting confidence.

Catering to Novice and Non-Braille Users

The application is easy-to-use and caters to novice users. The application is designed by carefully following W3C accessibility standards. Every page on the application has a welcome message when users land on it for the first time. All focusable elements and links on the web page provide audio descriptions of respective features. On the other hand, experienced users have an option to disable these repetitive audio descriptions on each page by pressing a key or using a voice command. Since interaction and navigation on the site are entirely speech-dependent, the Braille skills are not required to use the application. The application supports elementary, middle, and high school students.

3.2.2 Technical Development

The prototype of MyAccessible Math is implemented using Hypertext Markup Language (HTML), Cascading Style Sheets (CSS), and JavaScript as the front-end, and Java Server Pages (JSP) as the back-end language. A MySQL database is used for storing important user information such as name, email, encrypted password, and users' role like 'instructor' or 'student' and questions information. It also uses other open-source JavaScript libraries mentioned below:

Wiris MathType Editor

Wiris MathType editor [13] is embedded on web pages for the professor to add math questions. Math formulas can be exported to multiple formats and are compatible with LaTex and MathML. These questions with other important details such as, question points, math topic, description of the math topic, math question in MathML format, and question description, etc. are stored in a secure MySQL database.

Annyang.js

Annyang [23] is an open-source JavaScript speech recognition library used for voice navigation on the website. Custom voice commands and actions can be programmed on a website to make voice interaction possible for visually impaired students.

ResponsiveVoice.js

ResponsiveVoice [71] is an open-source text-to-speech library written in JavaScript, offering an easy way of adding voice to any website or application. The main advantage of using a JavaScript library over traditional SRs is the ability to personalize the text-to-speech mechanism based on how and when the user would interact with the page. In other words, the web application would provide a brief audio description of menus, links, buttons and text entry fields when user hovers the pointer over it.

mXparser

mXparser [59] is an open-source mathematical expressions parser and evaluator that provides the ability to solve mathematical expressions. We modified mXparser in a way that would read math questions MathML from the MySQL database, covert it to a mathematical formula and provide a step-by-step solution to users that would help them learn the math concept effectively.

Jwerty

After the initial meetings with the educators at the AIDB, keyboard shortcuts were programmed in the application to support keyboard navigation when speech recognition fails. Jwerty.js [1] is an open-source library that supports handling keyboard events on the web. Table 3.1 shows a list of a few keyboard commands supported on the application.

3.2.3 System Architecture

The MyAccessible Math web application is divided into two independent components to make more efficient use of the system, as shown in Figure 3.1. We developed the web application using the model-view-controller architecture that helps manage the resources effectively, saves development time, and is faster. The front-end component performs user-interaction-related operations. Essential duties include understanding speech commands

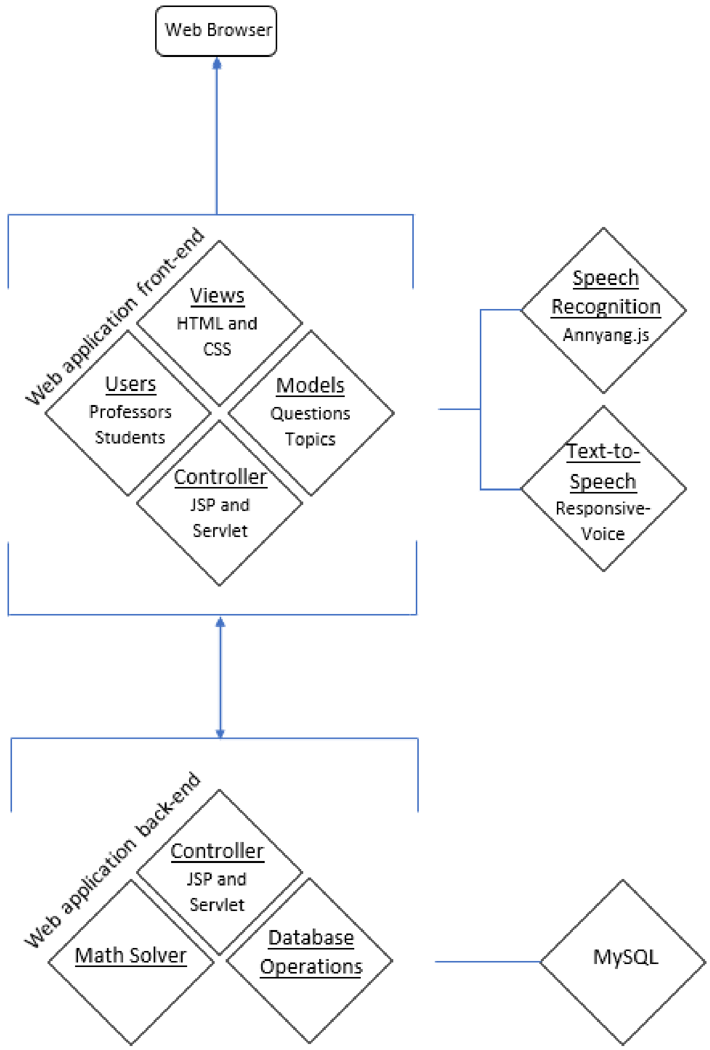

Figure 3.1: MyAccessible Math System Architecture

from the users and redirecting users to web pages based on their roles and voice commands. The back-end component acts as a controller and performs database, mathematical equation solving operations.

The web application consists of three subsystems: one devoted to translating mathematical formulas to a structured and less ambiguous MathML and storing it to the database; a speech recognition module that listens to commands from users for voice navigation and providing hints; and finally a math module that provides math questions with step-by-step solutions to users for a better understanding. In the following, we detail the implementation of each module.

Translating and storing mathematical formulae

MyAccessible Math uses Wiris MathType editor to add and convert mathematical questions to MathML. Figure 3.2 shows the MathType editor embedded on a website.

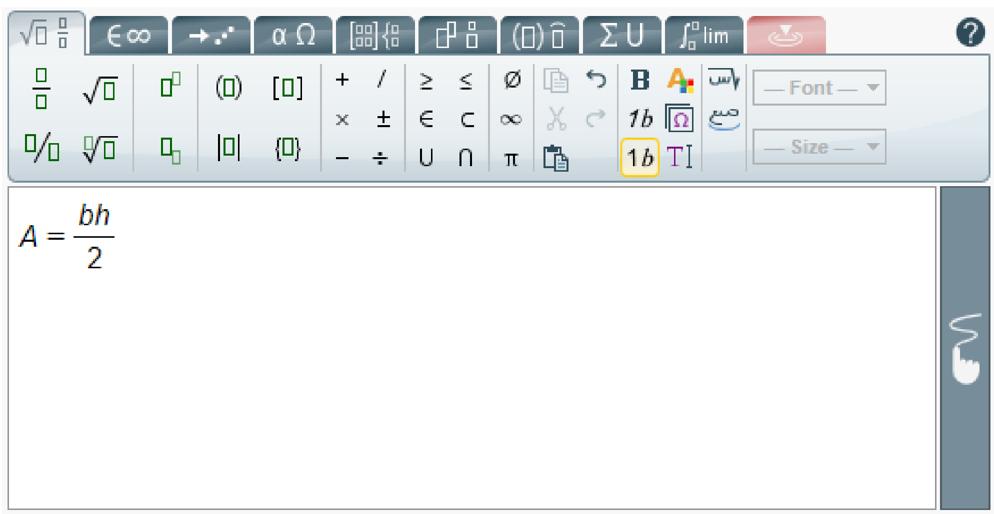

Figure 3.2: MathType Editor

According to the Wiris, the embedding is compounded by two steps. The first one displays the editor itself, and the second one is calling the editor Application programming interface (API) to retrieve the MathML [80].

Wiris MathType editor allows the professor to add one question at a time. The question then is converted to MathML to store the question efficiently. MathML allows complex equations to be stored as structured eXtensible Markup Language (XML) text rather than images. The example of the math formula and corresponding MathML is shown below in equation (3.1):

$$A = \frac{1}{2}(b * h) \tag{3.1}$$

```
<?xml version="1.0" encoding="UTF-8"?>
<math>
   <mi>A</mi>
   <mo>=</mo>
   <mfrac>
      <mrow>
         <mi>b</mi>
         <mi>h</mi>
      </mrow>
      <mn>2</mn>
   </mfrac>
   <mo> </mo>
</math>
```

Speech recognition module

Annyang [23] is an open-source JavaScript speech recognition library that makes adding voice commands to any website simple. Annyang works with all browsers that support speech recognition and supports multiple languages. Annyang understands commands with named variables, splats, and optional words. Table 3.1 shows a few of the voice commands supported by the current version of the application. With Annyang, more custom commands can be added in the future to extend the scope of the project.

Table 3.1: Voice and Keyboard Commands

Voice Commands	**Keyboard Shorcut Keys**	**Action**
‘first time’	‘1’	Welcome message
‘practice page’	‘3’	Redirects to practice
‘question’	‘4’	Picks a random question
‘previous hint’	‘7’	Repeats previous hint
‘next hint’	‘8’	Shows next hint
‘high school’	‘SHIFt+3’	To high school page
‘exit’	‘SHIFT+Q’	Exits the practice

Math module

The math module is responsible for teaching the mathematical topic selected by the student. This process is divided into three steps: The first step is to retrieve a brief description of the topic from the database and provide it to the student. This is implemented using the ResponsiveVoice.js [71] text-to-speech library. The second step is to select questions one at a time for the selected math topic from the database. Then, the math parser will take the question as an input and determines the steps to find the solution. Once the student is ready to practice questions, the student will be redirected to the practice questions page. If the student encounters any issues, the student can say terms such as "first hint" or "repeat question."

The current version of the math parser supports the following math concepts: place values, basic arithmetic, simplify fractions, and simplify linear equations.

One example of simplifying fractions with the step-by-step solution is shown below in equation (3.2) and table 3.2.

Simplify fraction,

$$\frac{5}{12} + \frac{1}{8} \tag{3.2}$$

Table 3.2: Steps to Simplify Fractions

Step index	Step	Result
Step 1	Find Greatest common divisor (GCD)	GCD of 12 and 8 is 4
Step 2	Find Least common multiple (LCM) using formula, a * b = GCD * LCM	LCM of 12 and 8 is 24
Step 3	Multiply first fraction with LCM	10
Step 4	Multiply second fraction with LCM	3
Step 5	Adding values from last two steps	13
Step 6	Result is addition from the last step divided by LCM	13/24

3.2.4 The User Interface

The web application has two user groups: the professor and the student. The users will be redirected based on the user roles stored in the MySQL database. Figure 3.3 and Figure 3.4 show interfaces for some of the pages that have been developed. In the future, these pages will be modified, as appropriate, based on information and feedback from the students. An example scenario of the application flow is shown in Appendix C.

The Professor's View

Since the professor will be responsible for adding questions and supervising students' activities, the professor module is not accessible for visually impaired users. Several web pages are designed for the professor to add questions, add math topics, and check the list of students. The following is the list of features implemented for the professor module.

1. The professor can add, modify, delete or navigate to math topics. The professor can add math questions, descriptions of math topics, and points once the topic is created.

2. Professors can add complex math expressions using the embedded MathType editor. These expressions will be converted to MathML and stored in a secured MySQL database.

3. These math questions can be combined to create assignments, practice exercises, or quizzes.

4. Professors can also check students' activities. These include the number of questions, practice exercises, and quizzes attempted.

The Student's View

Since the students are an essential entity in this project, all the web pages students can access have voice and keyboard interaction enabled. The following is the list of features implemented for the student module.

1. The practice commands allow users to navigate the practice module and attempt math questions. Students can pick random math questions or select a math topic to practice. Students can skip questions at any time.

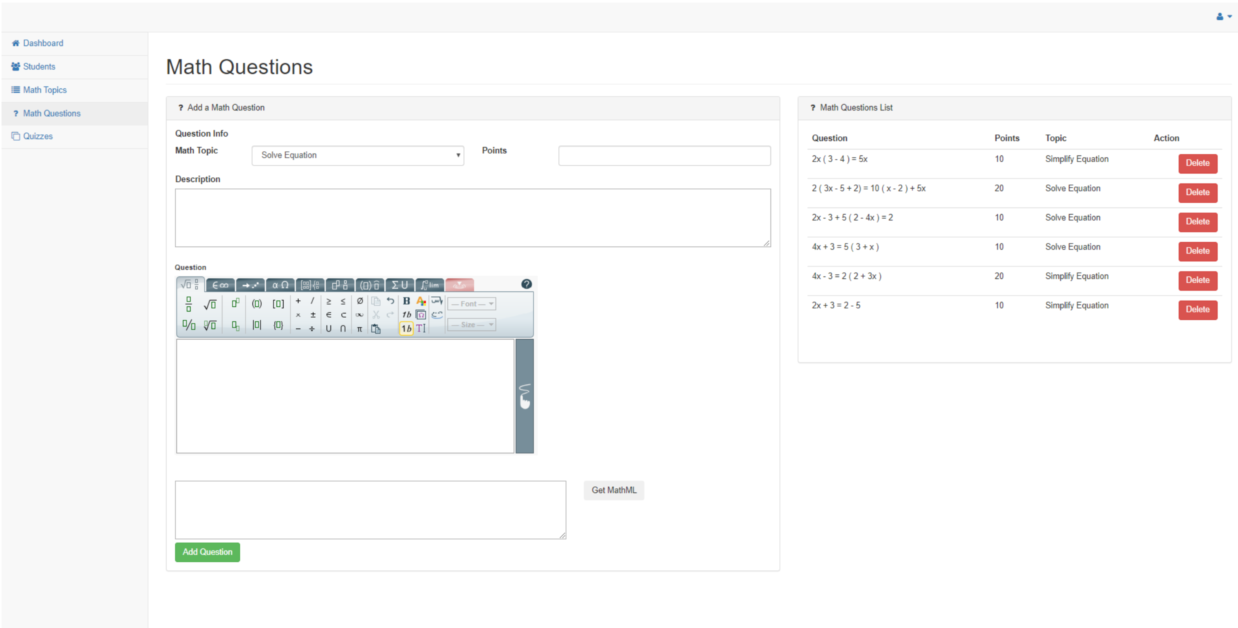

Figure 3.3: Professor's View

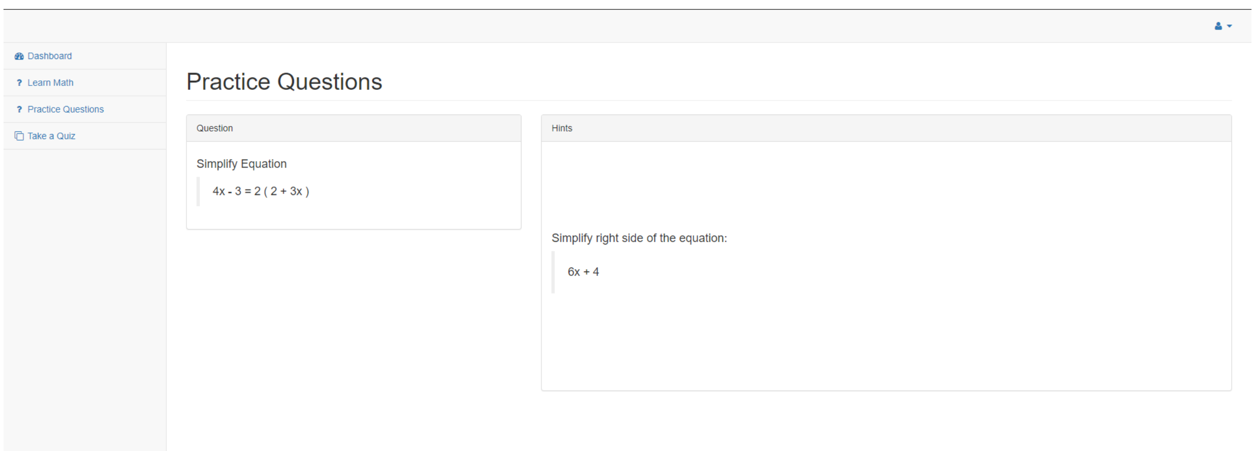

Figure 3.4: Student's View while Practicing Questions

2. The hint commands allow users to interact with the application using voice or keyboard keys. During an evaluation quiz, hints are disabled.

3. The navigation commands allow users to navigate through web pages swiftly. Welcome and focusable elements messages are enabled by default. Once comfortable with the application, users can disable these messages.

4. The learning commands allow users to select a math topic. The learning module starts with the description, provides a list of questions to practice, and delivers hints (or steps to solve) by default.

3.3 MyAccessible Math Research Study

The experimental research design investigated the effectiveness of the application with ten visually impaired elementary, middle, and high school students from Alabama Institute for the Deaf and Blind (AIDB) and Alabama School for the Blind (ASB).

Initial meetings

The pre-evaluation meetings were focused on identifying the technological needs of SVIs and their educators. We presented the prototype of the MyAccessible Math to educators at the AIDB. The email invitation used for the prototype evaluation is attached in Appendix D. We consulted six individuals, including assistive technology experts and instructors from the AIDB. These sessions were conducted at Auburn University and the E. H Gentry campus at the AIDB. The researcher gave demonstrations of the technologies used in MyAccessible Math. The meetings included questions about recent trends in assistive technology for math education for SVIs. Common concerns include cross-compatibility problems caused by many types of assistive devices and their operating systems.

The meetings concluded with identifying three following improvements with the application for SVIs:

1. Provide a way for users to navigate inside a math question.

2. Add a live speech-to-text conversion module for researchers to investigate issues related to speech recognition.

3. Integrate keyboard navigation using shortcut keys if speech recognition fails. The educators recommended using basic math questions and asked to add support for elementary, middle, and high school SVIs.

We chose to remodel the system based on information gathered from the interviews and a systematic literature review of assistive technology platforms.

Participants

Ten SVIs participated in this study. Students were selected based on (1) a disability of visual impairment, including low vision or blindness; (2) enrollment in elementary, middle, or high school at the AIDB or ASB, where the study was conducted; and (3) willingness to participate (informed consent). Three of ten students were blind, and seven had moderate to severe vision impairment. The participants spent between 45 and 60 minutes completing the study.

Setting and Materials

This study occurred at the AIDB on the E. H. gentry campus in the Assistive Technology labs. The Assistive Technology lab consisted of desks formed into a U-shaped sitting arrangement where the researcher had easy access to each student. Students worked individually with a member of the research team.

Materials included a computer and a headphone. The AIDB provided laptops with a built-in microphone and Google Chrome web browser for students to practice questions. At the end of the evaluation, students anonymously provided post-survey feedback. See post-survey questions in Appendix E.

Evaluation

We presented students with five math questions based on the difficulty levels for the evaluation. First, we described MyAccessible Math. Second, we demonstrated the accessibility features of the application. Students begin the assessment with the application by completing a short tutorial to familiarize themselves with the web application interaction. They learn to press "1" to learn shortcut keys, "4" to practice questions, "0" to skip the question, "7" to hear the previous hint, "8" to hear the next hint, and so forth. The application does not allow revisiting completed or skipped problems and does not keep track of students' activity. We asked students to provide anonymous feedback on the application's accessibility and interaction features. We asked students questions about their liked, disliked features and future improvements.

Results and Discussion

The participants used keyboard and voice navigation to practice math questions accurately. Educators at the AIDB provided math questions for the study. See math questions in Appendix F. These questions ranged from simple arithmetic operations to solving linear equations. Participants voluntarily chose options to evaluate the elementary, middle, or high school modules. After the evaluations, we interviewed participants to assess web accessibility. Moreover, the students provided information about their experience using the application and how to improve the accessibility features for users with low vision or who are blind. Participants' information was kept confidential.

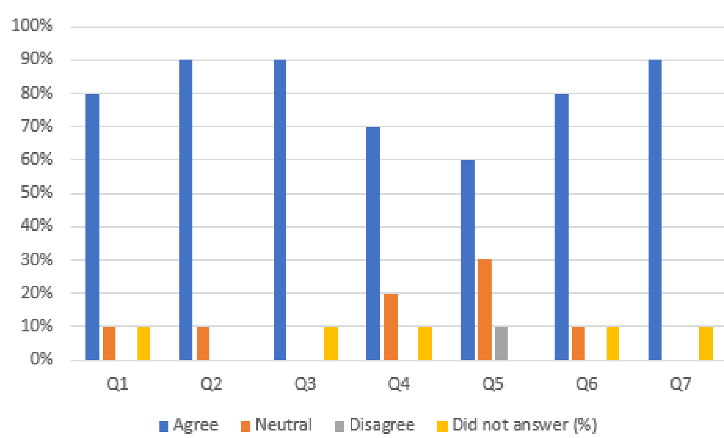

Figure 3.5: Students' Responses for Post-survey Questions

To evaluate the accessibility features on MyAccessible Math, we used a 3-point Likert scale. Figure 3.5 shows the post-survey responses from students.

Voice and Keyboard Interaction

Of the 10 participants, two participants stated that they had trouble understanding the U.K. English. Three participants mentioned that the speech rate was accurate and easy to understand. According to one student,

> "I liked how the application spoke clearly and was not a robot voice I could not understand."

Seven students liked keyboard interaction, which helped them a lot while navigating the web application. A student commented,

> "The keyboard interaction was not frustrating; just press a key and move on."

Four students mentioned how easy it was to use the application and liked the feature that the application would talk back and forth. One low vision student wanted the magnification on the mouse hover feature. Three students appreciated the part about using arrow keys to navigate inside a math question and how it would say each character out loud.

Educators' Feedback

Based on observations and experience working with SVIs over the users, educators provided valuable feedback about the application's accessibility features. For the evaluation, educators provided the list of questions but requested to have the ability to add questions for future evaluations. The current version of the application is not accessible for visually impaired instructors. According to a visually impaired instructor at the AIDB, having a Braille file upload module to add questions would be an excellent application feature.

Limitations

The students suggested various features they liked, disliked, and suggested further improvements in the application. Two students had trouble using the microphone and used keyboard interaction for the study duration. Since ten participants were situated in an enclosed room during the evaluation, some participants had difficulty using voice interaction due to voice mix-ups. Four students liked the application and suggested adding more math concepts. Two participants did not like the inability to add answers. Out of 10 participants, five participants did not have a preference or liked the black-on-white color theme of the application. Two low-vision participants did not like the color theme and preferred to have a darker theme. Five participants suggested adding an option to have a drop-down menu to choose the preferred color theme. Since participants have experience using NonVisual Desktop Access (NVDA), they suggested having shortcut keys consistent with the NVDA screen reader. For example, "CTRL" should be pressed to pause the speech instead of "5". Two elementary school students faced trouble locating shortcut keys on the keyboard.

3.4 Chapter Summary and Future Work

We showed how auditory methods could support users in math education. We gained valuable insights while evaluating the prototype with K-12 students. While auditory interaction methods are helpful in self-learning, especially if users do not know Braille, there are a few limitations of the application. Learning and remembering a new set of voice commands may be difficult for school students. If the exact voice command is not used, the interaction with the application fails. The text-to-speech library is embedded on the page, so users need to disable SRs on their computers. This prevents users from using other applications on their computers while working with the application.

In the next chapter, we summarize the limitations of the interaction techniques used in the prototype and introduce improvements. Designing and evaluating a system that solely provides auditory feedback for mathematics to blind individuals is a challenging research problem. With our prototype's development and by introducing further improvements, our emphasis is to promote self-directed learning tools for SVIs.

We also feel the following improvements can be made to increase the potential benefits:

1. Ability to change the color theme.
2. Ability to increase or decrease font-size.
3. Ability to respond to open-ended questions.
4. Provide a way for users to submit answers.
5. Having keyboard shortcut keys consistent with popular SRs.
6. Ability to change voice dialect.

Chapter 4

MyAccessible Math

We significantly expanded the original prototype design based on the research study's results. We transformed MyAccessible Math from a prototype to a fully functional system with new math concepts, more practice questions, and new interaction techniques so that users can use the system without instructors' assistance. Our evaluation changed from a lab setting to a System Usability Scale (SUS) to measure the system's usability. The prototype had no motivational techniques. We propose a cloud-based application with new features and motivational techniques to increase confidence. This chapter addresses two research questions: RQ3: *"How can we design the system to respond to open-ended questions?"* and RQ4: *"Can compiler construction theory approaches be used to solve and generate step-by-step solutions for users?"*. We evaluated MyAccessible Math with five visually-impaired people. The interaction preferences between participants varied greatly. Data collected from post-survey and SUS questions showed that the dedicated teaching module, motivational techniques, and interaction mechanisms effectively promote self-learning, reduce barriers and increase confidence for individuals with vision impairments. Participants expected more complex math concepts, specifically Geometry and Statistics, indicating that future work should also include support for visual and graphical representation of data.

4.1 Introduction

We reconsider the way high school students learn and practice mathematical questions [45]. The prototype uses text-to-speech and speech recognition JavaScript libraries that give speech control to the user. This approach enables communication with the system but limits the responses to closed-ended questions. The researcher must manually provide the questions and answers for the system to work as intended. The system intended to work for visually impaired students where clear communication is a key; this was a severe downside.

Additionally, the prototype uses an expression parser to parse and evaluate basic arithmetic questions and linear equations. The major drawback of using the proposed library is that it lacks support for the Python programming language and provides step-by-step solutions to only limited mathematical concepts.

Inspired by our study results, we redesigned the system with the following objectives:

- Improve the interaction by integrating Natural Language Toolkit (NLTK) to implement an intelligent bot for speech recognition.
- Implement a math evaluator that solves the math problems and provides step-by-step solutions to students.
- Provide non-verbal audio feedback to increase motivation.

4.1.1 MyAccessible Math Design Elements

MyAccessible Math offers various visual alteration and enhancement techniques to improve user interaction. These techniques allow users to change color themes, progressively magnify content on the screen, and provide non-verbal feedback when landing on a page, completing a step, or making a mistake while practicing. Although these techniques primarily aim to support low-vision users, it allows the general audience to understand page and math formula structure. We identified and improved the following design elements:

Magnification

MyAccessible offers a magnification of content on screen through on-screen buttons, speech commands, and keyboard keys. While standard zoom can help increase the font size overall, MyAccessible offers personalization settings to enlarge the font size for math content on the website at once. It stores user preferences through browser cookies. In addition, the application offers an extended magnification of math expression while hovering the mouse over it. The extended zoom on mouse-hover is limited to math expressions and sub-expressions only.

Color Contrast

Contrast sensitivity refers to the ability to detect differences between light and dark areas [3]; therefore, options to change background and foreground color can be a simple and most effective solution for low-vision users. Bright colors that reflect light are easier to detect for low-vision users. While some users prefer having a dark background and bright foreground colors, others may prefer the opposite. MyAccessible offers options to choose color themes and keeps users' preferences. Along with magnification on mouse-hover, the application also provides expression highlighting. In practice, the math expressions can be highlighted and magnified on mouse-hover.

Personalized Speech

The prototype evaluation study showed that some users found speech helpful while others had trouble understanding the U.K. English. In the extended version, we allow users to change voice dialect. In addition, while new users may find the speech on the application accurate, experienced users may find it slow, boring, and repetitive. We offer different speech modes for users based on their experience with the application. Users may choose between non-speech, limited, or extended audio modes. The application also allows users to change speech volume, pitch, and speech.

Non-verbal Audio Feedback

While speech feedback is essential in the application developed for visually-impaired users, audio messages become redundant and hinder students' progress. We incorporated non-speech audio notifications to increase users' confidence and increase productivity. Auditory confirmations inform users after a successful page redirect, completing a step, or finishing a math quiz. These sound notifications convey a sense of progress and provide positive encouragement. Overall, the learning process becomes easier, more entertaining, and more engaging.

4.2 System Overview

We transformed MyAccessible Math into a fully functional cloud-based web application. The website on the client-side provides an easy-to-learn interface for users to select a math concept to learn or practice. Microservices on the server-side are deployed as Amazon Web Services (AWS) Lambda functions written in Python. The front-end, written in ReactJS, invokes Lambda functions through API Gateway on user request. The system architecture is shown below in Figure 4.1.

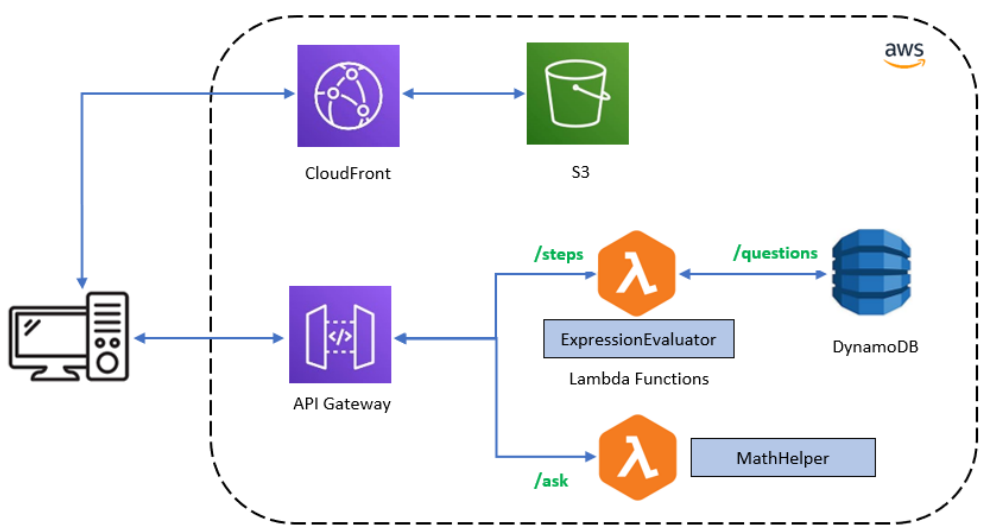

Figure 4.1: MyAccessible Math Architecture

The corresponding Lambda function is called depending on the request from the front end. The ExpressionEvaluator function is called if the user wants to practice and solve questions. MathHelper is called if the user wants to learn the math concept or asks open-ended questions. The goal of the ExpressionEvaluator is to provide steps for mathematical expressions. The MathHelper is a simple retrieval-based chatbot based on NLTK library. In the following section, we discuss these two functions:

4.2.1 The Expression Evaluator

The evaluator supports four operations: Addition, Subtraction, Multiplication, and Division. This process is divided into four components. These components take an input and produce an output. The previous component's output is then fed to the next component until the final component returns steps to solve the expression. The components are shown below in Figure 4.2.

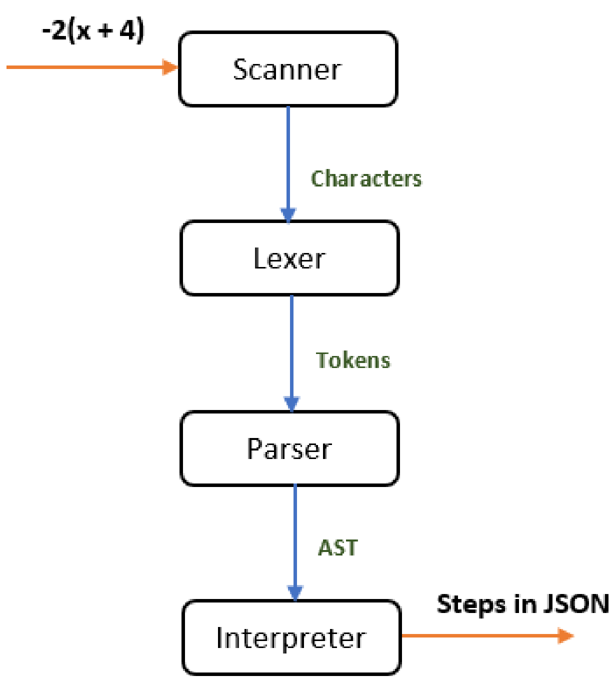

Figure 4.2: The Expression Evaluator Components

We defined basic mathematics 'rules' for evaluating expressions to ensure the correct order of operations. In other words, perform multiplication and division, then addition and subtraction. The current version of the evaluator supports grouping, power, factorial, negation, and decimal numbers.

The first component is Scanner. This class provides a simple mechanism to read characters one by one. The class has various methods that provide the character's position, the next character, and a boolean property to indicate the end of the expression. These characters are then parsed into Tokens by the Lexer. The Parser will read these tokens to generate an Abstract Syntax Tree (AST). The Parser is also responsible for syntax validation to make sure the database does not have any invalid math expressions. The rules for our grammar are translated to methods in the Parser. These rules consist of terminals and non-terminals. A terminal symbol cannot be divided into smaller parts. For example, a Number (2) in mathematics is a terminal that cannot be divided into smaller parts, but an expression (2x) can be divided into other terminals or non-terminals. One rule for the expression '1 + 2' expects to find a Number followed by an Operator followed by another Number.

The Parser then builds ASTs for math expressions. The AST models the relationship between tokens generated by Lexer - as a tree comprising nodes and the nodes containing children. Each node contains information about the token type and related data. For the expression: '2x + 3', Figure 4.3 shows the AST generated by the Parser.

The Interpreter visits each node of the AST and returns the JavaScript Object Notation (JSON) that shows steps for the expression. In general, the Interpreter takes an expression and returns the final result. We modified the Interpreter to traverse nodes, record operations before evaluating them, and then pass values to parent nodes.

For the Interpreter, we implemented the evaluate method that takes the ASTNode and calls respective methods based on the runtime type of the node. For example, if the type of the node is 'AdditionASTNode', the evaluate(type: ASTNode) will call evaluate(type: AdditionASTNode) for the addition operation. After the addition operation, evaluate(type:

NumberASTNode) is called to get the addition result. Each evaluate method also records the behaviour of the node for the response JSON.

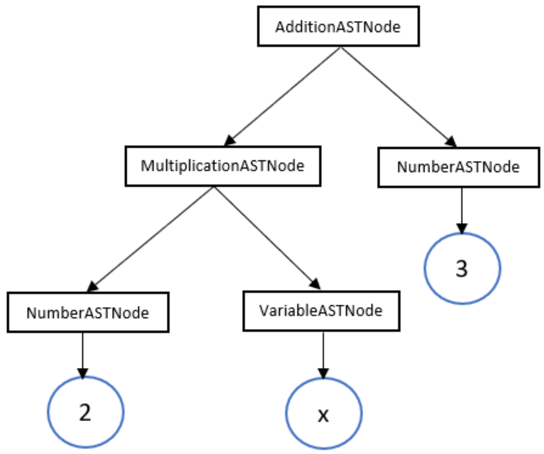

Figure 4.3: AST for the expression, 2x + 3

4.2.2 The Math Helper

Chatbots are software programs capable of making conversations via text or speech. To improve human-computer interaction, we introduce an intelligent conversational chatbot. We incorporated the NLTK library to perform basic text operations on a given dataset to search for an answer to students' questions. We use the NLTK library for data pre-processing and training the model. We decided to use NLTK because of its wide range of API features and precise documentation [45].

For this research, we gathered over 1000 questions that users may ask while interacting with the system. The dataset includes questions and answers related to knowing more about the system, learning mathematical concepts, and asking for help. Figure 4.4 shows the structure of the data.

The data is structured into tags, patterns, responses, and context.

- Tags: Categories that shows students' intention
- Patterns: Possible questions that students may ask

```
{"tag": "start_conversation",
 "patterns": ["Hi there", "Is anyone there?", "hey", "Hello", "Good day","Hi"],
 "responses": ["Hello", "Happy to have you here", "Good to see you."],
 "context": [""]
}
```

Figure 4.4: Dataset Structure

- Responses: Possible responses to the questions mentioned in patterns
- Context: Contextual words relating to a tag for better classification

Trying to build an intelligent agent is a complex task as the only knowledge the agent has access to is the information it has learned itself [15]. The dataset is stored in a JSON file. Since machine learning algorithms require data to be in a numerical feature vector rather than text, the dataset must be filtered carefully using statistical and numerical means. NLTK provides various text processing methods to clean the data:

- Conversion into lowercase or uppercase: In this step, the words are uniformly converted to lowercase or uppercase, so the algorithm does not treat the same words differently.
- Removing noise: This includes removing punctuation and special characters. This step also includes removing stopwords. Stopwords are the most common words in the text and removing those does not change the sentence's meaning. For example, 'about', 'me', 'something', etc.
- Tokenization: In tokenization, sentences are broken into a list of words, i.e., tokens.
- Stemming or Lemmatizing: Stemming or Lemmatizing is the process of reducing tokens to their root. The slight difference between stemming and lemmatizing is that the stemming can often create non-existent words.

After the initial processing phase, we need to transform the text into meaningful feature vectors. This process is called feature extraction. Bag-of-words is a simple and popular feature extraction method. In this method, the structure of words in a document is discarded and the model is only concerned with words in the document.

Table 4.1: Example Conversation with the Intelligent Agent

Entity	**Communication**
Student:	Hi there.
Chatbot:	Hello there. Happy to have you.
Student:	Who are you?
Chatbot:	I am MyAccessible Math. I can help you learn mathematical concepts.
Student:	What do you know about mathematics?
Chatbot:	Ask me a question about linear equation, or probability and I will try to answer.

Once the model is trained and saved, the intelligent agent responds to students' questions with 99% accuracy. The example conversation with an intelligent agent is shown in Table 4.1.

4.3 Study Description

To determine the system's usability, we conducted a survey and follow-up interviews with individuals who are blind or have low vision. Five participants participated in the study. Participants were encouraged to use the keyboard and voice to navigate and interact with the application. We were motivated to learn whether or not people with vision impairment would be interested in using MyAccessible Math for learning and practicing mathematics.

Table 4.2: Participants' Demographic Information

PID	Age	Highest Level of Education	Impairment		SR use	Braille use	Braille skills (Scale 1-5)
			Type	Onset			
P1	11	High School Student	Can see colors and read large print	Birth	1-2 years	5-10 years	5
P2	26	College Student	Blind	Birth	$>$ 10 years	$>$ 10 years	3
P3	28	College Graduate	Left: Blind Right: $<$ 20/200	1-5 years	$>$ 10 years	$<$ 1 year	1
P4	29	College Graduate	Blind	Birth	$>$ 10 years	$>$ 10 years	5
P5	54	College Graduate	Legally Blind (Rapidly Declining)	52	$<$ 1 year	$<$ 1 year	1

4.3.1 Participants

We posted study information to blind and low-vision social media groups (See the social media post in Appendix G). Five participants were interested in the evaluation of the application. We conducted pre-survey interviews with participants to learn more about their background, SRs use, Braille use, and skills (see questions in Appendix H). Participants were compensated $20 for their time in this study. The study was approved by the Institutional Review Board (IRB) at Auburn University to protect the human subjects involved (see IRB approval documents in Appendix I). There were three females and two males with an average age of 29.6 (SD=15.4). All but one participants were college students or had at least one college degree. One participant was a high school student. Table 4.2 shows demographic information and self-assessed skills in Braille on a scale from 1 to 5. Participants P2 and P4 were blind, and participant P1 could only see colors and read large prints with more than 1-inch font sizes. P5 started losing vision around 18 months ago, and their vision is rapidly declining. Participant P3 was blind in their left eye, and their right eye had visual acuity of less than 20/200 with correction. Our study refers to these participants as *legally blind*. Participants P1, P2, and P4 were blind since birth, and P2 lost vision between the age of 1 and 5 years old.

All but one participants felt confident in using computers. Participant P1 had their parent's help while working with the application. All participants have studied math concepts at least at the high school level, and three participants have further studied math at the college level. Three participants, P2, P3, and P4, have been using SRs or Braille for more than ten years, while one participant, P1, had no experience using SRs or Braille. Participants self-assessed their Braille skills on a scale of 1 to 5, with an average of 3 (SD=2).

4.3.2 Procedure

Before scheduling introductory and pre-survey meetings, we emailed informed consent documents to participants. Parental permission and minor assent documents were acquired for

P1. The study started with a description of the application, interaction techniques, and the scope of the study. On average, individual meetings with participants lasted for an hour. Then, participants' demographic information was collected.

During the training, we first explained how the system works and how to perform available actions. Participants were recommended to use Google Chrome and disable their SRs since the TTS engine is embedded on the website for speech interaction. Specifically, we showed participants this expression and interaction modalities to simplify it: $3(x + 4) + 3 - 2(5 + x)$. Their feedback, suggestions, and recommendations for novel features were transcribed anonymously.

The research study was conducted online, and interviews were scheduled on Zoom. Participants accessed the website through their own devices. One participant (P5) faced connectivity issues and had to provide instructions telephonically. Since MyAccessible Math uses speech as an interaction mechanism, participants were asked to use the latest version of Google Chrome. Also, they were asked to allow microphone access for the website on Google Chrome. Unfortunately, one participant (P5) could not assess voice interaction because of microphone-related issues and could only provide feedback on keyboard interaction. This participant's responses to voice-interaction and SUS questions were excluded and were not considered in the analysis. Math questions used for the study are attached in Appendix J.

After the meetings, participants were asked to use the system independently to assess the system usability. The participants were asked to respond to post-survey questions, including SUS questions (see Table 4.3) and additional 12 questions specific to interaction modalities and their experience using the application (see Table 4.4). These questions are also attached in Appendix K and L respectively. We received post-survey responses from all participants. However, only three participants responded to SUS questionnaire.

Table 4.3: System Usability Scale Questions

QID	Question
Q1	I think that I would like to use this system frequently.
Q2	I found the system unnecessarily complex.
Q3	I thought the system was easy to use.
Q4	I think that I would need the support of a technical person to be able to use this system.
Q5	I found the various functions in this system were well integrated.
Q6	I thought there was too much inconsistency in this system.
Q7	I would imagine that most people would learn to use this system very quickly.
Q8	I found the system very cumbersome to use.
Q9	I felt very confident using the system.
Q10	I needed to learn a lot of things before I could get going with this system.

Table 4.4: Post-survey Questions

PSQ ID	Question
PSQ1	Voice Interaction
PSQ2	Keyboard Interaction
PSQ3	Navigation on the web
PSQ4	Navigation within the question
PSQ5	Audio hints
PSQ6	Magnification
PSQ7	Color styles
PSQ8	What features did you like the most?
PSQ9	What features did you like the least?
PSQ10	What features were most confusing for you? Why?
PSQ11	What additional features do you think should be included?
PSQ12	Any other comments?

4.3.3 Results and Discussions

The participants could use the system proficiently and explore math questions using different interaction modalities. We gathered qualitative data during the study through interviews, pre-survey, post-survey, and SUS questionnaires. Following the study, we assessed participants' responses and evaluation of interaction modalities through a 5-point Likert scale. During meetings and after using the system on their own, participants provided explicit reasons for what they liked, what features they used the most, and how the system helped them.

The ability to practice while talking steps was the most noticed and well-received feature: *"The voice input seems to work very well and is an inclusive option for students with motor function impairments"* (P3). In particular, participants liked motivational techniques: *"I liked the way it lit up and made a nice sound when answered correctly"* (P1). A participant (P4) mentioned that they liked *"Stepping through results."*

The speech module was another feature that participants appreciated the most: *"The audio reading the questions was great"* (P3). Embedding a text-to-speech library reduces the burden of installing SRs: *"Building your own screen reader into the application is great for anyone who does not or cannot have one installed on their computer, and has a much lower learning curve than a fully-featured one"* (P2). A participant (P2) added appreciating personalized speech options on the application:

> *"Adding additional voice options for the TTS is a good comfort feature for all users, and especially helpful for students who have auditory impairments and may benefit from an easier to understand voice, or students on the autism spectrum who may find certain voices very distracting or even upsetting."*

Certain features were useful only for people with low vision: *"The magnification and colors made it very easy to see"* (P1). A participant (P3) described their past experience working with math expressions and graphs: *"I had limited vision in my right eye. While*

PanOptix lens helped, using large-print books with magnifying glasses were useful to see graphs." Another participant (P2) commented on increasing levels of magnifying added on the site: *"The magnification options were very good. Many websites jump from 250% to 400% with nothing in between. This is better because there are many more choices"*.

The content structure of the application received mixed feedback: *"Using a standard table for the steps in practice mode is a great idea for those using External Screen Readers"* (P2). When experienced users use non-speech mode, the horizontal page layout is not user-friendly with SRs: *"Keep a vertical question layout."* (P3).

Overall, the motivational techniques enhanced practicing. The participants were disappointed when they learned that adding steps was only possible through speech. Following are comments from participants about having an option to add steps through the keyboard:

> *"The ability to enter answers and practice step responses with the keyboard is absolutely vital for users who cannot use voice input due to an impairment, those in noisy environments, those with an inefficient or no microphone, and those who prefer their own modified input methods such as an eye-tracking keyboard or a set of switches"* (P2).
>
> *"I want an option to type answers besides just speaking them"* (P3).
>
> *"Add steps with the keyboard"* (P4).
>
> *"I'm concerned for students using school computers who encounter the same problem. A school may have shut off all the computer microphones for legal reasons or out of an abundance of caution, or perhaps even accidentally, like I seem to have done. Without an alternate source of input, what happens then?"* (P5).

While participants were excited to use the system, some factors made using the system challenging. In particular, a participant (P3) mentioned: *"Navigating the website was a bit tricky. As I have some vision, I would also like a large side menu."* The system only allowed navigation within questions using arrow keys, not within each math step: *"I wanted to review the numbers shown in each step with my arrow keys like I did with the question field, but I could not"* (P2).

While auditory methods on MyAccessible Math received a positive response from participants, they provided exciting suggestions for improving them: *"A command for repeating the last spoken phrase would also be a useful addition to the System Screen Reader. This could be used, for example, when a noise distracts the student, or if a student with learning impairments loses concentration"* (P2). The system only listens to commands when the user presses and holds a designated microphone key on the keyboard: *"It might be helpful for a quick beep to let you know it is listening"* (P1). Currently, the system does not support a feature to pause and resume speech. These features will be added in the next development iteration of the application.

Three participants were experienced Braille users and frequently use refreshable Braille displays to read content on the computer screen. Two participants explicitly requested having the ability to read web page content using a Braille display: *"Voice assistant is cool, but I would also like to have Braille output"* (P4).

They were disappointed to know that the current iteration of the application only supports learning and practicing to solve linear equations: *"I would like to see more complex math problems, for example, Calculus or statistics"* (P4). Another participant (P3) commented: *"When growing up, learning Geometry was difficult to learn. I would like to have graphs and more math problems."*

After the initial prototype evaluations, the keyboard keys are consistent with the NVDA SR. However, unlike SRs, the application does not support a combination of keys for common actions. A participant (P2) mentioned:

> *"Consider adding shortcut keys for common actions and jumping to major sections. For example: CTRL+ALT+H for 'homepage' or CTRL+ALT+1 to move*

through steps 1 to 12 or CTRL+ALT+Q to jump to the question field from anywhere on the page."

We made several changes in the system after the prototype evaluation, and the participants well received these changes. The ability to discuss steps with the system, receive feedback after each step, and personalized speech and color settings made learning and practicing math entertaining.

The magnification allowed users to magnify web page content progressively as required. The magnification varied based on the interaction mechanism used. For example, the font size increased by ten pixels using voice interaction and five pixels using keyboard interaction. It also made a chime sound every time an interaction mechanism was used. This prevented users from repeating specific actions and being unable to "see" the respective changes.

With the interaction mechanisms used in the prototype, sometimes it became tedious for experienced users to work with the system. For some users, it was because of the pitch, dialect, or speed of the TTS engine. Sometimes it was repetitive and not entertaining to use at all. With the introduction to personalized speech settings, users can now select speech options as they deem necessary. Different speech modes allow users to disable speech and only use non-speech audio.

4.3.4 System Usability Scale

The SUS scores (see Figure 4.5) show that the system was easy to use, and participants would like to use the system frequently. In particular, Q1 and Q7 received an A^+ ranking (90) according to [72]. Participants imagined that most people would learn to use this system very quickly. Based on results from Q4 and Q10, participants thought the features were easier to learn and would not require the support of a technical person to use the system. It is important to note that only two of five participants' scores are considered for SUS scores. As mentioned earlier, we did not consider the results from one participant since they could not evaluate the voice interaction due to technical issues.

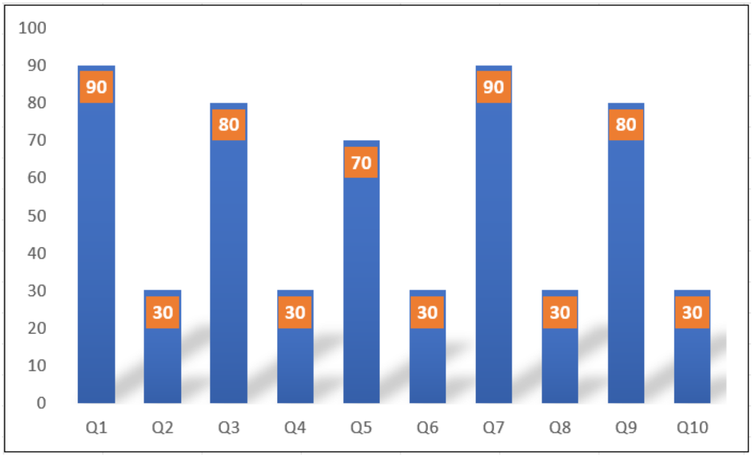

Figure 4.5: SUS Scores for MyAccessible Math

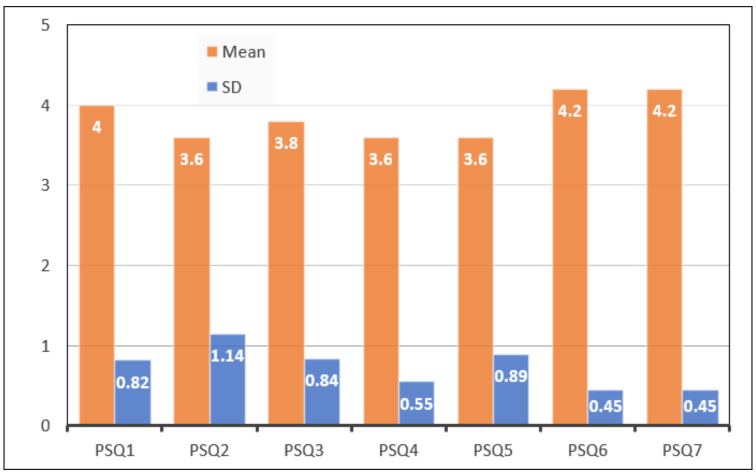

Figure 4.6: Post-survey Results for MyAccessible Math

Results from all five participants for post-survey questions were recorded and analyzed. See Figure 4.6 for post-survey results. In addition, the results for certain questions vary based on participants' ability to see. For example, low-vision individuals could only evaluate the system's magnification (PSQ6) and color styles (PSQ7). We can see that participants deemed voice interaction to be more beneficial than keyboard interaction. Three participants rated voice interaction with a score of more than 4 with an average of 4 (SD=0.82). Keyboard interaction was slightly less preferred for navigation and interaction, with an average of 3.6 (SD=1.14).

Participants with low-vision found magnification and color styles on the website beneficial, receiving an average rating of 4.2 (SD=0.45).

4.4 Chapter Summary

We developed MyAccessible Math, where individuals can learn and practice math concepts through "hands-free" interaction and discuss steps with the system as a tutor would. We improved and discussed a math solver and a chatbot developed in Python with basic functionalities. We believe that voice and keyboard interaction, combined with a step-by-step solver and motivation techniques, allow users to learn math independently and can help increase confidence. We plan to add more math problems with graphical representations in future development iterations and evaluations.

Chapter 5

Contributions and Future Work

In this chapter, we summarize contributions, previous chapters, and limitations, highlight areas of improvement, and make concluding remarks.

5.1 Summary of Chapters

In Chapter 1, we describe the need to reduce educational barriers that users with disabilities face in STEM education. We focus on math education for visually impaired students to improve their educational experiences. To support this goal, we recognize two areas of improvement: (1) improving access to math content on the Web and (2) creating systems to allow users to improve their math knowledge.

Chapter 2 highlights related work to provide foundations for (1) assistive technologies in mathematics, (2) limitations of Braille and Screen Readers, and (3) digital learning in mathematics. We summarized related research that has attempted to develop multimodal systems and described their limitations.

Chapter 3 presented our work investigating the first research question, RQ1: *"Can auditory methods allow students who are blind and do not know Braille to practice and learn math concepts?"* To answer this question, we developed the prototype of MyAccessible Math. We did a system presentation and follow-up interviews with educators from blind schools. The initial meetings provided new standpoints on the application, which we used to improve interaction modalities. To answer RQ2, *"How effective are voice-based interaction and navigation on the web application? Does this allow students to navigate within the math question?"*; we evaluated the application with ten elementary, middle, and high school students. The first evaluation provided empirical evidence of the advantages of auditory methods for web interaction and navigation. This approach is faster than traditional tools but requires students to remember voice and keyboard commands to use the system effectively. In addition, the system was too utilitarian and was not entertaining to use. We summarized limitations and proposed two improvements in interaction modalities.

In Chapter 4, we investigated the third research question, RQ3: *"How can we design the system to respond to open-ended questions?"*. The major limitation of using custom voice commands is that the interaction fails if students do not use the exact voice commands. We transformed a simple Java-based application into a cloud-based application with additional features. We incorporated the NLTK library to create an intelligent agent that responds to open-ended questions related to math concepts. The model is trained with over 1000 definitions from the math dictionary and contains most elementary, middle, and high school concepts. To answer research question RQ4, *"Can compiler construction theory approaches be used to solve and generate step-by-step solutions for users?"*; we implemented an evaluator to generate steps for a wide range of math expressions. We conducted a deployment study with five visually impaired individuals to evaluate the system's usability. The results showed that the motivational techniques helped increase confidence, and participants enjoyed working with the application.

5.2 Future Work

For our research in the field of Human-Computer Interaction and Assistive Technology, we interacted with people who are blind or low vision and their instructors. We addressed four research questions mentioned in the introduction and opened opportunities for future work in the space of promoting self-learning for people who are blind or low vision, particularly in three areas: (1) making the system available to as many users as possible, (2) keep improving application and interaction modalities based on user feedback, and (3) adding support for more mathematical concepts including Geometry.

We designed and evaluated MyAccessible Math with the motivation of making math concepts accessible. The evaluation studies were conducted either in a lab setting or online by following instructions from researchers. These studies were conducted in a private setting. However, in the future, we want to deploy the system for users to use in a public setting on a bigger scale. There are multiple language packs for the TTS engine, so adding support for other languages could open the application for people worldwide. Additionally, down the line, an exciting feature would be to provide support for instructors to add questions by uploading Braille documents. Accessible instructions that show how to use the system are essential before the system can be used in a public setting.

Although the evaluations show that the interaction mechanisms are well suited for users with disabilities, the system does not connect other users and instructors. Communication between students, parents, and instructors is essential if we hope to make the system available in math classrooms. In addition, if more students are in a classroom, voice interaction fails due to voice mix-ups. An interesting addition would be an option for users to enter answers using the keyboard.

5.3 Concluding Remarks

An accessible self-directed learning tool for SVIs is essential in the modern era with the increasing popularity of e-learning systems. It is necessary to integrate assistive technologies with e-learning platforms and designing educational content following accessibility guidelines.

We believe that the system we developed provided new opportunities for people with vision impairment. In the future, we will continue to work on the goal of making math education universal for all.

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Appendices

Appendix A

Interview Questions for Educators

1. Number of students: _____________

2. Approx. age of students: _____________

3. Which devices are currently being used in mathematics courses to support students who are visually impaired?

4. Is there a core set of devices that is perceived as beneficial for supporting advanced mathematics students who are visually impaired, regardless of specific subject?

5. Are there variations of the core set of devices, depending on the advanced mathematics subject being taught?

6. Preparation of lessons – the device being used by a faculty or staff member to prepare the
   mathematics lesson, notes, and/or materials for the lesson before the lesson itself took place.

7. Student lesson access – the device being used by the student during the lesson, on the actual day of the lesson, to access the notes/class material.

8. Teacher/student guided practice – the device being used by the student and classroom teacher or teachers with visual impairment, so they can simultaneously study, discuss, or work on mathematics problems.

9. Student independent practice – the device being used by the student in or out of the classroom to work on problems independently.

Appendix B

Nemeth Code vs. UEB Code

Numeric Indicator	Nemeth Code	Unified English Braille Code	Print Meaning
0	⠴	⠚	0
1	⠂	⠁	1
2	⠆	⠃	2
3	⠒	⠉	3
4	⠲	⠙	4
5	⠢	⠑	5
6	⠖	⠋	6
7	⠶	⠛	7
8	⠦	⠓	8
9	⠔	⠊	9
plus	⠬	⠐⠖	+
minus	⠤	⠐⠤	-
times	⠡	⠐⠦	*
divided by	⠌⠨	⠐⠌	÷
equals	⠨⠅	⠐⠶	=
opening bracket	⠷	⠐⠣	(
closing bracket	⠾	⠐⠜	)

Appendix C

Student - Application Interaction Flow for the Prototype

Student Actions	Student → Website (Voice Commands) Student ← Website (Text-to-Speech)	Website Actions
The student lands on homepage of the application.		
	"Welcome to MyA+ web application. If you are new to the site say, 'New User'. If you want to login to your account, please enter your username and password" ←	Activates Welcome speech.
The student enters username and password and click Login.		Authenticating user.
	"Welcome back, {*first name*}! Say 'Practice' if you want to practice questions, say 'Learn' if you want to learn a new math topic, say 'Help' if you need any help" ←	Detects a student login.
The student decides to practice questions.	"Practice" →	
	"You are on a practice page. You have {n} questions on a page. Say 'Attempt random' to start the practice, say 'Help' if you need any help" ←	Recognizes the speech and redirects to practice questions page.
The student wants to start the practice.	"Attempt random" →	
		Recognizes the speech, selects the question and redirects to question page.
	"You are on a question page. Say "repeat please' if you want to listen to the question again. Say 'hints' if you need any guidance in solving problem. Are you ready?" ←	
The student is ready.	"Yes" →	Fetches question information from database and finds the solution.
	"For a triangle with base 12 and height 5, what is the area of the triangle?" ←	Getting back to the student with more information.
The student needs help.	"Hints" →	Recognizes the speech.
The student calculates using the formula.	"Multiple the base and the height and divide the result by 2" ←	Getting back to the student with hints.
The student confirms the answer with the application.	"The answer is 30" →	Confirms the answer.

Appendix D

E-mail Invitation for the Prototype Evaluation

I am Daniela Marghitu, a faculty member in the Department of Computer Science at Auburn University. I would like to invite you to participate in research study of my student Abhishek Jariwala to evaluate the web application to test the mathematical knowledge. You may participate (*or may not participate*) if you are high school student and vision impairment.

As a participant, you will be asked to practice 10 math questions and asked to do the post survey for the evaluation of the web application.

If you would like to participate in this research study or have questions, please contact Abhishek at *avj0003@auburn.edu* or contact me at *marghda@auburn.edu*.

Thank you for your consideration.

Appendix E

Post-survey Questions for the Prototype Evaluation

1. The interaction with MyAccessible Math application is comfortable and adequate.
2. MyAccessible Math makes it easier for visually impaired as well as intellectual and motor impaired students to understand they are within the question.
3. MyAccessible Math hints were useful to solve math problems.
4. MyAccessible Math is supportive in providing enough help to clear up any confusion.
5. MyAccessible Math helps you in practicing math questions.
6. The content on MyAccessible Math is organized and easy to follow.
7. The training and evaluation experience will be useful in student's interest and participation in technology-related careers.

Appendix F

Math Questions for the Prototype Evaluation

Elementary School

3 + 1 = _____

16 + 12 = _____

6 * 8 = _____

15 / 3 = _____

1/2 + 3/8 = _____

5/12 * 1/8

2 3/4 - 1 5/6 = ______

Middle School

$15.37 - $9.68 = _____

x + 2 = 5

15 - x = 10

12x = 36

10x / 3 = 20

1/8x + 6 = 12

2(3x +7) -10 = 28

High School

$2\ (3x - 5 + 2) = 10\ (x - 2) + 5x$

$2x - 3 + 5\ (2 - 4x) = 2$

$4x + 3 = 5\ (3 + x)$

$2x + 3x + 7x = 4 - 2x$

$2x\ (3 - 4) = 5x$

$4x - 3 = 2\ (2 + 3x)$

$2x + 3 = 2 – 5$

Appendix G

Social Media Post for the Study Invitation

Hello,

My name is Abhishek Jariwala, and I'm a doctoral candidate at Auburn University. Currently we are seeking participants for research on how students with vision impairment learn and practice math concepts.

PARTICIPANT REQUIREMENTS
1. Must have severe visual impairment or blindness.
2. Must be able to hear.

WHAT YOU WILL DO
1. Participants will be asked to use a web application to practice math questions attached below.
2. The study will start with Pre-survey questions.
3. A brief Zoom meeting will be held to introduce students with the application.
4. Participants will be encouraged to take post-survey questions.
5. The study will take approximately 60 minutes to complete.

COMPENSATION
There will be $20 compensation given to the participant once the study is complete

WHEN AND WHERE
We will schedule the Zoom meeting and study at your convenience.

If you or someone you know is interested in participating – or if you have any questions -- please comment here or direct message me and we can take it from there.

Thank you for your time,
Abhishek Jariwala, Doctoral Candidate
Department of Computer Science and Software Engineering
Auburn University

Appendix H

Pre-survey Questions for MyAccessible Math Evaluation

How old are you?

What is the highest level of education you have completed?

- Middle school student
- High school student
- High school graduate
- College student
- College graduate
- Graduate student

What is College Major(s) or Intended Major(s) once you approach college?

How would you describe your ability to see?

→

Age of onset of Blindness? (I became legally blind at the following age)

- ○ Birth
- ○ 1-5 years old
- ○ 6-10 years old
- ○ 11-15 years old
- ○ 16-20 years old
- ○ 21 or older

How long have you been using computers for your screen reader use?

- ○ less than 1 year
- ○ 1-2 years
- ○ 2-3 years
- ○ 3-5 years
- ○ 5-10 years
- ○ over 10 years

How long have you been using braille?

- ○ less than 1 year
- ○ 1-2 years
- ○ 2-3 years
- ○ 3-5 years
- ○ 5-10 years
- ○ over 10 years

How would you rate your Braille skills?

5	4	3	2	1
○	○	○	○	○

→

Appendix I

IRB Approved Documents

COMPUTER SCIENCE
AND
SOFTWARE ENGINEERING

AUBURN UNIVERSITY

SAMUEL GINN COLLEGE
OF ENGINEERING

INFORMATION LETTER
for a Research Study entitled
"MyAccessible+ Math: Shining Light on Math Concepts for Visually Impaired Students"

Overview

You are invited to participate in a research study. This study has three goals:

- Provide visual impaired students with a platform to learn and practice mathematical problems.
- Evaluate how precise speech-based website navigation is for visually impaired students.
- Asses if training and evaluation experience will be useful in student's interest and participation in technology-related careers.

The study is being conducted by a graduate student, Abhishek Jariwala under the direction of Daniela Marghitu (Ph.D.) in the Department of Computer Science and Software Engineering at Auburn University.

You were selected as a possible participant because you are a visually impaired individial.

What will be involved if you participate?

Since the participants of this study are minors, parental permission is required. Parents can inform researchers upon receiving the Information Letter/Parental Permission form if they are not comfortable with their child participating in the study and the child will not be enrolled.

Once the participants and their parents have agreed for participation in this research study, participants will be asked to use two digital interfaces:
A web browser to access MyAccessible+ Math website, and the Qualtrics website.

We will provide you instructions to access MyAccessible+ Math website and necessary instructions to start the mathematical quiz.

Version Date (date document created): 04/12/2022

3101 Shelby Center for Engineering Technology, Auburn, AL 36849-5347, USA · 334-844-4330 · Fax 334-844-6329 · www.eng.auburn.edu/csse/

Qualtrics will be used to complete survey at the end of the study. The survey will take approximately 20-30 minutes to complete. If you participate in all aspects of the study, the total duration of participation is estimated to be around 2 hours.

Are there any risks or discomforts?

The risks associated with participating in this study are minimal, since the entire study will be anonymous and no personal/identifiable information will be stored.
- Participants may experience slight discomfort with using Zoom and attempting a mathematical quiz. Instructions will be available to help and answer questions. Students may skip to answer the quiz question if they like.
- We recommend the participants to be in private space while participating in this study. Even if - somebody else happen to read any information included in the study, it will not pose any embarrassment or emotional stress for the participants. The survey data will be protected and stored in secure Qualtrics severs.

Are there any benefits to you or others?

If you participate in this study, you can evaluate the application by filling out survey. The application will be used to teach mathematical concepts to students with vision impairment. We/I cannot promise you that you will receive any or all the benefits described.

Will you receive compensation for participating?

For participating in a study, $20 compensation will be offered once the study is complete.

Are there any costs?

The research study is completely free of cost.

If you change your mind about your participation, you can be withdrawn from the study at any time. Your participation is completely voluntary. Your decision about whether to participate or to stop participating will not jeopardize your future relations with Auburn University, the Department of Computer Science.
Your privacy will be protected. Any information obtained in connection with this study will remain anonymous. Information obtained through your participation may be published in professional conference/journal papers.

If you have questions about this study, please ask them now or contact *avj0003@auburn.edu* or *marghda@auburn.edu*.

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Research Compliance or the Institutional Review Board by phone (334)-844-5966 or e-mail at IRBadmin@auburn.edu or IRBChair@auburn.edu.

Abhishek ____ 06/17/2022
Investigator's signature Date

______Abhishek Jariwala_______________
Print Name

The Auburn University Institutional Review Board has approved this Document for use from
06/16/2022 to ----------
Protocol # 20-007 EP 2101

COMPUTER SCIENCE
AND
SOFTWARE ENGINEERING

AUBURN UNIVERSITY

SAMUEL GINN COLLEGE
OF ENGINEERING

MINOR ASSENT
for a research study entitled
"MyAccessible+ Math: Shining Light on Math Concepts for Visually Impaired Students"

You (*and your parents or guardian(s))* are invited to be in a research study to help us understand how students with visual impairment can practice and learn mathematical concepts.

If you decide you want to be in this study, the survey will begin with basic interview questions about your experience working with learning tools. Then, you will take a mathematical quiz. After the quiz, you will take a post survey telling us about your experience taking a quiz.

Since you are a minor, we will also need your parent's permission for your participation. You will not be enrolled if your parents are not comfortable with your participation in this study.

You can stop at any time. Just tell your parents or Mr. Abhishek or Mrs. Fatemeh if you do not want to answer questions anymore. No one will be angry with you if you stop.

If you have any questions about what you will do or what will happen, please ask your parents or guardian, or ask Mr. Abhishek now. If you have questions while you are answering questions, we want you to ask us.

Abhishek
Investigator obtaining consent

Abhishek Jariwala
Printed Name

06/17//2022
Date

Version Date (date document created): 04/12/2022

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www.eng.auburn.edu/csse/

COMPUTER SCIENCE
AND
SOFTWARE ENGINEERING

AUBURN UNIVERSITY

SAMUEL GINN COLLEGE
OF ENGINEERING

PARENTAL PERMISSION
for a research study entitled
"MyAccessible+ Math: Shining Light on Math Concepts for Visually Impaired Students"

Your son or daughter is invited to participate in a research study to help us understand how students with visual impairment can practice and learn mathematical concepts. This study is being conducted by Abhishek Jariwala, under the direction of Dr. Daniela Marghitu in the Auburn University Department of Computer Science and Software Engineering. Your son or daughter is invited to participate because he or she is visually impaired student. Since he/she is age 18 or younger we must have your permission to include him/her in the study.

If you decide you want your son/daughter to be in this study, he/she will be asked to answer a few questions about their experience working with learning tools. Then, they will take a mathematical quiz. After the quiz, he/she will take a post survey telling us about his/her experience taking a quiz. If you are not comfortable with your child's participation in this study, please inform us upon receiving this form and your child will not be enrolled for the study.

The risks associated with participating in this study are minimal since the entire study will be anonymous and no personal/identifiable information will be stored.

- The child may experience slight discomfort in answering mathematical quiz. To minimize this risk, they are permitted to skip questions as needed.
- Participants may experience slight discomfort with using Zoom and attempting a mathematical quiz. Instructions will be available to help and answer questions.
- We recommend the participants to be in private space while participating in this study. Even if - somebody else happen to read any information included in the study, it will not pose any embarrassment or emotional stress for the participants. The survey data will be protected and stored in secure Qualtrics severs.

Your child can stop at any time. Just inform Mr. Abhishek or Mrs. Fatemeh if he/she do not want to answer questions anymore. No one will be angry with him/her if he/she stops.

Version Date (date document created): 04/12/2022

The Auburn University Institutional Review Board has approved this Document for use from 06/16/2022 to ----------
Protocol # 20-007 EP 2101

3101 Shelby Center for Engineering Technology, Auburn, AL 36849-5347, USA · 334-844-4330 · Fax 334-844-6329 ·
www.eng.auburn.edu/csse/

If you change your mind about your participation, your child can be withdrawn from the study at any time. Your child's participation is completely voluntary. Your decision about whether to participate or to stop participating will not jeopardize your future relations with Auburn University, the Department of Computer Science.

Your privacy will be protected. Any information obtained in connection with this study will remain anonymous. Information obtained through your participation may be published in professional conference/journal papers.

There will also be a $20 compensation once the survey is complete.

If you have any questions about what you will do or what will happen, please ask Mr. Abhishek now. If you have questions while you are answering questions, we want you or your child to ask us.

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Research Compliance or the Institutional Review Board by phone (334)-844-5966 or e-mail at IRBadmin@auburn.edu or IRBChair@auburn.edu.

Abhishek	_Abhishek Jariwala_________	06/17/2022
Investigator obtaining consent	Printed Name	Date

Version Date (date document created): __04/12/2022___

The Auburn University Institutional Review Board has approved this Document for use from
06/16/2022 to ----------
Protocol # 20-007 EP 2101

Appendix J

Math Questions for MyAccessible Math Evaluation

Simplify,

1. 3(x + 4) + 3 - 2(5 + x)

2. 3(x + 3) – 6 (12) + x

3. -2(x + 1) + 3(x – 2) – 6

4. -2(x + 4)

5. 2x(3 – 4) + 7 = 5 x

Appendix K

Post-survey Questions for MyAccessible Math Evaluation

Voice Interaction

5	4	3	2	1
○	○	○	○	○

Keyboard Interaction

5	4	3	2	1
○	○	○	○	○

Navigation on the Web

5	4	3	2	1
○	○	○	○	○

Navigation within the Question

5	4	3	2	1
○	○	○	○	○

Audio Hints

5	4	3	2	1
○	○	○	○	○

Magnification

5	4	3	2	1
○	○	○	○	○

→

Color Styles

5	4	3	2	1
○	○	○	○	○

What features did you like the most?

What features did you like the least?

What features were most confusing for you? Why?

What additional features do you think should be included?

Any other comments?

→

Appendix L

System Usability Scale Questions for MyAccessible Math Evaluation

I think that I would like to use this system frequently.

5	4	3	2	1
○	○	○	○	○

I found the system unnecessarily complex.

5	4	3	2	1
○	○	○	○	○

I thought the system was easy to use.

5	4	3	2	1
○	○	○	○	○

I think that I would need the support of a technical person to be able to use this system.

5	4	3	2	1
○	○	○	○	○

I found the various functions in this system were well integrated.

5	4	3	2	1
○	○	○	○	○

→

I thought there was too much inconsistency in this system.

5	4	3	2	1
○	○	○	○	○

I would imagine that most people would learn to use this system very quickly.

5	4	3	2	1
○	○	○	○	○

I found the system very cumbersome to use.

5	4	3	2	1
○	○	○	○	○

I felt very confident using the system.

5	4	3	2	1
○	○	○	○	○

I needed to learn a lot of things before I could get going with this system.

5	4	3	2	1
○	○	○	○	○

→