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Using Assistive Technology to Help Visually Impaired People to Develop Their Mathematical Skills

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Table of Contents

List of Figures

List of Tables

Declaration

I, Muhammad Shoaib, certify that this thesis is my own work and has not been submitted for another degree at University College Cork or elsewhere.

Muhammad Shoaib

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Abstract

In the absence of vision, visually impaired people rely upon the tactile sense and hearing to obtain information about their surrounding environment. These senses cannot fully compensate for the absence of vision, so visually impaired people often experience difficulty with many tasks, including learning. When studying mathematics, it is difficult for visually impaired students to access rich visual information, such as graphs, algebraic notations, geometric shapes, and statistical formulas. However, if possible, it is always better for visually impaired people to learn mathematical skills alongside their sighted peers. This thesis explores the development and evaluation of technology-based solutions designed to improve access to mathematics teaching materials for visually impaired and blind students. This study investigates various modern techniques, tools, and methods to make learning more effective and accessible. The study started with an extensive review of existing solutions, highlighting significant developments in digital tools, tactile displays, and audio feedback that have the potential to enhance visually impaired students learning in mathematics. Another study was conducted in order to investigate the impact of remote learning during the COVID-19 pandemic, emphasizing assistive technology's vital role in enabling ongoing education in emergencies. Another contribution of this study is a survey of the accessibility of mathematics education in primary schools, evaluated by a thematic analysis of responses from students, teachers, and expert professionals. This analysis reveals several themes and subthemes that are very helpful in understanding the various perspectives of this group of stakeholders. Another study was conducted in which mobile application development platforms were assessed, comparing native and cross-platform environments: Xamarin, Unity, Android, and iOS. The advantages and disadvantages of these platforms were examined, particularly in regard to accessibility features and the implications of these for the design and development of accessible educational apps. We have also taken established guidelines, such as the Web Content Accessibility Guidelines (WCAG), primarily designed for web content, and explored how these standards and procedures can be applied and interpreted within a mobile context. Following this, two accessible solutions were developed, and the design process was described in detail, demonstrating how user-centered design principles, extended design guidelines, and accessibility features can be used to enhance learning mathematics. Using multimodal feedback helps visually impaired students to improve their problem-solving abilities and action awareness. User evaluations showed that the solutions were effective and easy to use. Overall, this thesis advances the field of assistive technology by offering a thorough evaluation of

available options, pointing out potential gaps, and suggesting novel strategies to help visually impaired and blind students with their mathematics education. The results emphasize how crucial it is to conduct further research and development in this field in order to provide inclusive and accessible learning environments.

Chapter 1

Introduction

1.1 Background and Context

Accessing educational information can be a challenging task for blind and visually impaired individuals, especially when it comes to mathematics. Mathematics education plays a significant role in improving problem-solving and critical-thinking skills. However, for blind and visually impaired students, learning mathematics poses unique challenges due to its dependence on visual representations such as graphs, charts, formulas, equations, and spatial configurations. The advancement of technology has opened new opportunities for overcoming these challenges in mathematics education. Several technology-based mathematical learning solutions have been developed to make mathematical concepts more accessible to visually impaired learners. We have reviewed research relating to the development of technology-based solutions for visually-impaired people, noting the objectives of the research and the findings. Assistive technologies, which range from tactile displays to smartphone applications, can make it easier for visually challenged people to learn mathematics. Nevertheless, despite these innovations and advancements, there are still significant gaps in the usability and efficacy of current solutions. Traditional teaching approaches typically fail to meet the requirements of blind and visually impaired students, leading to discrepancies in educational outcomes. By examining these students' obstacles, we set out to improve accessibility and inclusivity in education to help these individuals comprehend mathematics instructions. Recognizing this gap, our study focuses on exploring and creating technology-based accessible solutions to promote mathematical learning for visually impaired individuals.

The sudden outbreak of the COVID-19 pandemic has added new urgency to the quest for better educational tools for visually impaired children. The pandemic led to drastic changes worldwide, including travel restrictions, healthcare shortages, economic issues, and especially, the shutdown of educational institutions. As a result, there was a quick transition from face-to-face to remote teaching. However, most remote learning platforms are primarily developed for sighted students and do not effectively fulfill the needs of visually impaired learners. This insufficiency has worsened the educational difficulties experienced by these learners, emphasizing the necessity for more inclusive remote learning solutions.

To understand the depth of these challenges, we conducted a qualitative study focusing on the experiences of blind and visually impaired children learning mathematics in primary schools in Ireland. Through thematic analysis of the gathered data, we studied these students' instructional difficulties and identified teaching strategies that can enable an inclusive learning environment. In exploring technological solutions, we identified the importance of the development platforms used to develop accessible applications. We compared the accessibility features presented by Xamarin and Unity to those provided by native iOS and Android platforms.

Building upon our findings and understanding of the needs of visually impaired students, we developed two new learning systems designed to promote mathematical learning. The first e-learning platform is designed to improve the accessibility of smartphone applications used to enhance the basic mathematics skills of visually impaired students with some useful vision. A User-Centered Design approach was adopted to develop an effective solution for visually impaired students. The second platform is an interactive game designed to develop students' numbering skills, ability to perform basic mathematical operations and understanding of shapes and digits, because most school children struggle with these topics. The game was developed using data from a survey designed to investigate the needs of blind and visually impaired students and to identify enablers that improve the effectiveness of interactive learning platforms specifically for learning mathematics. These platforms collectively try to provide full assistance to visually impaired students, addressing the limitations of existing technologies. By focusing on both the technological and pedagogical aspects, we sought to design solutions that are not only accessible but also suitable for promoting mathematics understanding.

The organization of this thesis is illustrated in Figure 1.1. The research seeks to achieve three main objectives: firstly, to conduct an extensive literature survey to explore the current solutions for blind and visually impaired students; secondly, to conduct a study with students, teachers, and expert professionals to find out user-centered challenges and explore the accessibility features of the developmental platforms: and thirdly, to design and implement user-centered mobile e-learning platforms prioritizing accessibility and usability for visually impaired and blind students. Through these different activities, we also aim to assess the effectiveness of the developed platforms in enhancing mathematical learning outcomes and user satisfaction levels.

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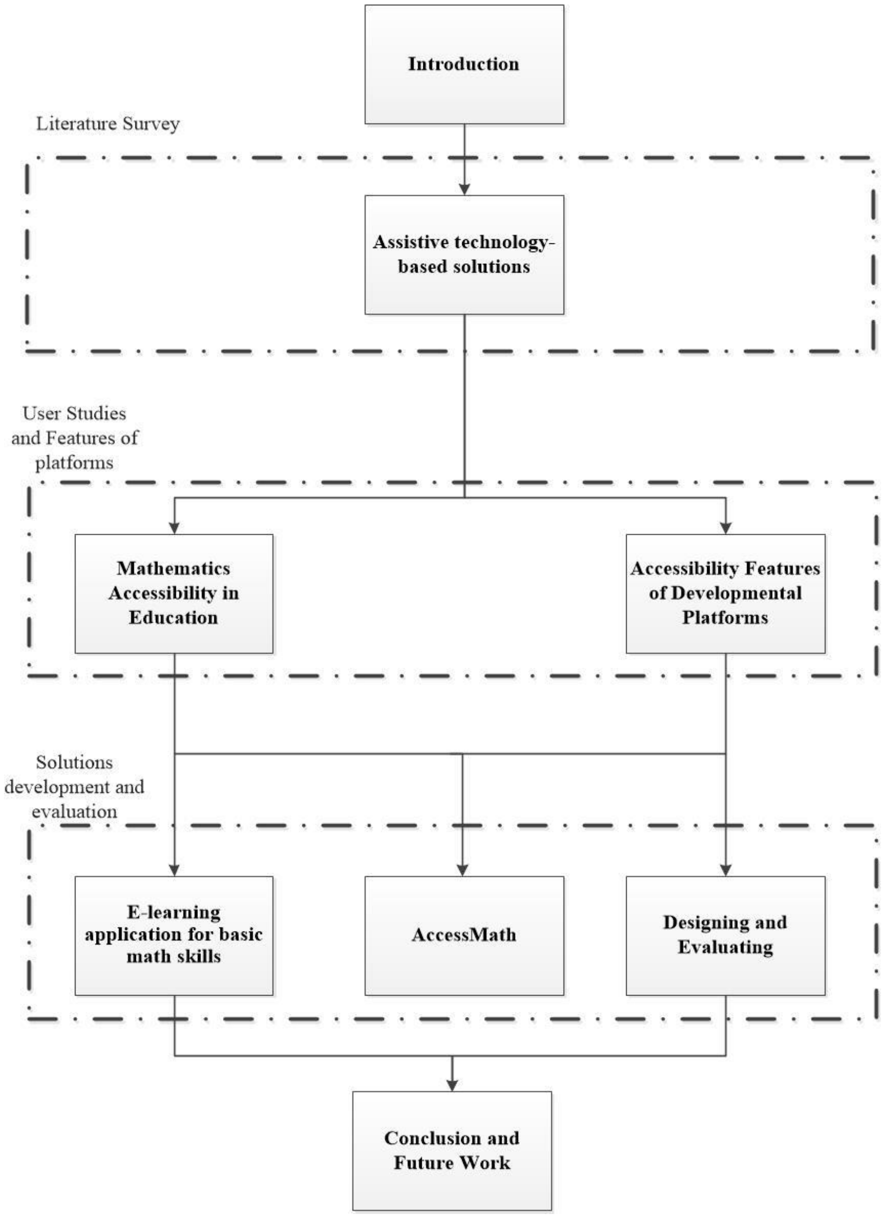

Figure 1.1: Hierarchical organization of the research topics we tackle in this thesis.

1.2 Problem Statement

Mathematics relies heavily on visual elements (graphs, charts, diagrams, etc.), which are inherently difficult for students with visual impairments. Inaccessible textbooks and materials leave blind and low-vision pupils at a disadvantage. For example, graphs, charts, diagrams, figures, and drawings used to convey math concepts are challenging or impossible for visually impaired (VI) students to use. A core research challenge is that blind and low-vision children face significant barriers in accessing early mathematics education due to the visual nature of math content. This thesis aims to address these barriers by exploring assistive technology solutions for mathematics. The objectives are to conduct a scoping review of existing tools, collect qualitative insights from stakeholders, and design and evaluate a prototype math app (AccessMath) for VI pupils. Visually impaired learners must compensate for visual information through other senses. For example, students with visual impairments have difficulty accessing mathematical textbooks because most mathematics texts are highly visual, containing images (Michell, 2025). Visual elements such as numbers, graphs, number lines, and charts are difficult to describe succinctly". Recognizing shapes by touch and imagining spatial configurations are, therefore, explicit learning objectives for blind math instruction (Emerson, 2018). Teachers often spend extra time converting graphical content into tactile or auditory formats (e.g., "I have to spend extra time converting diagrams to tactile form for my blind students" (T1)). These challenges motivate our focus: the thesis will address specific spatial/math elements (e.g., geometry shapes, number representation) and identify how technology can make them accessible.

1.3 Motivation

The motivation behind this study is the urgent need to enhance the educational experiences of blind and visually impaired students, especially in mathematics. Even if assistive technology development has advanced, more work has to be done to assess its effectiveness, solve its current shortcomings, and find new opportunities for innovation. This study aims to support the creation of more inclusive educational practices and enable visually impaired students to succeed in mathematics by examining the relationship between assistive technology and mathematical learning for blind and visually impaired students.

Focusing on early years learning: The scope is focused on early years (primary level) learning. Early numeracy skills are crucial predictors of later academic success (Chang, 2023). If blind and VI students do not receive sufficient help early on, there is a risk that they will never master maths and will fall behind their sighted peers. Research shows that "children's mathematical knowledge at school entry is the strongest predictor of later math success and success in other academic domains" (Raghubar, 2017). Thus, ensuring that blind and low-vision students build solid math foundations in primary school is vital. The rationale for this focus includes the high impact of early interventions and the fact that many VI children are integrated into general primary classrooms. By targeting primary-level needs, this work aims to support long-term math achievement for blind and low-vision learners.

Blind and low-vision primary school students: We deliberately study blind and low-vision primary school students. Including blind and VI students benefits from being educated together, and a primary aim here is inclusion. Educating students together is widely recognized and one of the reasons governments across the Western world now aim to educate virtually all students in mainstream schools, with special schools reserved only for those with exceptional needs (European Agency for Special Needs, 2025). Although both groups have visual impairments, their experiences differ. Total blindness entails no functional vision, requiring Braille, audio, and tactile input. Low-vision students have residual sight (e.g., partial acuity) and can use large print, magnification, or high-contrast displays (Legge, 2016). Both groups struggle with visual math content, but blind students rely entirely on non-visual cues, while low-vision students may partially rely on vision. For instance, low-vision learners benefit from contrast and brightness adjustments on screens, whereas blind learners depend more on audio and touch. Additionally, low-vision covers a broad range of visual conditions; not all will use the solutions mentioned. However, from a technical support standpoint, the key issue is that people with some residual vision generally prefer to use it rather than the option for TTS or other solutions. Thus, for the technology designer, the distinction between blind and low vision users is often based on user preference rather than a strict medical definition.

The stakeholder groups: We focused on three main groups for feedback and evaluation: VI students (primary users), their teachers, and domain experts (special education researchers and accessibility technologists). Including these groups follows standard practice in user-centered design for educational technology. **Students**: Primary-age learners with blindness or low vision. We engaged students in interviews (Ch3) and usability testing (Ch5–7) to capture their direct experiences and feedback. **Teachers**: Classroom teachers and teachers of the visually impaired (TVIs) participated in interviews (Ch3). Their expertise on pedagogical strategies and on how students cope in class provides crucial context. **Experts**: We also consulted subject matter experts (e.g., special education researchers and accessibility technologists) to guide design decisions(Ch3). This multi-stakeholder approach ensures the findings reflect real-world educational settings. By consulting all three groups, we ensure that the app is useful, pedagogically sound, and accessible.

1.4 Research Aim, Objective, and Questions

The overall aim is to design and evaluate an assistive math-learning technology for blind and low-vision primary pupils. The specific research objective and research questions are stated as follows:

RO1: Investigate technology-based solutions to enhance inclusivity and accessibility for visually impaired students.

RO2: Explore the experiences of students and teachers in mathematics education and gather expert opinions on introducing accessible solutions.

RO3: Compare the accessibility features of mobile development platforms to assist developers in choosing the most suitable platform for accessibility needs.

RO4: Develop and evaluate user-centered solutions to improve accessibility for visually impaired students in mathematics education.

RQ1: What are the current educational practices and accessibility challenges in teaching math to blind and low-vision children?

RQ2: What features of mobile accessibility apps provide support for mathematical content, and design guidelines help in this context?

RQ3: How can a mobile app be designed and evaluated (informed by RQ1-2) to effectively support math learning for these students?

1.5 Methodology

The thesis adopts a mixed-methods approach to ensure both depth of understanding and empirical validation across different research phases. The qualitative methods used in the earlier chapters were selected to explore experiences, perceptions, and contextual factors surrounding mathematics learning for blind and visually impaired students. Specifically, semi-structured interviews and thematic analysis were employed to capture rich, detailed insights that could not be obtained through purely quantitative measures. This qualitative exploration informed the design requirements and guided the development of accessible learning tools.

As the research progressed into the design, development, and evaluation stages, a more quantitative approach was adopted to objectively assess the usability, effectiveness, and accessibility of the developed prototypes. Quantitative evaluation allowed for measurable comparisons between design iterations and supported evidence-based refinement of the AccessMath system.

This combination of qualitative and quantitative methods ensured a comprehensive understanding, as qualitative methods provided depth and context, while quantitative methods enabled validation and generalization. Together, they established a solid empirical and experiential foundation for designing and evaluating inclusive mathematical learning solutions.

1.6 Contextualizing Accessibility, Assistive Technology, and Universal Design

In designing and developing learning tools for blind and visually impaired learners, it is vital to define the interrelationship among three fundamental concepts: Accessibility, Assistive Technology, and Universal Design.

• "Accessibility is the usability of a product, service, environment, or facility by people with the widest range of capabilities. " (ISO, 2008)

• "Assistive Technology (AT) refers to any specialized item, piece of equipment, or product system that is used to increase, maintain, or improve the functional capabilities of individuals with disabilities." (AT Act, 2004)

• "On the other hand, Universal Design is the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design." (CUD, 1997)

These concepts are fundamental and have a strong relationship with each other. The main point to understand is that, for a long time, blind and visually impaired people needed AT in order to perform almost any task using a digital device. For example, blind people need additional technology, such as a screen reader, in order to use a computer. The screen reader provided access but added to the cost of the computer and introduced technical complications, often requiring setup by a sighted person. It would obviously be better if blind people could use the same technology as other users without requiring specialist adaptations. This is one of the goals of Universal Design, and many devices are now immediately usable by people with special needs (including blind and visually impaired people), with no need for special adaptations or AT. For example, most major operating systems now have built-in screen-reading facilities. We could say Universal Design seeks to make mainstream solutions generally usable, whereas

AT is still needed in certain circumstances; as in this thesis, I am using mainstream accessibility principles when practicable and adding assistive technology where needed to ensure that the final apps match the intended criteria of blind and visually impaired learners without introducing any technical complications. Also, it respects the importance of universal design guidelines while recognizing that specialized tools can still benefit specific contexts to maximize inclusivity.

1.7 Contribution

The following are some of the contributions this thesis provides to the fields of assistive technology and mathematical education for blind and visually impaired students.

Understanding the Core Challenges in Mathematics Accessibility for VI Students (Ch 2): We deliver a comprehensive overview of smartphone-based math assistive tools and their accessibility issues. For example, we extend prior app accessibility studies by focusing on educational apps and classify the research studies categorized the assistive technology-based solutions, highlight the common features of the applications, identify the key challenges faced by visually impaired students and highlight the value of smartphone-based solutions. These findings aid developers by identifying common pitfalls (e.g., missing labels, poor contrast) and help researchers see trends in this niche.

A Multi-Stakeholder Qualitative Analysis-Insights Into Real Classroom Experiences (Ch 3): We present new empirical insights into how primary-level teachers and blind/low-vision students perceive math learning challenges. Also got the opinion of expert professionals on it. This fills a gap noted in the literature where few studies focus specifically on math education for VI children. The themes (in Ch3) will inform educators and researchers about real classroom needs.

Guide for Mobile Accessibility Development Platforms-Clarifying Strengths and Limitations (Ch 4): We compared Android, iOS, Xamarin, and Unity on accessibility features. Found native platforms offer better access to screen reader APIs and gesture handling, where cross-platform tools lack consistent accessibility support and documentation. Cross-platform tools (Xamarin and Unity) present a viable solution for developers seeking code reusability, but require additional work for full accessibility support. Also, proposed key recommendations for researchers and developers like Plan Accessibility Early, Choose Platforms Wisely, Leverage Official Guidelines, Test with Real Users, Stay Updated.

Empirical Validation Through User-Centred Prototypes-Demonstrating What Works in Practice (Ch 5, 6, 7): Through iterative evaluation with blind and low-vision students, the effectiveness of the proposed guidelines and framework was validated in improving task completion, engagement, and comprehension. Our prototype is a mobile math-learning app for visually impaired (VI) children in primary school, featuring multimodal interaction. It integrates auditory instructions, tactile/haptic feedback, and visual elements (for low-vision users) to teach basic math concepts through draw-and-check tasks (e.g., drawing numbers or shapes on the screen). For example, the app can speak a prompt like "draw the number 3," allow the child to draw using touch, and then give audio feedback on accuracy. The novelty lies in targeting primary mathematics with an accessible, user-informed interface. Unlike most apps, which are either general-audience or focus on high-level concepts, this is one of the first tools specifically designed for young blind and VI learners to practice writing numbers and shapes. The UI was informed by our user-needs analysis and accessibility guidelines (e.g., swipe control, clear audio cues, high-contrast visuals) to ensure it meets the needs of blind and low-vision children. As we document each feature rationale, educational software developers can build on this design. We provide the first published usability evaluation of a math learning app with VI children. This yields practical recommendations (e.g., design adjustments for each group) and suggests improvements to accessibility guidelines. We propose modifications to WCAG and mobile UX guidelines based on our design and evaluation to better serve math-learning contexts. These refined guidelines have potential value for academics and practitioners: researchers can adopt them when studying educational accessibility, and app designers can use them to improve similar tools.

Proposed Directions for Future Research-A Roadmap for Inclusive Mathematics Learning Technologies (Ch 8): Also, suggested directions for further investigation and advancement based on the study's results. These include exploring innovative technologies, pedagogical strategies, and collaborations to promote the utilization of assistive technology in mathematics education for people with visual impairments.

Together, these contributions shed light on the challenges and opportunities associated with giving blind and visually impaired students fair access to mathematics education, and open the door for further advancements in this vital field for educators, researchers, legislators, and innovators. Our thesis advances assistive technology and mathematical education for people with visual impairments by offering new ideas, suggestions, and insights to overcome current problems and encourage inclusivity in the classroom.

1.8 Outcomes

Several publications describe the outcomes of this thesis and are presented as chapters of this document. The work presented in this thesis also has various outreach initiatives aimed at the general public and industry.

Publications

1. **Shoaib, M.,** Fitzpatrick, D., & Pitt, I. (2023). Assistive technology-based solutions in learning mathematics for visually-impaired people: exploring issues, challenges, and opportunities. Multimedia Tools and Applications, 1-32. https://doi.org/10.1007/978-3-031-35992-7_51

   My Contribution: As the lead author, I outlined the paper's fundamental assumptions and conducted an extensive literature review. I started the process of drafting and contributed significantly to the successive iterations. My co-authors were actively involved throughout the writing process and offered insightful feedback at every turn.

2. **Shoaib, M.,** R. Minghim., Fitzpatrick, D., & Pitt, I. (2024).Mathematics Accessibility in Primary Education: Enhancing Mathematics Learning Skills and Overcoming Barriers for Visually Impaired Primary Students. Accepted at International Conference on Computers Helping People with Special Needs - ICCHP 24, JKU Linz, Austria

   My Contribution: As the lead author, I oversaw participant recruiting, analyzed the collected data quantitatively, and planned the development survey's design and implementation. I took the lead in writing the paper's first draft and significantly contributed to its later modifications. My co-authors were very involved in the project from the beginning to the end, offering insightful comments and suggestions at every stage.
3. **Shoaib, M.,** Fitzpatrick, D., & Pitt, I. (2024). Accessibility Features of Developmental Platforms: Towards Developing Accessible Mobile Applications with Cross-Platform, Research Challenges and Opportunities. Published at "The 5th International Workshop

on "Digitization and E-Inclusion in Mathematics and Science 2024" (DEIMS2024)", Tokyo, Japan. https://hdl.handle.net/10468/15658

My Contribution: As the lead author, I researched the native and Cross-Platform, wrote the first version, and helped refine later versions. My co-authors were fully involved in the process from the beginning to the end, contributing their insightful opinions and teamwork to ensure the work was accurate.

4. **Shoaib, M.,** Khan, S., Fitzpatrick, D., & Pitt, I. (2023). A mobile e-learning application for enhancement of basic mathematical skills in visually impaired children. Universal Access in the Information Society, 1-11. https://doi.org/10.1007/s10209-023-00990-3

   My Contribution: As the lead author, I have created the study's methodology and determined the problem domain. I led the quantitative and qualitative study described in the results section. I started the paper's drafting process, which was crucial to improving its later iterations. My co-authors were actively involved throughout the process and contributed great advice and insight at every stage.

5. **Shoaib, M.,** R. Minghim., Fitzpatrick, D., & Pitt, I. (2024). AccessMath: Towards developing an accessible interactive learning platform to overcome the Challenges of blind and visually impaired students in learning mathematics. Published at 26th International Conference on Human-Computer Interaction, Washington DC, USA https://doi.org/10.1007/978-3-031-60884-1_12

   My Contribution: As the lead author, I carried out the qualitative investigation and developed the application. I started the paper's drafting process and improved this in later iterations. My co-authors were involved in the project from the beginning to the end, offering insightful comments and advice at every turn.

6. **Shoaib, M.,** R. Minghim., & Pitt, I. (2024). Designing and evaluating an accessible smartphone-based app for blind and visually impaired students for learning mathematics. Accepted at 19th annual International Technology, Education and Development Conference

   My Contribution: As lead author, I carried out the qualitative and quantitative investigation and extended the design guidelines for mobile applications specifically for blind and visually impaired individuals. I started the paper's drafting process and improved this in later iterations. My co-authors were involved in the project from the beginning to the end, offering insightful comments and advice at every turn.

Appendix A: Shoaib, M., Jiang, S., Jin, L., Fitzpatrick, D., & Pitt, I. (2023, July). An Artificial Intelligence-Based Interactive Learning Platform to Assist Visually Impaired Children in Learning Mathematics. In International Conference on Human-Computer Interaction (pp. 366-373). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-35992-7_51

My Contribution: I designed the study protocols in my capacity as lead author. I examined the data that I had gathered using qualitative analysis. I took the lead in writing the paper's first draft and substantially contributed to its later modifications. My co-authors were actively involved in the prototype development, offering helpful advice and input at every stage of development.

Appendix B: Shoaib, M., Fitzpatrick, D., & Pitt, I. (2023, September). Remote Learning of Mathematics for Visually Impaired Students During COVID-19: Exploring Online Intervention, Resources, Challenges and Issues. In Intelligent Systems Conference (pp. 145-156). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-47715-7_11

My Contribution: As the lead author, I conducted the paper's research, penned the first draft, and participated in further modifications. At every level, my coauthors were closely involved.

Note: This study introduced an artificial intelligence-based interactive learning platform that can enhance the mathematical skills of visually impaired children. This platform can assist teachers in the classroom by providing accessible and interactive materials to their visually impaired students. The proposed platform uses text-to-speech and vibrotactile and auditory feedback to help visually impaired students better understand mathematical material. *It is intended that follow-up studies will be conducted later, so we have added this to the appendix section of this thesis.*

Outreach

- Muhammad Shoaib spoke about work presented in a paper titled "Designing and Evaluating an Accessible Smartphone-Based App for Blind and Visually Impaired Students for Learning Mathematics." At the International Technology, Education and Development Conference – INTEND 2025 Valencia, Spain.
- Muhammad Shoaib spoke about work presented in a paper titled "Mathematics Accessibility in Primary Education: Enhancing Mathematics Learning Skills and Overcoming Barriers for Visually Impaired Primary Students." at the International

Conference on Computers Helping People with Special Needs - ICCHP 24, JKU Linz, Austria.

- Muhammad Shoaib spoke about work presented in a paper titled “AccessMath: Towards developing an accessible interactive learning platform to overcome the Challenges of blind and visually impaired students in learning mathematics” at the 26th International Conference on Human-Computer Interaction, Washington DC, USA.
- Muhammad Shoaib spoke about work presented in a paper titled “Accessibility Features of Developmental Platforms: Towards Developing Accessible Mobile Applications with Cross-Platform, Research Challenges and Opportunities” in The 5th International Workshop on "Digitization and E-Inclusion in Mathematics and Science 2024" (DEIMS2024) at Nihon University, Tokyo, Japan.
- Muhammad Shoaib spoke about work presented in a paper titled “Remote Learning of Mathematics for Visually Impaired Students During COVID-19: Exploring Online Intervention, Resources, Challenges and Issues” in Intelligent Systems Conference 2023 (IntelliSys 2023) at Van der Valk Hotel Amsterdam, Netherlands.
- Muhammad Shoaib spoke about work presented in a paper titled “An Artificial Intelligence-Based Interactive Learning Platform to Assist Visually Impaired Children in Learning Mathematics” at the International Conference on Human-Computer Interaction International 2023 (HCII 2023) at AC Bella Sky Hotel and Bella Center, Copenhagen, Denmark.
- Muhammad Shoaib joined the National Disability Authority (NDA) in Dublin, Ireland, for four months of work placement. This work placement opened the way for collaboration between University College Cork and NDA.

1.9 Outline of the Thesis

The following chapters of the dissertation cover the contributions mentioned in Section 1.7 in the same chronological order as the publications listed in Section 1.8. The thesis is concluded in Chapter 8, which also summarizes possible future study areas.

Chapter 2

Assistive technology-based solutions in learning mathematics

This chapter was published by Shoaib, M., Fitzpatrick, D., & Pitt, I. (2023). Assistive technology-based solutions in learning mathematics for visually-impaired people: exploring issues, challenges, and opportunities. Multimedia Tools and Applications, 82(29), 46153-46184. DOI: https://doi.org/10.1007/s11042-023-17409-z.

2.1 Abstract

In the absence of vision, visually impaired and blind people rely upon the tactile sense and hearing to obtain information about their surrounding environment. These senses cannot fully compensate for the absence of vision, so visually impaired and blind people experience difficulty with many tasks, including learning. This is particularly true of mathematical learning. Nowadays, technology provides many effective and affordable solutions to help visually impaired and blind people acquire mathematical skills. This paper is based on a systematic review of technology-based mathematical learning solutions for visually impaired people and discusses the findings and objectives for technological improvements. It analyses the issues, challenges, and limitations of existing techniques. We note that audio feedback, tactile displays, a supportive academic environment, digital textbooks, and other forms of accessible math applications improve the quality of learning mathematics in visually impaired and blind people. Based on these findings, it is suggested that smartphone-based solutions could be more convenient and affordable than desktop/laptop-based solutions as a means to enhance mathematical learning. Additionally, future research directions are discussed, which may assist researchers to propose further solutions that will improve the quality of life for visually impaired and blind people.

2.2 Introduction

People may have various degrees of sight loss, ranging from low vision (usually defined as having a level of visual acuity in the better eye which falls below a certain standard despite correction) through to complete or nearly complete absence of vision. Blindness affects a significant minority of the human population. According to a report, 2.2 billion people are estimated to be visually impaired worldwide, and one billion of these have a vision impairment that is yet to be addressed (Tedros, 2019).

Interaction with computers and smartphones is predominantly based on vision, limiting or precluding access for those who are visually impaired or blind. Similarly, teaching methodologies heavily depend on visual information in educational institutes, i.e., instructor gestures, slide shows, writing, and sketching on a board. Visually impaired and blind people can use technology to perform daily tasks such as communicating with their friends, accessing online information, and e-learning.

Mathematics is essential in education, from primary to higher education. Mathematics requires an understanding of several concepts, including addition, subtraction, multiplication, division, expressions, formulas, logic, graphs, algebra, and algorithms. Ideally, visually impaired students should learn these concepts in the early stages of their education, at the same time as their fully-sighted peers. However, mathematics has rich visual content and information, which may present problems for visually impaired students (Schleppenbach, 1997). During mathematical learning, visually impaired students may have difficulty recognizing symbols, identifying equations, understanding graphs, and performing arithmetic operations. Emerson et al. (2018) noted that materials used in mathematics education may include visual images supporting related content, making it inaccessible for visually impaired students. Diagrams, figures and graphs are used to express the relationship between data in a way which is helpful for fully-sighted students but may present barriers for visually impaired students (Akar & Övez, 2018). Mathematics students should be able to use the information presented in graphs, etc., and apply it in order to solve problems, but this may not be possible for visually impaired students (Rosenblum et al., 2018; Rosenblum & Herzberg, 2010).

Computer-based learning has a positive impact on enhancing mathematical skills (Li and Ma, 2010). Continual enrichment in digital technologies increases the use of technological tools in mathematics learning (NCSM, 2015; Clark-Wilson et al., 2021; Kelly, 2023). Technology provides an opportunity for visually impaired students to access mathematical information using audio-based interfaces, tactile devices and Braille (Beal & Rosenblum, 2018; Pitchford et al., 2018; Supalo et al., 2014; Klingenberg, 2020; Maguvhe, 2015; Rule et al., 2011; Mulloy et al., 2014). These Assistive Technology (AT) based learning tools can make educational platforms more interactive, engaging and easy to use for visually impaired and blind people, and can also facilitate collaboration. Web-based applications are also very useful because the material - provided it is correctly formatted - can be accessed by everyone regardless of their disability. Smartphone-based solutions are also of interest because, although smartphones may be less accessible and adaptable than other devices, they are also generally less expensive, have a wide range of features, and are widely used throughout the world, including by visually impaired and blind people (Irvine et al., 2014). These solutions have important features which are very useful for visually impaired and blind people, i.e., Text-to-Speech, Speak Selection, Voice Over/TalkBack, adjustable contrast, zoom and voice command along with several non-speech audio feedback options (Yesilada & Harper, 2019).

The previous surveys provide an overview of the currently available software tools for accessing mathematical documents and content. They also discussed the advantages and disadvantages of several key technologies used to interact with mathematics documents. Additionally, they review the importance of the most common formats and languages behind these tools. In this article, we are dealing with assistive technology-based solutions for learning mathematics for visually-impaired people and exploring the issues, challenges, and opportunities in a broader scope. We have reviewed previous studies that explored experimental and commercial applications, running on various platforms (laptop/desktop, smartphones, and the web) to illustrate how visually impaired and blind students can learn mathematics by using them. We have considered both general solutions and those designed to support specific tasks in order to obtain information on the accessibility of mathematics learning tools. We have investigated AT-based tools, techniques, algorithms, systems, and projects, and provided a comparison of their major functions, the nature of the feedback they provide, input and output mechanisms, and the mathematical operations which they are designed to support. We have also considered the challenges that visually impaired individuals faced when learning mathematics using commercial and experimental smartphone applications and discussed how we can address these challenges in novel ways. In addition, we have extracted the features of these math learning applications and proposed a categorization of these solutions that we hope will prove useful to researchers and developers seeking to develop effective solutions for visually impaired and blind students. Based on the findings, recommendations are made for researchers who are working to enhance learning among visually impaired and blind people. Finally, this article discusses the need for further research to improve the development of mathematical software tools that are designed specifically for visually impaired and blind individuals, taking into account their unique needs and challenges.

The paper is organized as follows: Section 2.3 describes the methodology used for the review; Section 2.4 reviews relevant theoretical work, Section 2.5 provides an overview of experimental solutions proposed to assist blind and visually-impaired people in teaching or learning mathematics, both general solutions and those designed to support specific tasks; Section 2.6 discusses commercial and research-based applications available for learning mathematics; Section 2.7 presents a discussion of the findings; Section 2.8 concludes the current study and Section 2.9 contains recommendations for future research.

2.3 Research Methodology

In our systematic literature review, we have followed the guidelines proposed by Kitchenham & Charters (2007). In this section, we have defined the research questions, search strategies, study selection criteria, and classification of the research articles.

2.3.1 Research Questions

To assess the significance of technology on the development of mathematical abilities among visually impaired and blind students, we have addressed the following research questions:
RQ1. What is the impact of technology on the development of mathematical abilities among visually impaired and blind students?
RQ2. What are the challenges/issues facing visually impaired and blind students using commercial and researcher-based applications?
RQ3. Can the development of smartphone-based applications be useful in helping visually impaired and blind people to learn mathematics?

2.3.2 Search Strategy

This study involved a systematic search of articles and studies that were published after January 1990. The targeted population of the study is visually impaired and blind people.

1) *Identifying Search Terms*

For this study, we extracted major terms from the research questions and also explored the synonyms of these terms. We searched relevant research articles and verified the keywords. Additionally, we used Boolean operations, i.e., 'OR' for conjunction, 'AND' for concatenation.

2) *Search Strings*

[("Technology" OR "Assistive Technology" OR "Digital Tools") AND ("mathematical ability" OR "math skill" OR "Learning mathematics") AND ("visually impaired" OR "blind" OR "low vision"), AND ("Commercial Applications" OR "researcher-based application" OR "assistive technology") AND ("visually impaired" OR "blind" OR "low vision") AND ("challenges" OR "issues" OR "barriers" OR "obstacles") AND ("mathematics" OR "math learning"), ("Smartphone-based application" OR "mobile application" OR "mobile learning") AND ("visually impaired" OR "blind" OR "low vision") AND ("mathematics" OR "math learning") AND ("assistive technology" OR "accessibility"), ("Blind" OR "Visually Impaired" OR "Low Vision" OR "unsighted" OR "partially sighted") AND ("Information Technology" OR "Innovative Technology" OR "Computer-Based system" OR "Virtual Reality" OR "Assistive Technology" OR "Smartphones" OR "games") AND ("Learning mathematics" OR "Math skills" OR "Useful mathematics learning applications" OR "Helpful math learning applications" OR "Development of mathematical abilities")]

3) Trial Search

Our search strategy included multiple well-known academic databases and platforms to capture relevant publications on accessible math learning and assistive technology. Systematic review best practices advise searching at least several major indices to achieve high recall. Accordingly, we searched the most popular databases such as Google Scholar, IEEE Xplore, ACM Digital Library, SpringerLink, and Web of Science. These databases were chosen for their strong coverage of computing, human-computer interaction, and educational technology research. Using multiple sources is recommended because no single index contains all relevant studies. Table 2.1 lists the number of results found on various electronic data sources.

Table 2.1: Trail search results and electronic data sources name

S.No	Digital library	Data sources Link	Search	Conduction Date
1	Researchgate	researchgate.net	60	01 May 2023
2	Citeseer	citeseer.ist.psu.edu	50	24 April 2023
3	SpringerLink	springerlink.com	421	05 May 2023
4	Google Scholar	scholar.google.com.pk	270	07 May 2023
5	IEEE Xplore	ieeexplore.ieee.org	220	05 May 2023
6	ACM	acm.org	30	09 May 2023
7	ScienceDirect	sciencedirect.com	30	15 April 2023
8	Scopus	scopus.com	240	01 April 2022

4) open search strategy

For the survey of commercial apps, we clarified the open search process. We searched both the Google Play Store and Apple App Store using keywords like "mathematics", "math", "blind", "visually impaired", and "accessible learning". The aim was to identify math-related apps intended for visually impaired users or that claim accessibility features. We included any app whose description mentioned math education and accessibility. We documented the search terms. This strategy focused on mobile accessibility apps, specifically those targeting math learning or usable by visually impaired learners.

2.3.3 Study Selection Criteria

We have searched for articles using the above search strategies. Relevant studies, which are in English and have been peer-reviewed (i.e., journal articles and conference papers) were selected for inclusion in this study.

1) Inclusion Criteria

We included studies that met the following criteria:

- Studies that express the theoretical and evidence-based concept of mathematical learning for visually impaired students.
- Studies that contain AT-based solutions to help visually impaired or blind people learn mathematics.
- All related studies that define search terms, answer the research questions, and are in the English language were considered for this article.

2) Exclusion Criteria

We have excluded the studies that did not link with learning mathematics, AT, and visually impaired or blind people. Studies that were out of scope did not answer the research questions, did not define the search terms, or were not written in English were also excluded. Research articles without original data were also excluded.

3) Data Extraction and Assessment of Study Quality

According to our inclusion criteria, all relevant data that fulfilled the requirements and were within the scope were considered for this study. During data extraction and assessment of study quality, we have considered the following points:

• Proper matching of inclusion and exclusion criteria with the selected studies.
• Studies included their findings to help answer the main research questions.
• Literature search has covered all the relevant studies.
• Duplicate articles and articles without empirical evidence.
• The quality of included studies has been assessed properly by authors and reviewers.
• Articles that did not meet the aims and objectives of this study.
• Articles for which the full text was not available.

4) Cross-reference the citations

Cross-referencing is a powerful tool that can be used to quickly find related material and enhance our quality of work. We have performed a cross-reference search of the citations to ensure that all relevant studies are included in the review. It helped us in the identification of some additional studies that were not captured in the initial database search and increased the completeness of the review. We repeated this process until a saturation point was reached, at which no new relevant information emerged from the literature search, indicating that the search had been comprehensive.

Using the above criteria, we have identified 72 articles published between January 1990 and May 2023. Figure 2.1 shows the structure of our research methodology and the total number of articles included in this study.

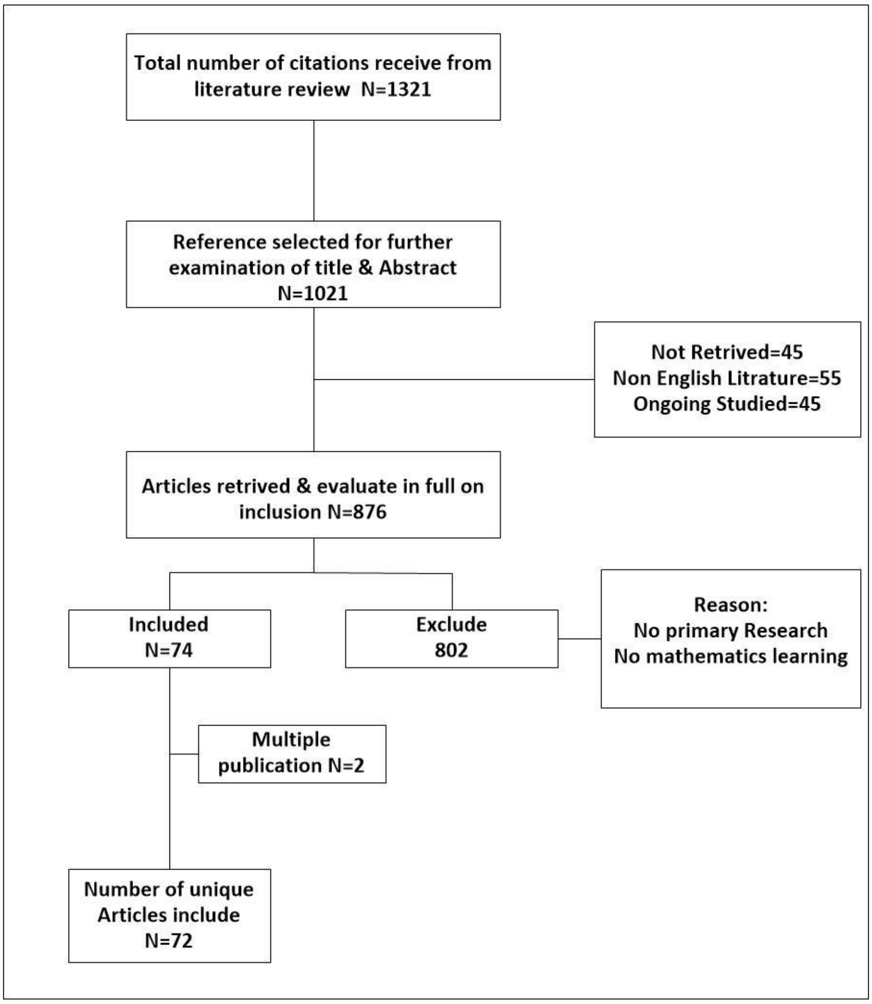

Figure 2.1 Research Methodology

2.3.4 Classification of the research articles

This section helps to understand the classification of the research articles that are part of the current study.

a)Theoretical literature review: Studies that help to define, explore, understand, and conclude the topic under consideration. It included psychological, physiological, pedagogical, and other relevant theories. Studies in this section do not describe general and targeted solutions.

The papers in this category are considered in Section 2.4.

b) Papers which describe practical solutions addressing general issues, with user studies: These studies address more general issues (e.g., use of speech, non-speech audio, or Braille potentially across a range of applications) and have experimental evaluation through participants' involvement. We have summarised them by listing their objectives, participants involvement during experiments, and listed their key findings.

The papers in this category are considered in Section 2.5.1.

c) Papers which describe practical solutions designed to support specific tasks, without user studies: These papers all describe solutions aimed at specific problems within mathematics (e.g., learning algebra, exploring graphs, etc.), but none of them include user studies. We have summarised their major features, the mathematical operations they address, and the feedback and input/output mechanisms they employ. This data is presented in the form of a table.

The papers in this category are considered in Section 2.5.2.

e) Commercially available applications: This category covers applications which are available commercially or for free download which have not been described in published research papers, and therefore are not considered under any of the above categories. They include smartphone applications which are available from charitable and educational organizations or through the Google Play Store or the Apple App Store.

The papers in this category are considered in Section 2.6.1.

d) Papers which describe practical solutions designed to run on smartphones.

Only articles describing solutions designed to run on smartphones are included in this category. Most are designed to support specific tasks rather than general solutions. Most of these applications have been evaluated through user studies.

The papers in this category are considered in Section 2.6.2.

2.4 Background and literature review

We looked at theoretical studies that consider psychological, physiological, pedagogical, and other relevant theories but do not describe practical solutions and do not present the results of user studies aimed at assessing how previous research might be applied in the design of solutions. Visually-impaired people face a number of problems during learning mathematics. Several researchers have developed AT-based solutions which may be useful for visually-impaired people in learning mathematics. Mejia et al. surveyed currently available tools that are useful for accessing mathematical content (Mejía et al., 2021). Armano et al. (2015) conducted a study to examine the issues faced by visually impaired students when accessing mathematical content in University Teaching Materials (UTM). They described instruments and software-based learning methods for visually impaired students such as LeanMath, which makes it easier for visually impaired students to use a graphical interface; MathType, which makes graphs more accessible in Word documents with the help of speech synthesis and hotkeys; MathPlayer, which makes formulas more accessible by using MathType; LaTex and BlindMath, which makes TeX easier for visually impaired people to use; LAMBDA, which is used to write math formulas. These solutions empower visually impaired students to write the text along with mathematical content. Visually impaired students can face trouble in managing structural elements of mathematical formulas. The Universal Mathematics Accessibility (UMA) system was developed in association with multiple institutes. The main purpose of this system is to make mathematics accessible all over the world. UMA has a translator that converts documents into formats that can easily be accessed by visually impaired people. It provides support for the inter-conversion of different math representations i.e., visual markups and Braille. Visually impaired people can also uniformly access and navigate mathematical expressions independently (Karshmer et al., 2003).

Due to the diverse nature of mathematical notations, it is hard to share documents internationally. LAMBDA (Schweikhardt et al., 2006) was a European project aimed at assisting visually impaired students in accessing mathematics. LAMBDA uses 8 dot Braille code, whereas many countries (e.g., Germany, Italy and France) generally use 6 dot notation. This project had two major components, the first was the LAMBDA code, and the second was a mathematical editor. The LAMBDA system offers functional integration of the mathematical code, an editor for writing, and the proper utilization of texts for better understanding (Nicotra et al., 2010).

MathPlayer (Soiffer, 2005) is a free plug-in for Microsoft's Internet Explorer which offers MathML (Ausbrooks et al., 2003) for visually impaired people. It can also be used with other browsers, e.g., Firefox. It dynamically displays the expression, supports multiple font sizes, provides screen magnification, and supports speech generation. It also integrates with different screen readers, e.g., JAWS, Window-Eyes and NVDA.

REMathEx (Gaura, 2002) enables visually impaired and blind students to access complex mathematical expressions. The proposed system uses a Braille display and speech synthesis outputs together to offer all necessary information relevant to the mathematical expressions. Users can navigate within the expression easily, and can also modify the expression using REMathEx.

2.5 General and targeted solutions

In this section, we first looked at studies that explore the development of mathematical skills among visually impaired and/or blind students through user studies. We then look at tools which are designed to perform specific tasks (e.g., tools for presenting graphs, learning algebra, etc.) concerning mathematics learning among visually impaired and/or blind people. The papers in the latter group do not include user studies.

2.5.1 Papers which describe practical solutions addressing general issues, with user studies

In this section, we looked at studies concerning mathematics learning among visually impaired and/or blind people that clearly stated research objectives and were evaluated in practical studies with members of the target groups. Table 2.2 summarises these studies, listing their objectives, participants involvement during experiments, and key findings.

Table 2.2: Summaries of previous studies relating to the development of mathematical skills in visually-impaired people

Article authors /year	**Objectives of the Study**	**Participants**	**Main Findings**
(Maćkowski et al., 2022)	They evaluated eleven detailed assessment categories used in the process of learning mathematics by visually impaired students.	Thirty visually impaired students of a high school course take part in this study.	They proposed a system with four main elements: elementary division of exercise, checking the results at every stage, performing user interaction, and providing contextual support with the help of hints. The alternative teaching method showed significant improvement in four materials out of eleven: adjusting problems in learning, the appearance of the material, approval

			(group or individual) and alternative representation of math material. The visually impaired students also reported increased motivation to learn mathematics.
(Stevens et al., 1997)	They used computers to produce multimodal renderings of mathematical information.	Speech and nonspeech audio feedback was provided to four blind participants. Six fully sighted participants were used in the evaluation of the task. Twelve fully sighted participants were also used in the Algebra Earcons evaluation.	The proposed "Mathtalk" offers multimodal mathematical information accessing mechanism which conveys algebraic structure in synthetically spoken expressions based upon algebra earcons.
(Pires et al., 2022)	They analyzed the current practices in mathematics teaching and designed a novel system that supports learning mathematics.	Sixteen children were involved in designing and developing tangible and auditory stimuli.	They conducted participatory design sessions with visually impaired students and their teachers. They introduced a novel system to enhance the learning of the students. Sixteen participants took part in this study. They worked on creating tangibles and auditory stimuli to represent numbers, as well as exploring activities to utilize with a tangible user interface. The results demonstrated that their mathematical abilities improved.
(Ferreira & Cavaco, 2014)	Provides a game-based learning environment that motivates visually impaired students to learn mathematics.	Experiments were conducted on six visually impaired students attending two different schools who were divided into three groups. Group1: 1 Blind and 1 Low vision,	2D spatialized auditory feedback was used here so it can be played without seeing the graphics. The authors used the methodologies of Virvou (2005) and Ketamo (2003) to test the game which consists of evaluation quizzes before and after the study. The results demonstrated that this game has a

		Group2: 1 sighted with no feedback, Group3: 2 visually Impaired and 1 sighted	positive impact on learning mathematics.
(Maćkowski et al., 2018)	Proposed a technique used for interactive decomposition of math problems, and provides an alternate representation of formulas that were accessible for visually impaired students.	In this study, around 1000 sighted and 40 visually impaired students from six different departments of the university used this platform.	They introduced a set of rules for describing mathematical formulas after consultation with mathematicians and teachers of visually-impaired people. A web-based application was developed, using PHP and JavaScript. Study results demonstrated that this platform provided a better understanding of mathematical formulas as compared to previously used Braille'a notation based upon translations of conventional mathematical notation.
(Crollen et al., 2011)	This article aimed to explore finger numeral representation to check 'general cognitive abilities', 'use of finger counting and finger monitoring strategies', and 'habits of finger counting and finger monitoring'. .	Three test sets were examined to check general cognitive abilities, finger—use strategies and habits of finger counting and monitoring by visually impaired people. A total of 14 congenitally blind, and 14 matched sighted children with an age range between 7-13 years participated in this study.	Visually impaired children used their fingers less spontaneously as a way to count and show the different quantities. The results demonstrated that in the absence of vision they introduced a typical finger numeral representation, and suggested that the use of canonical finger-counting depends upon the visual recognition of particular hand shapes.
(Giesen et al., 2012)	The main objective was to determine whether a more supportive academic environment can enhance the development of mathematical skills in	Data from the Special Education Elementary Longitudinal Study (SEELS) was analyzed and examined to measure	Results showed that good academic support enhanced the learning process, and the level of academic support was directly associated with the mathematics achievement of visually impaired students. But where a cognitive disability was present, both academic

	students with visual impairments.	mathematical achievement. This is a six-year study based on a sample of approximately 13,000 special education students ages 6 to 12. The authors limited their study to 292 visually impaired students.	support and specialized support were required to improve achievement in mathematics.
(Klingenberg et al., 2012)	The main purpose was to investigate the mechanism by which two students read Braille and try to complete a geometric task. Also, analyze how they shaped the mental representations of the same objects.	Experiments were conducted on two visually impaired students aged 10 and 11 years, both of whom had good skills in mathematics and reading Braille. A case study approach was used, and data was collected.	The two students performed different body movements and postures associated with the shapes of different objects. They rotated with objects. Normally, they rotated and experimented with three-dimensional objects. During this process, continually geometric properties were measured i.e., length, area, and volume to “see” the shapes of objects.
(Leo et al., 2016)	An important objective was to explore the benefits of using tactile displays to help visually impaired students develop spatial skills.	Four training sessions were conducted with 16 visually impaired participants aged 6-22 years.	The results demonstrated that visually impaired students were able to enhance their spatial skills considerably by using programmable tactile graphics. It was observed that learning was enhanced by using the experimental system. It was also noticed that there was no significant performance difference between blind and low-vision students.
(Bouck et al., 2016)	The main aim was to examine the mechanism used to access algebra with the help of a digital textbook in 5 high school visually impaired students.	They mainly used qualitative research methodologies on 5 visually impaired students in an algebra class aged between 16-22 years.	Visually impaired students showed a dependency on traditional methods of instruction i.e., large print and Braille. Their instructor motivated them to use the digital textbook. After the instructor's inspiration, students were able to use the digital textbook for learning algebra and were able to access

			the content as easily as when using traditional methods.
(Huang et al., 2015)	Proposed a novel e-learning technique to help visually impaired students learn mathematics skills.	They conducted interviews with 12 visually impaired students and their teachers. Also, arranged the assessment session on different four days and then introduced DAISY E-textbook to the students.	With the help of a newly designed mathematics curriculum along with the integration of the Digital Accessible Information System (DAISY), the student accuracy rate improved. The authors also mentioned that student proficiency in learning mathematics was significantly enhanced.
(Mukherjee et al., 2014)	The authors proposed a new technique that provided tactile mapping of geometry diagrams on low-cost Braille printers.	They provided one-month initial training to 16 visually impaired users to enhance their skills in perceiving Braille characters. Four sighted teachers were also part of this study.	Visually-impaired students can usually recognize Braille diagrams but find it difficult to understand them in a short time. By using the experimental system, visually impaired students were able to convert the geometry word problem into a Braille printout. Findings demonstrated that this was a useful tool for teaching/learning geometry diagrams.

2.5.2 Papers which describe practical solutions designed to support specific tasks, without user studies

In this section, we have considered only those research-based studies that have important activities, mathematical operations to solve, feedback mechanisms, and input/output associated with them. We considered tools, techniques, algorithms, systems, and projects for this purpose i.e., Electrostatic haptic touchscreen system, The Haptic Deictic System, Speaking Math, AfL system, MathSpeak, ASTER, Mathtalk, CONGRATS, Mathgrasp, MATHS and MAVIS.

An electrostatic haptic touchscreen system (Bateman et al., 2018) was used to present dynamic, graph-based data to visually-impaired users and device experts. A total of 12 visually impaired users aged between 9-50 years participated in this study. The results demonstrated that users were able to find the haptic points accurately and developed effective patterns of interaction while using the touch screens. Some haptic components were positioned at the corners of the screen, and these were easily explored by users.

The Haptic Deictic System (HDS) enables visually impaired and blind people to understand the instructor's gestures in the classroom with the help of a haptic glove and cameras. The haptic glove fingertip also facilitates the replacement of visual information during reading. The authors conducted an exploratory study with four visually impaired and two sighted students who have teaching experience and acted as their guides. With the help of the experimental system, an instructor could be confident that all students were following the lecture content, able to tell when students were confused, and could verbalize the information represented in the graphs. All of the visually impaired students reported that they could easily understand mathematical concepts when using the system and that the system was not annoying for them (Oliveira et al., 2011).

A computer-based VISO (Voice Input, Speech Output) calculator assists visually impaired students in solving computational problems in mathematics. A single-subject design was used for the training, assessment, and intervention of three visually impaired students of ages 18-19 years. The findings suggest that the time and average number of attempts to solve problems significantly decreased when using the VISO calculator. The visually impaired students reported that problem-solving was easier when using this calculator as compared to other typical means of calculation. Lastly, participants reported that they would like to have an accessible graphing calculator (Bouck et al., 2011).

Adaptive Content with Evidence-based Diagnosis (ACED) allows visually impaired people to explore the usability of the AfL (Assessment for Learning) system to access algebra content using audio-tactile graphics. It was used to support four visually impaired students, aged 17-29 years, in learning algebra. Participants were interviewed before and after the study. The results showed that users felt comfortable with the audio and interactive tactile graphics. All participants gave positive feedback on the accessible features of the AfL system (Hansen et al., 2010).

Isaacson et al., (2010) designed an algorithm for enhancing the synthetic speech used in the MathSpeak application. They performed efficiency testing on a developed algorithm by considering some parameters i.e., quality of synthetic speech, reception accuracy and MathSpeak processing capacity. Six visually impaired and twenty-one sighted students took part in this study. The results demonstrated that the use of the experimental algorithm improved the performance of MathSpeak, and the capabilities of participants to perform mathematical activities to fulfill their needs were enhanced.

ASTER (Raman, 1994) provides visually impaired people with access to technical documents using auditory representations of the content. Various rendering rules are written in AFL (Audio Formatting Language) to produce different views of the information. OCR-based document recognition was used to browse the internal structure of a document which provides appropriate information to the users. ASTER was implemented using Lisp-CLOS along with an Emacs front-end to present several types of content to visually impaired users.

The Mathtalk system (Stevens, 1996; Stevens & Edwards, 1994) enables visually impaired people to read algebraic expressions and provides speech and non-speech-based ways to interact with the user interface. This was developed in three phases: presentation of the information based upon speech; addition of browsing to identify the best control features in the reading process; and inclusion of an audio glance to facilitate rapid audio access to information. A variety of interactive features are introduced to facilitate visually impaired people i.e., auditory mode, direct manipulation style interaction, and information flow control. With the help of these features, Mathtalk transforms passive listeners into active readers.

CONGRATS (Raman & Krishnamoorthy, 1992), proposed by T.V. Raman, is designed to provide a wide range of aid to visually impaired people in plotting and scanning curves. Users can build a computer display either by selecting the options or by specifying the equation of the curves. Once the curve is drawn on-screen, users can access it using audio scans. With the help of sound, a large amount of information can easily be accessed by visually impaired people.

Mathgrasp (Harling et al., 1995) is a nonvisual application that combines spatial sounds and gestures to allow visually impaired students to manipulate algebra notation. Algebraic expressions are divided into parts, and visually impaired students can access them using synthetic speech. Gestures are very important during conversation with others, so gestural interaction was used to investigate the effect of body movement on gestural interfaces. Users have variations in their gestures, so algorithms were developed to recognize them. The authors introduced gesture-based interfaces to manipulate the algebraic equations and displayed them on a (vertical) auditory spatial display.

The MATHS (Cahill & McCarthy, 1994) project was an initiative of the Commission of the European Communities TIDE (Technology Initiative for Disabled and Elderly People) program. It aimed to provide better access to reading and manipulation of mathematics equations for blind and visually impaired students. It could be used for educational, occupational, and personal purposes. It was quite complex to achieve the functionalities of each aspect, so a four-layered approach was used: distributed layer, cognitive layer, perceptual layer, and mechanical layer. The authors enhanced the mechanism through which the visual representation was assessed using spatial audio. Second and third-level students could easily read and practice mathematics on MATHS workstations according to their educational preferences, making it useful for a wide range of potential users.

MAVIS (Karshmeret al., 1998) was developed using logic programming. The main goal was to facilitate visually impaired students in reading and writing complex mathematical notations. The best educational mechanism for visually impaired students requires two-way communication, visual or printed output for sighted instructors, and quality tactile materials or audio feedback for visually impaired students. This is a comprehensive approach which facilitates users and provides more convenient access to the information. Table 2.3 provides a detailed comparison of the tools, techniques, algorithms, systems, and projects discussed in the proceeding text.

Table 2.3: Comparison of mathematical tools, techniques, algorithms, systems, and projects that have solved some mathematical operations and used specific feedback.

Systems, Tools and Projects	**Important Activities**	**Solving Mathematical Operations**	**Feedback Used**	**Input**	**Output**
Electrostatic haptic touchscreen system	1. User-centered approach 2. Tanvas electrostatic haptic touchscreen 3. Haptic localization task 4. Usability study	Visualizing graph-based information	1. Haptic 2. Auditory	1. Single finger 2. Static UI elements 3. Graph objects	1. Haptic representation 2. Textures shape representations
The Haptic Deictic System (HDS)	1. Conjunction of speech with fingertip reading .2. Use of haptic gloves to replace the visual information. 3. Use of the phrase charade game to check the capacity of active engagement (skill training game)	Making instructor gestures accessible in the math class	1. Speech 2. Haptic	1. Teacher gestures 2. student's fingertip reading 3. camera video	1. Vibrating actuator array to guide the user 2. Awareness of both teacher and student

					pointing info with speech
Speaking Math: Voice Input Speech Output (VISO)	1. Computer-based VISO calculator 2. Speech recognition function based upon MathSpeak 3. Support scientific calculator operations (e.g., roots, log, sin)	VISO calculator to solve computational problems in mathematics.	1. Speech	1. voice input 2. Mouse 3. Keyboard short keys	2. Speech output of the solutions.
Adaptive Content with Evidence-based Diagnosis (ACED) based upon AfL system	1. Regular mode 2. Low vision 3. Blind mode 4. Identification of the mode 5. Use of adaptive sequencing for Geometry	Access algebra content using audio-tactile graphics	1. Speech 2. Synthetic Speech	1. Text and Pictures 2. keyboard 3. Touch Graphics	1. Magnified data 2. Prerecorded speech
MathSpeak syntactic speech rendering	1. Data for algorithm i.e., teacher recordings and analysis of pauses 2. TTS rendering of expression information 3. Audio instructions of the math rules	Designing an algorithm to increase the quality of syntactic speech rendering.	1. Synthetic Speech 2. Auditory	1. Math expression recordings of teachers 2. Text-based math	1. Spoken mathematics 2. Audio rendering of data
ASTER (Audio System for Technical Reading)	1. Recognizing high-level document structure 2. AFL: Audio Formatting Language 3. Rendering rules and styles 4. Browsing audio documents	Quasi-Prefix notation was used to hold the content and structure of the math formulas	1. Synthetic Speech 2. Non-speech	1. TeX, LaTeX and AMS-TeX	1. Audio renderings of electronic documents
Mathtalk (Promotes active reading of content and structure of algebraic formulas)	1. Speaking Algebra Notation (Present the information in speech) 2. Controlling the Information Flow (Add browsing) 3. The Audio glance (*algebra earcons*)	Reading of algebra notation	1. Speech 2. Non-speech	1. Own plain text format	1. Audio access to the information

CONGRATS (Convert Graphics into Sound)	1. Develop a computer display by using audio scans 2. Develop a functional representation of the curve display 3. Interactively plotting and scanning curves	Learn Geometry using sound cues	1. Sound cues 2. Synthetic Speech 3. Speech	1. Geometry Objects	1. Auditory information of curve displayed
Mathgrasp (Algebra manipulation tool which used spatial sound and manual gestures)	1. Extension of Mathtalk by using spatial and structural information 2. Gesture-based model to handle the algebra notations 3. Algorithm to solve the problem of segmentation and the use of unnatural gestures	Algebra expressions manipulation	1. Synthetic speech 2. Non-speech 3. Haptic	1. Gestures and spatial sound	1. By using spatial sound and manual gestures provided a direct manipulation interface for algebra
MATHS (Provides usable access to reading and manipulating mathematical expressions)	1. Recognition 2. Syntactic discrimination 3. Interpretation 4. Glancing and browsing 5. Manipulation and Editing	Mathematical problems of reading and writing. Also, manipulating algebraic expressions	1. Speech 2. Non-speech	1. Reading through visual, tactile and auditory media.	1. Auditory information of a wide range of algebraic expressions.
MAVIS (Provides easy access to complex math equations)	1. Translate LaTeX to Nemeth code 2. Nemeth Code to LaTeX translation 3. Developed a screen reader for mathematical Information 4. developed the tool for reading and creating the mathematical equations	Reading and writing complex math equations	1. Speech 2. tones	1. Latex markup language and Nemeth Code	1. Translate Latex to Nemeth Code, Latex/Nemeth Code to audio

2.6 Commercial and research-based smartphone solution

In this section, we have described commercial and research-based applications. Listed the features and categorization of available solutions. Additionally, discussed a conceptual model of learning mathematics.

2.6.1 Commercially available applications

The chapter discussed above describes research studies, some of which have yielded tools and systems which are available for free download or through charitable and educational organizations. In addition, there are several computer-based, iOS and Android-based commercial applications which are designed to aid visually impaired students in learning mathematics. Most apps use a voice support function which allows users to have action awareness within the app. These apps are available for all age groups and are generally easy for visually impaired and blind people to use. Table 2.4 lists various iOS and android-based applications along with features, findings, challenges, and issues.

Table 2.4: Describes the features, platform, comments, challenges, and issues of the applications.

Name of Application	**Features**	**Platform**	**Comments/ Challenges/ Issues**	**Developers**
Math Melodies[1]	Math Melodies facilitates visually impaired students to understand mathematics easily. With the help of the Voice Support function, it provides audio feedback to users. This application has multiple modules i.e., video-game and math workbook. Math Melodies enables the exploration of audio-visual elements on a touchscreen and provides multi-modal feedback that entertains and engages both visually impaired and sighted children simultaneously. It also has audio icons for all elements of the user interfaces.	Android and IOS	The interaction mechanism of Math Melodies has been changed with the help of the Voice Support function, and it has been fully translated into English. In this application, some information presented in visual form may cause problems for visually-impaired people.	Retina Italia Onlus
Math Robot™[2]	Math Robot was designed especially for blind and visually impaired students but	IOS	Math Robot app works well, particularly in	American Printing

[1] https://play.google.com/store/apps/details?id=com.mathmelodies&hl=en&gl=US
[2] https://apps.apple.com/us/app/math-robot/id704570512

	sighted students can also use it. It provides entertaining exercises for simple math problems. This application can be accessed by VoiceOver and self-voicing functions. It also has some important functions i.e., low vision mode, braille support and retina graphics.		low vision mode where users can easily choose a problem. The developer has fixed the screen appearance issue which affected some devices and introduced a feedback button in the app. Additionally, it's better to introduce the word problems in the coming version.	House for the Blind (APH)
TouchMath Counting[3]	TouchMath Counting app introduces a multisensory system that uses the actual numbers from 0-9 and has corresponding TouchPoints to the digit's value. With the help of TouchPoints, students can learn the real numbers 0-9, number values, counting patterns, and quantity association. It provides the facility to make critical mathematics concepts appealing and accessible for the students.	Android and IOS	They have fixed some bugs and made some internal improvements such as making the numeric keypad buttons work properly, and the voice of DIGIT the robot has been re-recorded with higher quality. Some improvements are required i.e., easy navigational mechanism, independent learning, introducing math challenges and counting objects.	Innovative Learning Concepts Inc.
UAbacus[4]	UAbacus allows users to perform addition and subtraction using the "logic method". Users who want to learn abacus computation can practice and enhance their learning skills by using this app. They can get help step by step and verify their answer here. Users can	IOS	Instruction in abacus causes some confusion for students but this application provides a clear and concise overview to the new learner with the help of	University of Arizona

[3] https://play.google.com/store/apps/details?id=com.mediakube.touchmath.tcpatternspro
[4] https://apps.apple.com/us/app/uabacus/id688547692

	also learn the computing mechanism of the Cranmer abacus.		speaking bead numbers and appropriate sound effects. Additionally, some new modules can be introduced which will cover other areas of math. It has a limited selection of accessible features.	
Slapstack Math[5]	Slapstack Math uses math flashcards instead of playing cards and is accessible to all users. Users have to choose one of the following game variations: addition, subtraction, multiplication, division, addition and subtraction, multiplication and division or all four operations. Some numbers have associated actions, requiring players to perform a lot of calculations, physical movement and mental association. The app: is fully self-voicing and compatible with VoiceOver.	IOS	Slapstack Math offers a pleasurable environment for basic mathematics learning. Users can change the speed of play in several situations. It also provides high colour contrast and large print numbers.	American Printing House for the Blind (APH)
Draw2Measure Protractor[6]	Draw2Measure Protractor is mainly designed for visually impaired students, allowing users to measure angles easily. Students can place an angle onto the screen of the device and trace the sides of the angle by touching the screen. The app will record the tracing and calculate the angle. If any object does not fit on the screen the student can find the angle by rotating the device. This application has better accessibility which allows students to measure angles by tracing the sides instead of reading the measurements.	IOS	Draw2Measure is useful for blind, low vision and sighted students. It measures the angle both in degrees and radians.	American Printing House for the Blind (APH)

[5] https://apps.apple.com/us/app/slapstack-math/id1209184917
[6] https://apps.apple.com/us/app/draw2measure-protractor/id1097557700

Practice2Master Fractions[7]	Practice2Master Fractions is mainly used for learning fraction calculations and provides a large number of exercises and problems to practice. Students can practice fraction subtraction, division, addition, and multiplication. It provides machine-generated calculation problems as well as allows teachers to create problems. Students can save the problems for their future practice. It also provides full compatibility with the iPad's native screen reader VoiceOver.	IOS	This app can store reports on exercises attempted and provides user-selectable options. Students can exchange problem lists. It also provides large print numbers and high-contrast colours to assist visually impaired students. In future, they can enhance the practice values of learning skills by carefully expanding the design feature i.e. by introducing a self-explanatory element of the interfaces.	American Printing House for the Blind (APH)

2.6.2 Papers which describe practical solutions designed to run on smartphones

Studies describing smartphone-based applications that have been published in research are part of this section, i.e., i-Math, iCETA, and AudioMath. The i-Math (Wongkia et al., 2012) is an automatic math expression reading system used to facilitate visually impaired students in retrieving mathematics material. It works with a screen reader and provides an auditory output on a computer system. Students can access the information, and teachers can prepare their handouts and exercises in audio form. A total of 78 visually impaired students and six teachers participated in an evaluation of the system. The results showed that mathematical material is easily available and accessible for visually impaired students using iMath. The students were able to practice the mathematical task independently and comfortably. The iCETA game (Pires et al., 2019) provides an interactive learning environment to visually impaired children using haptic and auditory feedback. Visually impaired students can easily understand numbers

[7] https://apps.apple.com/us/app/practice2master-fractions/id1257764758

concepts with the help of various representations i.e., color, Braille, haptic, and audio feedback. AudioMath used auditory interfaces to enhance the mathematics skills of blind children. Ten children participated in this study. Results showed that with the help of the proposed interfaces mathematical skills were improved (Sánchez & Flores, 2005).

2.6.3 Features of Commercial and research-based math learning applications

In this section, we listed the features of commercially-available applications discussed in Section 2.5.1, and the smartphone-based applications discussed in Section 2.5.2. We have mentioned ten commercially and research-based available applications, namely Math Robot™, Draw2Measure Protractor, Slapstack Math, Practice2Master Fractions, UAbacus, Math Melodies, TouchMath Counting, i-Math, iCETA Tangible Math and AudioMath and extracted their common features. Table 2.5 lists the names of the commercial and research-based applications along with their feature.

Table 2.5: Shows the applications names and their features.

Application Name	Multiple modes	Magnification	VoiceOver support	Braille support	Interactive interface
Math Robot™	✓	✓	✓	✓	✓
Draw2Measure Protractor	×	×	✓	×	✓
Slapstack Math	✓	✓	✓	×	✓
Practice2Master Fractions	✓	✓	✓	×	✓
UAbacus	✓	×	✓	×	✓
Math Melodies	✓	×	✓	×	✓
TouchMath Counting	×	✓	✓	×	×
i-Math	✓	×	✓	✓	✓
iCETA Tangible Math	×	×	✓	✓	✓
AudioMath	✓	✓	✓	×	✓

Figure 2.2 shows that seven applications have multiple modes, five applications have magnification, ten applications have voice support function, three applications have braille support, and nine applications offer an interactive interface (i.e., easy interaction, clear purpose, high usability, better color contrast, and sizes of the UI element).

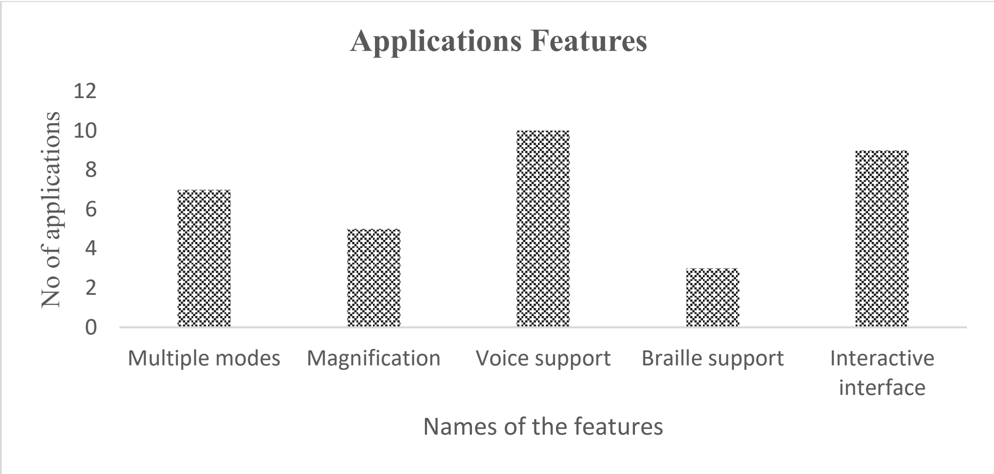

Figure 2.2: Math learning applications features.

2.6.4 Categorization of available solutions

We have categorized the available solutions described in the papers as Multimodal, Braille, Desktop, and Smartphone-based solutions. Multimodal approaches include two solutions, namely REMathEx and LAMBDA. There were three Braille-based solutions, namely 3D printers, tactile graphics, and Braille mapping of geometry diagrams. There are eight desktop-based solutions, namely MathPlayer, MathML, LaTeX-access, Speaking Math calculator, Audio Math, AfL system, Mathtalk, and Mathematics for all. Ten smartphone-based solutions formed part of the current study, namely Math Robot™, Draw2Measure Protractor, Slapstack Math, Practice2Master Fractions, UAbacus, Math Melodies, TouchMath Counting, i-Math, iCETA Tangible Math, and MathSpeak. Figure 2.3 showed the information on available solutions in the current study.

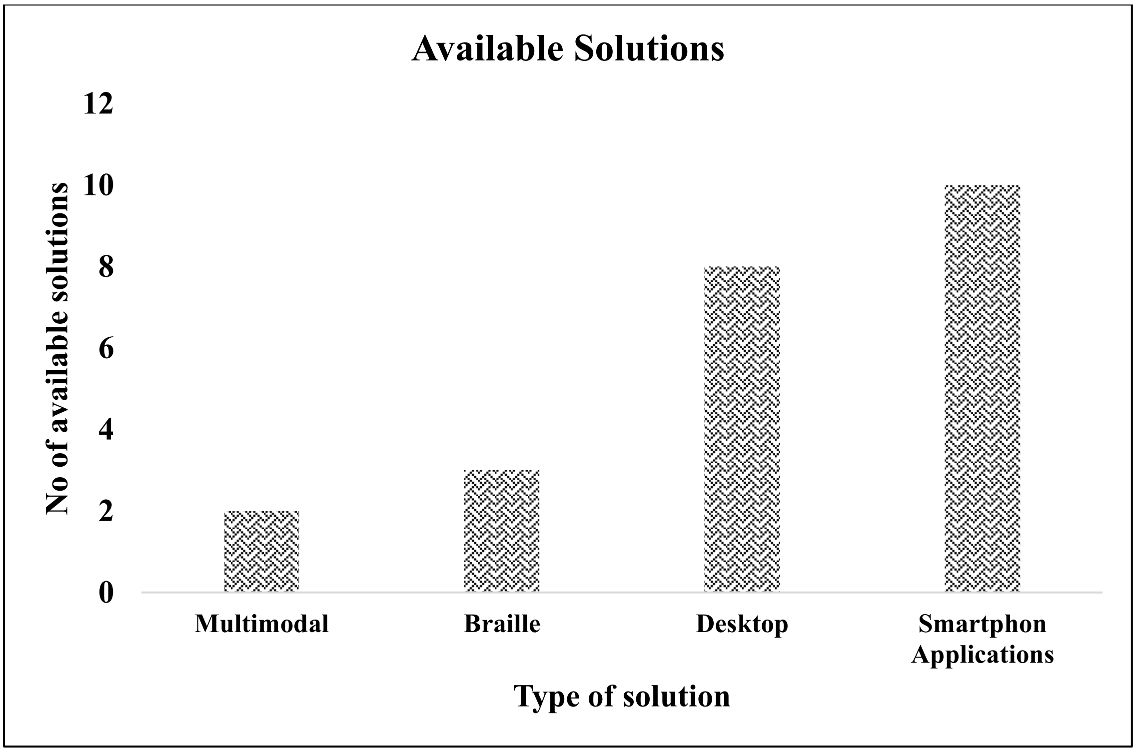

Figure 2.3: Available solutions in the current study

2.6.5 Conceptual Model of learning mathematics

Mathematics plays an important role in education, and every student should have the opportunity to learn mathematics. Learning is a process whereby anyone can enhance his knowledge by transforming his experience. Visually impaired students normally use the auditory and tactile senses in the absence of a visual channel. So, for visually impaired students, the quality of the learning experience depends upon a good teacher and AT-based solutions. Teachers should design the course content, assignments, handouts, and other activities by using assistive technologies so that learning becomes easier.

Figure 2.4 provides a conceptual model of learning mathematical skills using AT. They can communicate with other devices, the learning environment, other people, and their teachers by using AT. This model shows that AT empowers visually impaired users to significantly enhance their mathematical skills.

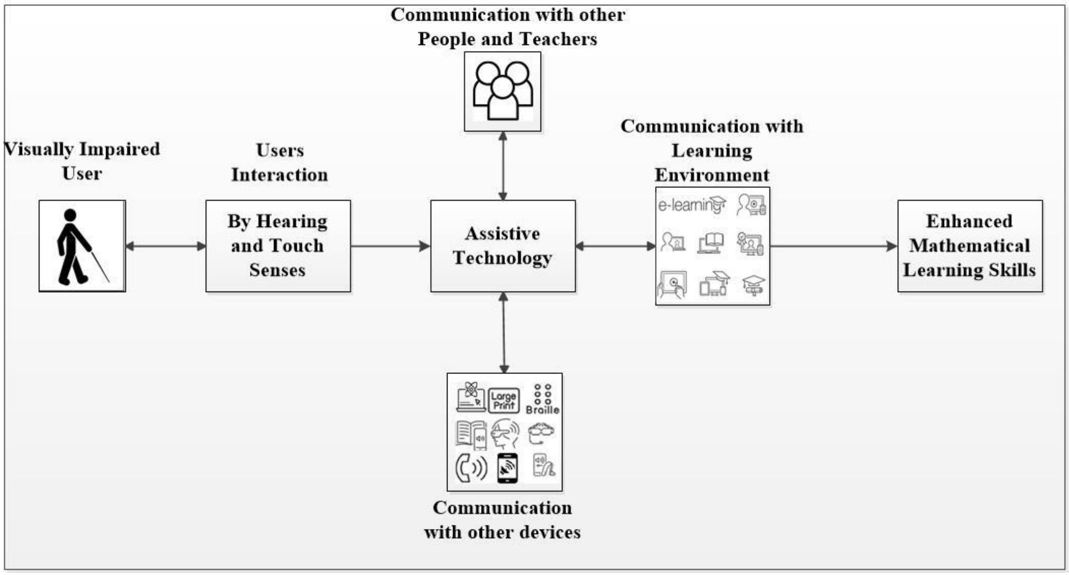

Figure 2.4: Conceptual model of learning mathematical skills by using AT.

2.7 Discussion

Previous research has shown that AT provides the opportunity for visually impaired and blind students to enhance their learning process by using accessible mathematical materials. This discussion section has three parts to elaborate on the impact of technology on the development of mathematical abilities among visually impaired and blind students.

1. The first part provides an overview of teaching mathematics to visually impaired people
2. The second part is about the applications and their features for learning Mathematics in AT.
3. The third part presents a categorization of available solutions.

Firstly, a systematic review of previous studies was conducted. Most studies were evaluated on visually impaired and/or blind participants. The findings showed that accessible math materials(material that is in a format which is optimized for accessibility), academic support, haptic feedback, tactile graphics, digital books and audio-based platforms are very useful to address the challenges of visually impaired people. Earlier research also demonstrates that mathematical material can be made easily understandable for visually impaired students, and by using that material, their learning process can be enhanced (Marshall et al., 2008; LaVenture, 2007). It is a challenging task for visually impaired students to access information presented in graphic form. This information can be accessed using AT-based solutions where the focus is shifted towards hearing and touch-based techniques. The comparison of tools, techniques, algorithms, systems, and projects provides a detailed overview of the current solutions used for enhancing the mathematical skills of blind and visually impaired people. These solutions offer several functionalities such as: converting graphics into sound, syntactic speech rendering, audio-tactile graphics, designing gestural interfaces and introducing audio-based mathematical reading systems (i.e., technical content and mathematical formulas). We have also listed the feedback mechanism, and the input and output mechanisms used by each system used to handle different mathematical operations i.e., visualizing graph-based information and accessing algebra content using audio-tactile graphics. It is also found that users can access math formulas, algebra expressions, complex math equations, and geometry shapes using these solutions. Several forms of feedback were used in the designing of these solutions i.e., synthetic speech, non-speech, haptic, sound cues, and tones. It is also noticed that whenever spatial sound, auditory, and hepatic feedback is available along with visual and textual information then visually impaired users can easily perceive the information. (RQ1)

Secondly, we have discussed commercial and research-based applications of learning Mathematics in AT. These applications present the graphical information of mathematics to visually impaired students using Braille notation, tactile displays, interactive interfaces, screen readers, voice synthesizers, and zooming programs. The voice support function of the applications is quite useful for visually impaired and blind people. They can access mathematical formulas and solve problems using this function. Research shows that applications with the combination of audio and tactile feedback significantly enhance the process of learning mathematics. We have also explored the features of available applications such as voice support function, audio-visual elements, multi-modal feedback, audio icons, self-voicing functions, low vision mode, braille support, multisensory support, and math flashcards. These features are available in current applications to facilitate visually impaired and blind students. We have also provided a comparison of some common features of the applications i.e., interactive interface, multiple modes, magnification, voice, and braille support. Comparison results showed that every application has a voice support function, and with the help of this function, visually impaired students can access the material easily. Visually impaired and blind students faced several challenges during the use of commercial and researcher-based applications. For example, applications are not designed according to the accessibility features and are unable to cater to the needs of visually impaired and blind students i.e., problems with feedback (lack of screen reader). It is noticed that some applications are not designed in a way that blind and visually impaired students can use them easily i.e., have rich visual information and a complex navigation mechanism. Some applications have limited functionalities which can make it challenging for these students who are looking for a solution that provides support to them on various topics of mathematics.(RQ2)

Thirdly, the categorization of the available solutions is described as Multimodal, Braille, Desktop and Smartphone-based solutions. These categorizations clearly showed that smartphone-based solutions are more prominent and there is a lack of multimodal approaches to provide support to visually impaired and blind students in learning mathematics. On the other hand, researchers' intentions towards developing smartphone-based solutions are quite high as compared to Braille and computer-based solutions. Mostly, visually impaired people can easily afford mobile devices and have satisfactory experiences with them. Also, several useful and free applications are available from app stores. With the help of smartphone-based solutions, users educational abilities could enhance, and their learning behaviour can be significantly improved. It was also noted that educational material supported by smartphone-based applications gave a positive impact on the learning outcomes of visually impaired students. Smartphones are also equipped with accessibility functions that provide easiness to visually impaired people in accessing information. (RQ3)

The findings show that while various assistive tools exist (e.g., tactile graphics, audio players), few leverage the ubiquity of smartphones. I would have thought that smartphone use is particularly widespread among youth and support multimodal interfaces, we argue that focusing on mobile math apps is justified. As one source notes, "traditional mobile apps rely primarily on visual interfaces, making them difficult for those with visual impairments. This gap impedes the educational development of these students" (Shoaib, 2025). Thus, tailoring mobile applications to VI students is both needed (to fill gaps in existing tools) and promising (due to built-in accessibility features like screen readers and vibration). We tie this back to the thesis goal of creating a smartphone-based math learning app for blind and low-vision children. The discussion concludes by linking the review's insights to the next chapters, because most math apps are not fully accessible.

2.8 Conclusion

We have concluded in this article that AT facilitates visually impaired and blind people in learning mathematics and provided a detailed review of some existing tools, techniques, applications and games. Developments in e-learning have proved beneficial for educational enhancement, but also pose challenges for visually impaired students (Asebriy et al., 2018; Ashraf et al., 2016; Líška et al., 2015 and Morash & Mckerracher, 2014). Research has shown that various challenges and issues were overcome using AT-based solutions, i.e., accessing graphical information, lack of independent learning, high color contrast and large print numbers. We have found that unimodal learning systems are less effective than systems that offer multimodal approaches to access math resources. In multimodal techniques, we can combine different approaches i.e., Braille, synthetic speech, tactile visual display, tangible resources and tangible user interfaces. With the help of innovative technologies, various computer-equipped solutions have been developed, such as a GUI calculator and a virtual learning platform for the web environment (Kleanthous & Meletiou-Mavrotheris, 2016 and Merchant et al., 2014).

Additionally, mobile devices and app-based interventions are very useful, affordable and have a positive impact on the educational system (Kucirkova & Falloon 2016). The smartphone-based solutions also provide multiple representations of information i.e., audio and tactile feedback, zooming, pictures, video, animation, user control, and repetition of tasks, and can serve to create a personalized learning environment (Rose et al., 2005; Martiniello et al., 2022 and Karshmer et al., 1999).

Furthermore, the learning environment, technology-based training, student motivation and teacher expertise play an important role in the learning of visually impaired and blind people. It is also recommended to have academic, technological and specialized support for visually impaired and blind people learning mathematics. Visually impaired and blind students prefer applications that allow them to practice mathematical tasks independently and comfortably. We have seen that AT-based solutions can minimize several challenges faced when accessing graphical and visual content in mathematics, and enhance problem-solving skills in visually impaired and blind students.

Moreover, different study designs, data collection and analysis approaches were used in previous research i.e., qualitative research methodologies, UCD, usability studies, exploratory studies, single-subject designs and efficiency testing of algorithm parameters. Previous research studies showed that interviews, questionnaires and participant observation were very useful for the assessment of studies. Pre-study training sessions gradually enhance the skills of visually impaired and blind people and are also helpful for their learning intervention.

The research reviewed here suggests that provided the instructor successfully motivates students regarding the use of digital textbooks, it can be more useful for them to access mathematics material in this way rather than using traditional methods. Finally, earlier studies showed that AT-based solutions have a positive impact on the learning skills of visually impaired and blind people. Assistive and innovative technologies are also very useful for overcoming challenges and issues facing visually impaired and blind people. The development of smartphone-based solutions empowers visually impaired and blind users by providing them with accessible material on mathematics.

Lastly, we have introduced a conceptual model of learning mathematical skills using Assistive Technology (AT). This model shows that AT empowers visually impaired users to significantly enhance their mathematical skills. We have categorized the available solutions described in the papers as Multimodal, Braille, Desktop and Smartphone-based solutions that could be helpful for readers and other researchers. We have discussed the commercially available and research-based applications. Extract their features i.e., multiple modes, magnification, voice support function, braille support, and interactive interface. We have identified the challenges/issues faced by visually impaired and blind students using current solutions and provided this information in the discussion section which is very useful for other readers. We are trying to encourage researchers to get familiar with the unsolved challenges of this topic.

Researchers and app developers should keep in mind that every visually impaired and blind student has a different level of knowledge and intellectual abilities. Therefore, newly-designed applications should offer learning modules at various levels, integrated with Artificial Intelligence-based modules that can identify the user's abilities and identify the learning level of the users. In addition, adopting a Universal Design approach may help to meet the needs of all users. Artifacts developed using universal design can be accessed and understood by all kinds of users regardless of their abilities, knowledge or disabilities. Universal design can provide an accessible, usable, suitable, and pleasurable environment to everyone.

There are also some issues and limitations in current applications. Due to these limitations visually impaired and blind students feel difficulty in accessing structural information and mathematical formulas. To address these problems, developers should introduce an ‘ask for help’ module which offers additional clues about the specific task and assists visually impaired students when they cannot remember the next steps. Additionally, desktop-based solutions have some drawbacks such as limited portability, lack of touch screens, increased space and cabling requirements, and access to mains power. Smartphone-based solutions offer advantages for visually impaired and blind people because they are more convenient, less expensive and easily available for everyone.

2.9 Future Work

We have provided future directions and recommendations for the development of smartphone-based applications that can be useful in helping visually impaired and blind people in learning mathematics.

Earlier research showed that the focus has shifted from vision to hearing in eyes-free environments (Fallah, 2010; Ran, 2004; and Loomis et al., 2005). Recent innovative technologies use hearing, haptic, and multimodal combinations of senses to help visually impaired and blind people learn mathematics. Most of them support only the English language, in future, a solution may be developed which has no language dependency. Therefore, people whose first language is not English may have a chance to develop their mathematical skills easily.

In future, researchers can investigate how math teachers effectively teach advanced-level mathematics skills to visually impaired and blind students using AT. For this purpose, haptic feedback is very useful because, in the absence of vision, it can be used with visual input to construct mathematical learning systems. Lastly, in the field of mathematics, there is a need for more adaptive systems. Developers should introduce adaptive systems and applications which automatically change their configuration and behaviour based on the interaction of the user.

2.10 Concluding Remarks

Building upon our research of assistive technology-based solutions in learning mathematics for visually impaired individuals, we have revealed various issues, obstacles, and opportunities inherent in these technologies. While these solutions have considerably enhanced accessibility and educational outcomes, they are not without limitations and require continued development. Building on these observations, Chapter 3 focuses on improving mathematics learning skills and overcoming the difficulties that visually impaired students face. We dive into the world of mathematics accessibility within primary education, trying to develop practical solutions that fulfill both the pedagogical and accessibility demands of young learners. This chapter gives educators, developers, and policymakers a path to construct more equitable and prosperous learning environments by studying pedagogical approaches, assistive technology, and inclusive practices. The transition from the general issues of remote learning to the specific context of primary school allows us to concentrate on core skills and early interventions that can have a lasting impact on the academic paths of visually impaired children.

Chapter 3

Mathematics Accessibility in Primary Education

This chapter was published as: Shoaib, M., Minghim, R., Fitzpatrick, D., & Pitt, I. (2024, July). Mathematics Accessibility in Primary Education: Enhancing Mathematics Learning Skills and Overcoming Barriers for Visually Impaired Primary Students. In International Conference on Computers Helping People with Special Needs (pp. 192-202). Cham: Springer Nature Switzerland. DOI: https://doi.org/10.1007/978-3-031-62846-7_23

3.1 Abstract

This paper describes a qualitative study concerning the experiences of blind and visually impaired students learning mathematics in primary schools in Ireland, along with a thematic analysis of the findings. It investigates the instructional challenges and teaching techniques that facilitate an inclusive learning environment through flexible assessment plans. Key focus areas include adapting class collaboration activities, using digital and non-digital materials, and deploying specialized strategies to boost learning skills. This study identified significant barriers, including technology accessibility, classroom mobility, and the need for supportive educational aids such as tactile materials and Braille resources. This paper also discusses the importance of support and assistance, including teacher training, parental involvement, and peer support processes. Based on expert opinions, the study identifies gaps in current solutions and suggests future research and development directions. These include the advancement of User-Centred Design (UCD), the integration of multimodal techniques, and the improvement of collaborative and interactive learning solutions. Furthermore, this study recommends reforming educational policy and comprehensive training programs for educators to ensure that visually impaired students receive an equitable mathematics education. This study lays the groundwork for future advancements in teaching methodologies and assistive technologies, aiming to remove educational barriers and foster academic excellence within blind and visually impaired students.

3.2 Introduction and Background Context

Educational inclusion is still a cornerstone of equal schooling. The unique academic requirements of blind and visually-impaired children are often not adequately met during primary education. This chapter presents a thematic analysis that investigates three main areas: the mathematical learning experiences of blind and visually-impaired students, the pedagogical approaches of teachers, and expert viewpoints on accessible educational solutions in primary schools.

3.2.1 Mathematical Learning Experiences of Blind and Visually-Impaired Students

The first area of attention concerns the unique challenges and techniques of mathematics learning for blind and visually impaired students. Previous research includes many studies focusing on specific teaching strategies for these students and identifying several key aspects of mathematics learning. Maćkowski & Brzoza (2022) introduced a tutoring platform developed for visually impaired children. The platform utilizes audio-tactile visuals to enhance the learning process for mathematics topics. The efficiency of this platform was examined through quantitative and qualitative research with students from primary and secondary schools. The study attempts to improve learning effectiveness through tailored audio explanations and exercises, catering specifically to the educational needs of visually impaired students. Hayes & Proulx (2024) examine the issues faced by students with visual impairments during standard scientific and mathematics instruction. They stress the significance of classroom adjustments, such as hands-on experiences and extra instructional time, to promote their learning. They also highlighted findings concerning educational policies and practices, i.e., effective adaptation of teaching materials and helping students acquire skills that enhance their independent learning. Steinbach addressed the obstacles students with visual impairments face in obtaining and understanding the mathematics curriculum. It examines several techniques of conveying mathematical information to these children, such as auditory, tactile, and multi-sensory approaches. This study also underlines the need to adjust instructional strategies and resources to suit the needs of visually impaired students, concentrating on boosting their engagement and understanding of mathematical ideas. The study highlights the need for inclusive educational approaches and the development of appropriate multi-sensory solutions to help the mathematical education of visually impaired children (Steinbach, 2022).

Drijvers & Sinclair reviewed how digital technologies were employed in mathematics instruction. They created a framework encompassing five aims for employing DTs: increasing learning, understanding learning processes, designing for learning, guaranteeing equal access, and influencing curriculum and teaching practices. They address various theoretical foundations, methodologies, and outcomes relevant to these aims, illustrating the evolving nature of research on this topic and the rising relationship between digital technology and mathematical education. The article underlines the significant impact of DTs on the nature of mathematics education and learning (Drijvers & Sinclair, 2024). Bobomurod focused on the educational obstacles and methods of teaching mathematics to visually impaired students. It highlights the need to understand children's attitudes toward mathematics learning from an early age to prevent the development of negative opinions about this subject. Moreover, it examines the content and objectives of the mathematics course, highlighting the need for corrective and developmental conditions, particular techniques, and cognitive activity development. It underlines the significance of adjusting educational methodologies to accommodate the specific demands of visually impaired students, trying for their optimal growth and social adaptation (Bobomurod, 2023).

3.2.2 Investigation of Teachers' Experiences while Teaching Mathematics to Blind and Visually Impaired Students

The second area of attention is teachers' experiences when educating blind and visually impaired students. The literature shows that teachers are essential in designing inclusive education. They often experience unique pedagogical problems and lack proper preparation. Rushahu conducted a study focusing on the issues and skills of lecturers in Tanzanian higher education institutions to serve visually impaired pupils. A qualitative method was employed with interviews and focus group discussions among 40 participants, including students with visual impairments and professors. The survey demonstrates that most professors lack the abilities and knowledge to identify and address the unique learning demands of these students. It underscores the need for redesigned university curricula, adequate training for professors, and more significant state funding for inclusive education (Rushahu, 2023). A thesis by Amanda Esmeralda Mungunda, finished in April 2023, explores the specific obstacles that secondary school mathematics teachers confront when educating learners with vision impairment. Focusing on the Khomas region in Namibia, the study adopts Bruner's idea of constructivism as its theoretical base. Utilizing qualitative research methodologies, it comprises observations and semi-structured interviews with a selected sample of teachers and visually impaired students. The study intends to improve visually impaired students' teaching and learning experiences and offers successful teaching practices, including the need for assistive technologies and instructional materials (Mungunda, 2023). Baykaldı explored the experiences of high school mathematics teachers in teaching students with visual impairments. They investigate the challenges faced by the teachers, along with their teaching styles, curriculum preparation, assessment strategies, and ideas regarding inclusive education. The study, conducted through interviews with eight instructors, highlighted a lack of proper training and resources for inclusive education, although they demonstrated 'high teaching efficacy' generally (e.g., with non-visually-impaired students) and had high ideals regarding teaching (e.g., were highly motivated to help visually impaired students. The findings underline the need for increased teacher training and resource development to facilitate inclusive education (Baykaldı et al., 2023). Mbulaheni Maguvhe proposed a study focusing on the problems and opportunities in teaching science and mathematics to visually impaired children. The study is based on a case study approach, underlining the critical role of instructors and the necessity for specialized resources and training. It highlights the need to empower instructors to serve visually impaired students in various courses successfully and recognizes the vital role of inclusive education methods. The research gives valuable insights for increasing the learning abilities of visually impaired students in science and mathematics, helping the broader conversation on inclusive education (Maguvhe, 2015).

3.2.3 Expert Viewpoints on Accessible Educational Solutions in Primary Schools

Thirdly, the study included professionals to obtain suggestions for potential solutions for these children. Integrating expert perspectives is vital in bridging the gap between theoretical knowledge and actual application. Previously, several studies were conducted without the opinion of experts or professionals. IrisMath is a web program developed to aid visually impaired people in executing mathematical operations, notably for engineering students. Inspired by Jupyter Notebooks, this system supports multiple output formats such as LaTex, CMathML, JSON, and audio, assuring accessibility and comprehensibility for visually impaired users. The paper explores the architecture, development, and evaluation of IrisMath, showing its potential as a helpful tool for inclusive education in technical and engineering subjects (Zambrano et al., 2023). Bayram et al. (2015) investigate the experiences of visually impairment children in inclusive math courses in Turkey. It focuses on the obstacles these students experience, their opinions on learning methods, and the usefulness of the resources adopted. The study underlines the gap between these children's social and academic demands, underlining a shortage of teacher preparation and reservations towards inclusive education. It emphasizes the need for increased teacher training and creating resources to help visually impaired children in mathematics. A study was conducted on building tools to help visually challenged children learn mathematics. They address the issue of writing and reading complicated mathematical formulas for children. The project at New Mexico State University includes developing logic programming-based systems and interfaces to improve the utilization of mathematical information. This includes building a method for converting Nemeth Code to LaTeX and vice versa, boosting collaboration among blind students and sighted lecturers. The research also discusses employing encoded musical notes and signals of sound to express mathematical concepts, seeking to complete the education cycle with accessible resources for visually impaired children (Karshmer et al., 1999).

In this chapter, we have explored the challenges of blind and visually impaired primary school students. A study was conducted with teachers intended to add depth to this knowledge by examining the lived experiences of teaching in primary schools. Find out the viewpoints of professionals and expert persons. Their thoughts can help researchers and developers build more prosperous, inclusive educational platforms for blind and visually impaired students. This thematic analysis contributes to the ongoing conversation about inclusive education. It strives not only to expose the existing obstacles and opportunities in teaching mathematics to blind and visually impaired primary students but also to provide actionable ideas for improvement, pulling from both academic and practical domains. The remaining chapter is organized as follows: Section 3.3 explains the methodology; Section 3.4 illustrates the results in the form of extracted themes; Section 3.5 concludes this article; Section 3.6 provides recommendations for future work; and Section 3.7 provides the concluding remarks.

3.3 Methodology

The research employed a qualitative study design, employing semi-structured interviews for data collection. Thematic analysis was used to analyze the gathered data.

3.3.1 Participants

This study involved nineteen participants divided into three categories: students, teachers, and domain experts. Firstly, this study included five visually-impaired participants from various primary schools, two males and three females. These individuals were recruited from different primary schools. Their ages ranged from 9 to 12 years, with a mean age of 10.80 (Std. Deviation = 1.3 and Variance = 1.7). Student participants in the study met the criteria for legal blindness (visual acuity 20/400 or less). Among the participants, three were completely blind (P1, P2, and P4), and two participants (P3 and P5) had low vision. Most students identified as Republic of Ireland nationals (4), and EU nationals (1), Secondly, nine primary school teachers (P6-P14) took part in this study. They have diverse roles within the primary school context, including class teachers (1), Support teachers (2), and Special Educational Needs teachers (6), boasting experience ranging from 3 to 22 years. The age range of participants spanned from 26 to 54 years, with a notable gender difference (7 females, 2 males). The majority of participants identified as Republic of Ireland nationals (4), EU Nationals (2), Asian (2), or United Kingdom (1), aligning with broader demographic trends in the teaching profession. Thirdly, five focus group persons (P15-P19) from several organizations, i.e., National Disability Authority (1), National Council for Special Education (1), Saint John of God (1), and VisitEDUfinn Ltd (2), participated in this study. The age range of participants spanned from 40 to 58 years, with a notable gender difference (3 females, 2 males). Their professional experience ranges from 5 to 20 years. The majority of participants identified as Republic of Ireland nationals (2) and EU National (2), United Kingdom (1), aligning with broader demographic trends in their professional careers. Overall, teachers and focus group participants ages ranged from 26 to 58 years, with a mean age of 43.64 (Std. Deviation = 9.44 and Variance = 89.02). Their experience ranges from 3 to 22 years, with a mean experience of 13 (Std. Deviation = 6.28 and Variance = 39.39). For additional demographic details, refer to Table 3.1 and Table 3.2. Table 3.1 provides participant details, including participant ID, age, gender, nationality, a description of vision impairment, blind or low vision, and Educational arrangements. Table 3.2 provides participant details, including participant ID, age, gender, nationality, and experience in number of years.

Table 3.1: Detailed information of student participants

Participants ID	Age	Gender	Nationality	Description of vision-impaired	Educational Arrangments
P1	12	Female	EU Country	Blind	Special education class
P2	10	Male	EU Country	Blind	General education along with special education
P3	11	Female	EU Country	Low Vision	General education along with special education
P4	9	Male	Republic of Ireland	Blind	General education along with special education
P5	12	Female	Republic of Ireland	Vow Vision	General education along with special education

Table 3.2: Detailed information of Teachers and Focus group participants

Participants ID	Age	Gender	Nationality	Experience in No. of Years
P6	52	Female	Asian	20
P7	42	Female	EU Country	19
P8	26	Female	Asian	3
P9	29	Female	EU Country	18
P10	45	Male	United Kingdom	10
P11	37	Male	Republic of Ireland	14
P12	43	Female	Republic of Ireland	22
P13	54	Female	Republic of Ireland	7
P14	44	Female	Republic of Ireland	10
P15	43	Female	EU Country	13
P16	58	Male	EU Country	15
P17	40	Male	United Kingdom	5
P18	57	Female	Republic of Ireland	20
P19	41	Female	Republic of Ireland	6

3.3.2 Data Collection and Analysis

Interviews were conducted with each stakeholder group. Teachers were interviewed in quiet rooms at their schools. Students were interviewed one-on-one in familiar settings (e.g., their classroom), and their teachers were in the room. Experts were interviewed online or in offices. Informed consent (and child assent) was obtained in advance. The semi-structured interview guides (appendix) covered questions like: "Do you find that have to make additional effort to enable blind and visually-impaired students to understand numbering topics in mathematics (compared with teaching the same topics to other students)?", and "Would you like to share some useful strategies which better support students in learning mathematics?" These open-ended questions were tailored by the group but focused on challenges, strategies, and wishes for tech support.

One technique for finding, examining, and summarizing patterns in qualitative data is thematic analysis. Using this methodology, data can be transformed into rich, in-depth knowledge through text analysis. Thematic analysis is a tool for identifying and explaining facts and capturing crucial details related to the data and research question. Thematic analysis is an iterative and distinctive approach to text evaluation that offers a specific understanding and interpretation of the study issue, according to researchers (Bogdan & Biklen, 1998; Brooks et al., 2018). Thus, in the current study, the concerns of visually impaired students and teachers were identified and extracted using thematic analysis.

The data was examined using the inductive thematic analysis procedure outlined in this study (Braun & Clarke, 2006). Thematic analysis was chosen for its adaptability and capacity to yield insightful, interpretative comments (Boyatzis, 1998). This approach is not theory-driven but instead data-driven, enabling the researcher to uncover unforeseen insights. The analysis adhered to Braun and Clarke's six-step method. Firstly, the researchers read and familiarized themselves with the data. Secondly, codes were manually generated on the transcripts' margins based on the entire dataset. The same unit of text could be encompassed in more than one code, and relevant data for each code were compiled. Thirdly, the coded data were systematically reviewed, cross-checked, and organized into themes. Fourthly, themes were cross-checked against the coded data and the entire dataset and concluded by creating a thematic 'map.' Fifthly, themes were defined and labeled. Finally, the themes underwent in-depth analysis, with selected data extracts examined in relation to the research question, existing literature, and the subsequent report.

Initially, we reviewed notes and transcripts to identify potential codes (e.g. "difficulty with diagrams", "haptic preference"). In successive coding rounds, some early codes were merged or refined; for example, initial codes like "graph confusion" and "diagram difficulty" were consolidated into a theme "visual content barriers." The coding was iterative: after each review round, we compared codes across the teacher, student, and expert groups, refining definitions. For instance, when a teacher noted "I feel like blind students can't access number lines easily," we coded it as a number-line accessibility issue. An expert comment like "audio descriptions help but students get overwhelmed by long sentences" led to a code cognitive load of audio. These codes were grouped into themes like "Techniques, methods to fulfill learning need", "Challenges, Obstacles and Issues", "Ways to make learning mathematics easy", etc. Our analysis unfolded through memoing and constant comparison, ensuring themes captured the breadth of perspectives.

3.4 Results

3.4.1 A Thematic Analysis of Mathematics Learning of Blind and Visually Impaired Students in Primary Schools Perceptions of Learning Challenges, Strategies, Support, Resources

After examining the five transcripts, five prominent themes concerning students' viewpoints were found. Figure 3.1 presents a comprehensive visual representation of the factors affecting the learning process of visually impaired students in mathematics. The diagram also represents a thematic analysis related to the mathematics learning of blind and visually impaired students in primary schools. It is structured around a central theme, "Investigating Mathematics learning of Blind and visually impaired students in primary schools", with related factors branching out into specific categories such as: "Mathematics Topics", "Class Collaboration Activities", "Challenges, Obstacles, and Issues", "Techniques and Methods to Fulfill Learning Needs", and "Assistance and Support".

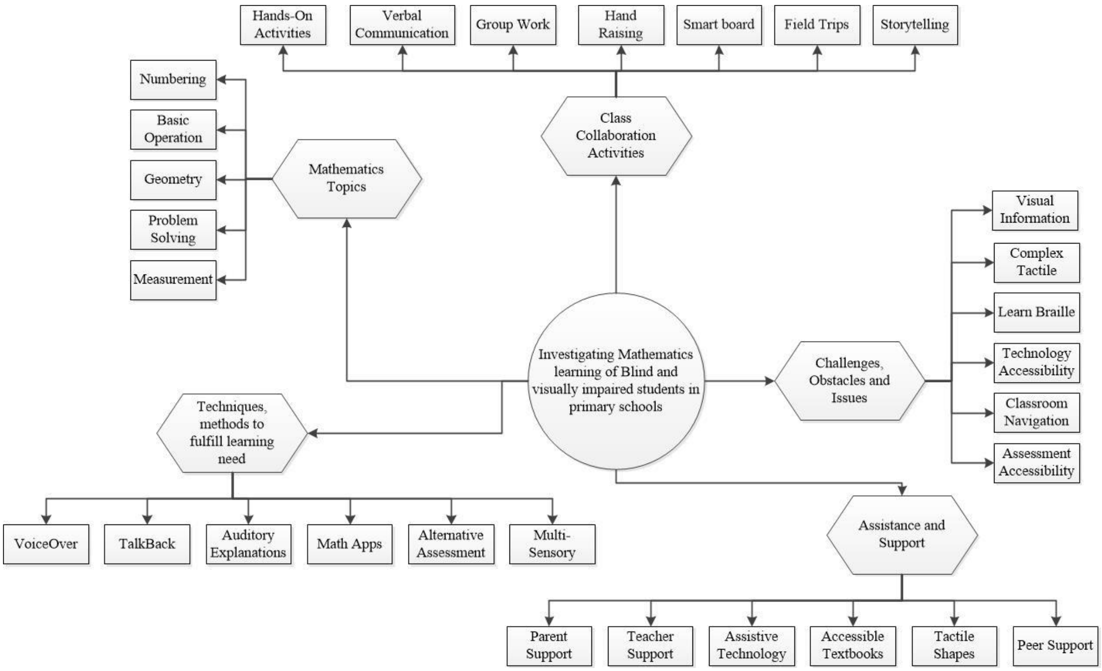

Figure 3.1: A thematic analysis of Mathematics learning of Blind and visually impaired students

3.4.2 Investigation of Teacher Experiences while Teaching Mathematics to Blind and Visually Impaired Students in Primary Schools

An analysis of nine transcripts revealed four leading themes concerning teachers' viewpoints. Figure 3.2 presents a comprehensive analysis of the various factors affecting the teaching process and the potential strategies to overcome challenges, facilitating a better learning experience for visually impaired students in primary schools. This diagram also represents the thematic analysis of teacher experiences while teaching mathematics to blind and visually impaired students in primary schools. Here's an explanation of its structure: The central theme of the diagram is the "Investigation of teacher experiences while teaching mathematics to Blind and visually impaired students in primary schools." Branching out from this central theme are four main categories: "Barriers, obstacles, and Challenges faced by teachers", "Digital resources", "Non-digital resources", and "Ways to make learning mathematics easy".

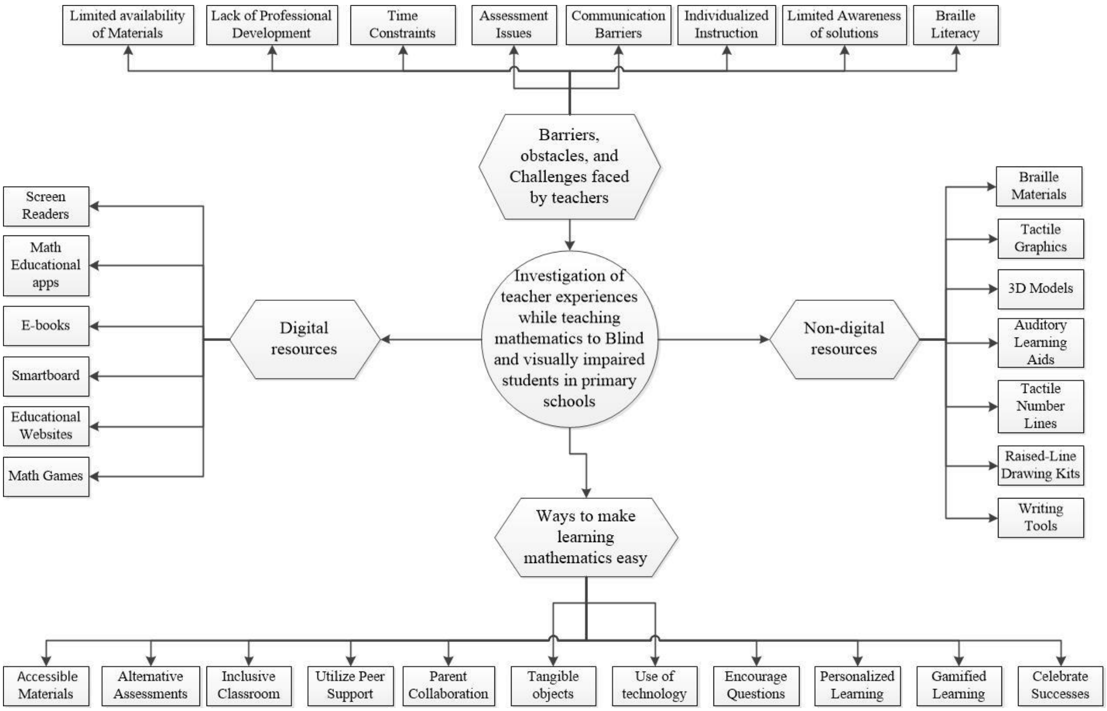

Figure 3.2: A thematic analysis of teachers' experiences

3.4.3 Opinions of Expert Persons to Introduce Accessible Solutions for Blind and Visually Impaired Students.

After the exploration of five transcripts disclosed four leading themes concerning focus group persons' viewpoints, figure 3.3 serves as a comprehensive representation of expert perspectives on creating a more inclusive and accessible learning environment for blind and visually impaired students, particularly in the context of mathematics education. It suggests a multi-faceted approach that includes both the refinement of existing solutions and the development of new strategies and tools. This diagram also represents a thematic analysis of the opinions of experts on introducing accessible solutions for blind and visually impaired students. It organizes these opinions into several categories, named: "Valuable strategies for learning mathematics", "Missing features from current solutions", "Creative approaches for designing mathematics solutions", and "Guidelines/methods for developers".

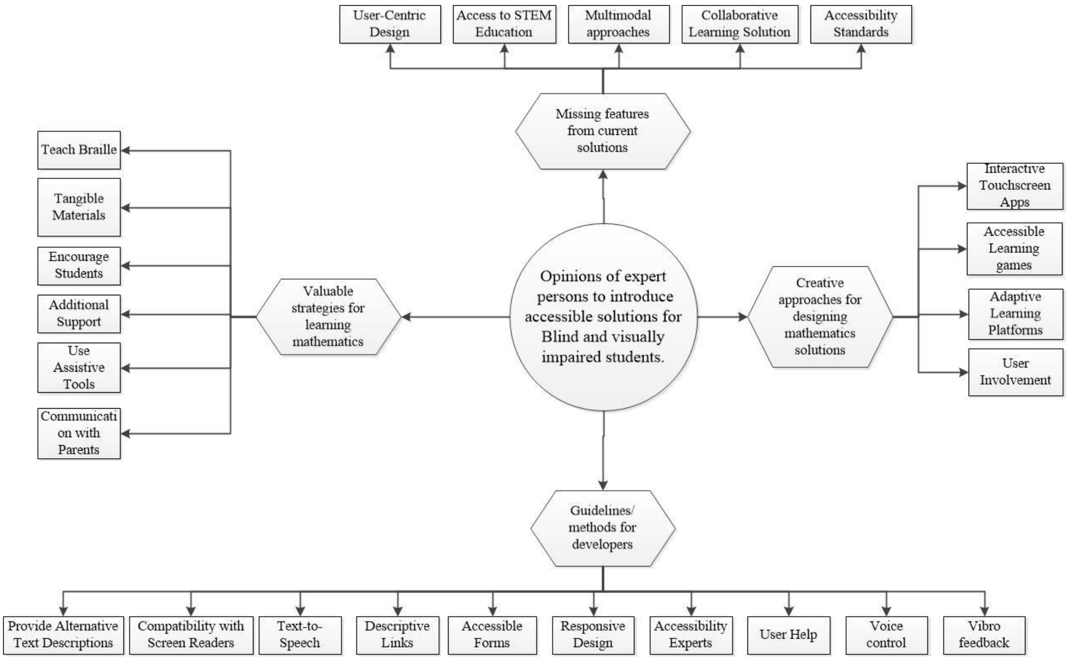

Figure 3.3: A thematic analysis of professional experts to introduce accessible solutions

3.4.4 Inductive Thematic Analysis from Each Stakeholder Group

Each stakeholder group showed distinctive thematic patterns.

Students: Blind and low-vision pupils both mentioned Dependence on Non-Visual Cues. A blind student said, "I imagine shapes by feeling my finger, but sometimes it's confusing," indicating challenges with geometry. A low-vision student remarked, "If I can turn the brightness way up, I can sometimes see the number on the screen." These quotes reflect themes of needing tactile/math tools and screen adjustments. A blind student said, "I enjoy solving math problems with my friends because they describe the shapes for me." This quote illustrates how student-peer interaction mitigates the lack of sight by verbal description and shared problem-solving. Another student said that, "Sometimes I can't keep up when the teacher writes on the board, I miss what was drawn, and I fall behind." This quote highlights a real obstacle: standard visual teaching (e.g., board work or projected problems) is not perceivable by the student. Another theme was Desire for Independence: for instance, a low-vision pupil expressed frustration at always needing a helper to check answers. We interpret these findings to mean that students seek direct interaction (drawing, touch) and more self-feedback.

Teachers: The main themes were Inaccessibility of Visual Materials and Adaptation Effort. Teachers frequently described spending extra time preparing materials. One teacher noted, "When presenting graphing exercises, I struggle because there's no accessible format for these students," illustrating the burden of converting content. Many teachers reported a lack of specialized math teaching aids; for example, a teacher said, "We have braille for numbers, but no braille graphics for geometry." These data excerpts highlight how teachers perceive systemic resource gaps. Another teacher said, "We use Braille math textbooks and an abacus. The student also uses a talking calculator and a computer with screen-reader software when solving problems." The quote shows specific methods (Braille books, abacus, talking calculator) used to meet learning needs. Such techniques ensure that mathematical concepts are accessible; for instance, teachers noted that algebra equations are rendered in Nemeth Braille code, and digital tools read aloud numbers and operations. Another teacher said, "I always meet individually with the student after class to review problems I covered on the board. We also have a resource teacher who helps adapt assignments." The quote shows concrete support: extra review sessions and specialized staff.

Experts: Specialists (e.g., accessibility consultants) highlighted Design Principles and Pitfalls. One expert emphasized, "Apps should not just read text; they need structured math interactions." An expert said that "Most math apps don't have screen-reader compatibility or audio explanations. For example, an online graphing calculator I tested gave no spoken output for plotted graphs." The quote highlights a specific missing feature (audio output for graphs). Another expert has said that "Developers should include verbal cues for all actions and ensure math content is compatible with braille displays. They should also test with blind students from the start." This quote outlines specific developer actions (verbal cues, braille compatibility, and user testing). They also identified issues like inconsistent screen reader support in many math apps. For example, an expert pointed out that buttons were labeled inconsistently, making navigation hard. The theme Importance of Multimodal Feedback emerged strongly from experts, noting that audio description, vibration cues, and clear visual contrast should all be employed.

3.4.5 Thematic Analysis

- **Class Collaboration Activities:** This sub-theme captures how students rely on and value working with peers during math lessons. For example, a student noted that classmates help describe visual elements of problems. One student emphasized the importance of teamwork in class:

"I enjoy solving math problems with my friends because they describe the shapes for me." P3

This quote illustrates how student peer interaction mitigates the lack of sight by verbal description and shared problem-solving. Teachers also observed that group activities support understanding: for instance, P6 encouraged pair work so that sighted students "explain diagrams or graphs" to blind classmates. The coded idea *"peer assistance"* underpins this theme: students described collaborative learning situations where peers actively support their understanding of mathematical content.

- **Mathematics Topics:** Participants discussed the specific math topics taught and how they are learned. Both students and teachers noted that the curriculum covers standard topics (e.g.
arithmetic, geometry, fractions), but with adapted methods. A teacher explained how geometry is taught:

"We teach shapes and fractions just like the standard curriculum, but we use tactile diagrams. For circles and triangles, the blind student feels a 3D model of the shape." P12

Here, the teacher describes how core *Mathematics Topics* such as geometry and fractions are covered through tactile and auditory means. The codes grouped under this theme included *"geometry with models," "braille equations,"* and *"counting aids,"* reflecting various content areas and how they are addressed. Students confirmed learning topics hands-on (e.g. feeling coins to count money), indicating that the subject matter remains similar to sighted students but delivered through multisensory approaches.

- **Techniques and Methods to Fulfill Learning Needs:** This sub-theme reflects the instructional techniques and methods used to adapt math learning for blind students. Participants frequently mentioned tools like Braille materials, manipulatives, and assistive technology. For example, one teacher described the multimodal approach:

"We use braille math textbooks and an abacus. The student also uses a talking calculator and a computer with screen-reader software when solving problems." P7 Codes such as *"braille use," "manipulatives,"* and *"assistive*

tech" were grouped here. The quote shows specific methods (Braille books, abacus, talking calculator) used to meet learning needs. Such techniques ensure that mathematical concepts are accessible; for instance, teachers noted that algebra equations are rendered in Nemeth Braille code, and digital tools read aloud numbers and operations.

- **Challenges, Obstacles and Issues:** This theme covers difficulties faced by students in learning mathematics. Both students and teachers reported issues like inaccessible materials and comprehension gaps. A student described a common challenge:

  "Sometimes I can't keep up when the teacher writes on the board, I miss what was drawn and I fall behind." P1
  This quote highlights a real obstacle: standard visual teaching (e.g. board work or projected problems) is not perceivable by the student. Codes such as *"board visibility," "slow pace," "resource limitations,"* and *"communication delay"* were collated under this theme. Teachers noted related issues: for example, P7 mentioned that "many worksheets with graphs aren't accessible," pointing to systemic obstacles in materials and pacing. This theme makes clear the practical barriers (technical and instructional) that can hinder learning.

- **Assistance and Support:** This sub-theme encompasses the various supports provided to students. It includes one-on-one help, accommodations, and external resources. A teacher summed up typical support:

  "I always meet individually with the student after class to review problems I covered on the board. We also have a resource teacher who helps adapt assignments." P6 The codes here (e.g. *"one-on-one help," "resource teacher support," "*extra time") all point to assistance strategies. The quote shows concrete support: extra review sessions and specialized staff. Other examples include peer "buddies" assigned to read problems aloud and the use of audio recordings of lessons. Together, these supportive measures form a pattern where blind students receive tailored help, evidencing the "Assistance and Support" theme.

- **Barriers and Challenges Faced by Teachers:** Teachers themselves reported challenges in instructing blind students. Commonly cited barriers were lack of training and limited resources. For instance, one teacher confessed:

  > *"I wasn't trained for special education in math. It's hard to find accessible math software, and I struggle to adapt every diagram."* P8
  > This quote encapsulates key barriers: *"lack of training"* and *"resource scarcity"*. Codes such as *"insufficient training," "time constraints," "no accessible materials,"* and *"curriculum rigidity"* were captured here. Teachers expressed needing more professional development on accessibility and lamented that mainstream math content often isn't designed with visual impairments in mind. This sub-theme highlights that teachers face systemic and skill-based obstacles when trying to make math accessible.

- **Digital Resources:** This theme concerns teachers' use (or lack thereof) of digital tools. Teachers noted that while technology has potential, current digital math resources often lack accessibility. One teacher explained:

  > *"We tried an online math game, but it was all visual – no audio cues. There's simply no curriculum-aligned software that reads math content aloud."* P9
  > The relevant codes were *"inaccessible apps," "no audio support,"* and *"lack of accessible content."* The quote illustrates a missing feature: many math apps assume vision. Teachers mentioned using generic screen readers or repurposing apps from other subjects, but these often fell short (e.g. numbers not spoken). This sub-theme shows a gap in digital solutions: teachers recognize the value of tech but find current options inadequate.

- **Non-Digital Resources:** In contrast, teachers described traditional (non-digital) tools they rely on. High-quality Braille textbooks, tactile math kits, and physical manipulatives were frequently mentioned. A teacher described their toolkit:

  > *"Our classroom has raised-line graph paper, an abacus, and a set of tactile geometry shapes. These help a lot, but preparing them takes extra time."* P7
  > Codes grouped here include *"Braille math books," "tactile materials,"* and *"adapted worksheets."* The quote shows what is in use (raised-line paper, etc.)

but also the labor involved. Teachers often have to create or manually convert materials. This theme emphasizes that while non-digital aids exist (and are valuable), they can be hard to produce and may not cover all needs.

- **Ways to Make Learning Mathematics Easy:** Teachers suggested strategies to facilitate learning. These included pedagogical adjustments and accommodations. For example, one teacher recommended:

    "I simplify language and describe every visual step. Allowing the student to answer orally or use a talking calculator also helps." P12
    Codes like *"verbal description," "extended time," "hands-on examples,"* and *"flexible assessment"* were sorted under this theme. The teacher's quote illustrates concrete tactics: verbally explaining visuals and giving alternate ways to respond. Other strategies mentioned were pairing students for mutual support and using real-life examples. This theme captures teachers' practical advice for easing math learning (e.g. focusing on multisensory instruction and personalized pacing).

- **Opinions of Expert Persons:** Expert professionals (such as special-education specialists and technologists) provided additional insights about teaching math to visually impaired students. They underscored the need for training and system-level support. An expert in accessible education commented:

    "Teachers need guidance manuals and in-service training on accessible math pedagogy. Administrators should also ensure funding for adaptive resources." P16 The codes here included *"professional development," "policy support,"* and *"collaboration."* The quote shows that experts emphasize institutional support for teachers (not just individual strategies). Experts recommended creating teaching guidelines and fostering teacher networks to share best practices. This theme aggregates expert suggestions that complement teacher experiences by highlighting broader solutions and resources needed in the education system.

- **Missing Features from Current Solutions:** Experts identified gaps in existing educational technology for math. A common point was that many digital math tools lack accessibility features like audio or tactile output. One specialist noted:

  > *"Most math apps don't have screen-reader compatibility or audio explanations. For example, an online graphing calculator I tested gave no spoken output for plotted graphs."* P17

  Codes such as *"no audio feedback," "unlabeled graphs,"* and *"inaccessible interfaces"* underlie this theme. The quote highlights a specific missing feature (audio output for graphs). Overall, experts pointed out that current solutions often assume sighted use; features like text-to-speech for equations, braille display support, or haptic feedback are largely absent. The Missing Features theme captures the concrete shortcomings (e.g. lack of alt text on equations, absence of magnification) that developers need to address.

- **Valuable Strategies for Learning Mathematics:** Experts also recommended effective strategies tailored to blind learners. These included multi-sensory and individualized approaches. For instance, an accessibility consultant suggested:

  > *"Combining auditory descriptions with physical manipulation reinforces concepts. For example, while talking through a geometry problem, let the student feel a raised triangle."* P18

  Codes grouped here were *"multisensory teaching," "personalized learning,"* and *"interactive feedback."* The quote exemplifies the recommended strategy of simultaneous audio+tactile learning. Experts emphasized that strategies like sequentially introducing concepts (to reduce overload) and using metaphorical language (to convey visuals) greatly aid understanding. This theme highlights the pedagogical strategies that experts find most effective in accessible math instruction.

- **Guidelines for Developers:** Experts offered design guidelines for creators of math learning tools. They stressed following accessibility standards (e.g. WCAG) and involving users in design. One expert advised:

"Developers should include verbal cues for all actions and ensure math content is compatible with braille displays. They should also test with blind students from the start." P19

This reflects codes like *"user involvement," "accessibility standards,"* and *"design inclusively."* The quote outlines specific developer actions (verbal cues, braille compatibility, user testing). In general, experts recommended features such as properly marked-up equations, customizable interfaces (font/contrast), and game-like tutorials that rely on sound. The Guidelines theme thus distills experts' advice for building truly accessible math tools.

- **Creative Approaches for Designing Mathematics Solutions:** Finally, experts envisioned innovative solutions beyond current practice. For example, one expert described a novel idea:

"One creative approach is using augmented-reality audio guides say, wearable glasses that describe a geometric figure's angles via sound as the student traces it." P16

This aligns with codes like *"AR/VR tech," "game-based learning,"* and *"sonification."* The quote suggests an imaginative tech solution (audio-guided AR). Other creative ideas from experts included "audio puzzles" that teach algebraic thinking or collaborative online games where blind and sighted students solve problems together. This theme showcases the forward-looking, inventive concepts experts believe could revolutionize math learning for visually impaired students.

3.5 Discussion and Conclusion

The thematic analysis provided in this chapter emphasizes the challenging task of offering an accessible educational setting for blind and visually impaired primary school learners, especially in mathematics. Our research has identified several significant areas of attention, such as the material available for mathematics education, assistance and support for blind and visually impaired students, mathematics topics that require attention, class collaboration activities that are useful for learning, pedagogical methodologies, challenges/obstacles and issues encountered by students and teachers, available essential technologies and approaches to fulfilling learning need, ways to make learning mathematics easier, guidelines/methods for developers, more effective strategies for learning mathematics, missing features from current solutions, creative approaches for designing mathematics solutions and an overall support system encompassing both digital and non-digital resources. Through comprehensive investigation, it is evident that while there are multiple challenges (ranging from the availability of resources and technology integration to the necessity for ongoing professional development of teachers), there are also many approaches that might reduce these challenges and obstacles. Effective strategies such as using tactile resources, Braille understanding, and using assistive technology have emerged as solid enablers in learning.

Moreover, this chapter has underlined the importance of multimodal approaches in educational tools and the demand to develop UCD-based accessible solutions. The insights from expert perspectives have supported the notion that a team effort is essential to build inventive and flexible math solutions that are interactive and enjoyable for blind and visually impaired students. Due to the ongoing progress of technology, the concept of assistive technology is evolving over time. Because of this, a key component in improving mathematics education for visually impaired pupils is determining how best to adopt and integrate assistive technology in schools in order to provide access to the curriculum. Considering our analysis, we recommend the implementation of extensive training initiatives for teachers that provide them with the knowledge and abilities essential to effectively implement assistive technology-based solutions in classrooms. For the purpose of training, attention to policy reform is necessary to ensure that the current frameworks guarantee the training of teachers for inclusive learning experiences to better support blind and visually impaired students. The collaborative activities inside classrooms, together with personalized instruction and assistance of parents and classmates, comprise a comprehensive strategy that may significantly improve the educational experience of visually impaired students. Implementing these findings needs an intense effort that includes continual development and evaluation of methods of instruction, resources, and assistive technologies.

Furthermore, collecting data from children and multiple stakeholders introduced special challenges. Building rapport with young pupils required patience and often using interactive props (e.g., counting beads or drawing sketches) to keep them engaged, as is recommended in multisensory teaching. We overcame communication hurdles by using clear, simple language and confirming understanding (e.g., letting students repeat a question in their own words). Scheduling was coordinated with school staff to minimize disruption. From teachers' input, we learned that accommodating each child's needs is an iterative process; we mirrored this by being flexible in our approach. In sum, involving children necessitated child-centered interview techniques and working closely with schools, which enriched the data by capturing authentic classroom contexts.

3.6 Future Work

This research has created a platform for further investigation into the improvement of mathematics teaching for blind and visually impaired children. Additional studies should attempt to verify the impact of the suggested strategies on student learning skills. We intend to expand on these findings by introducing an inclusive educational platform with innovative digital learning features. The primary objective of this platform is obvious: to minimize challenges and promote a learning atmosphere in which blind and visually impaired students can succeed in mathematics education. This can ensure that these learners are enabled and fully integrated into the structure of educational excellence. In this educational platform, researchers and developers should use touch gestures, audio feedback, and vibro feedback to assist blind and visually impaired students. The development of interactive learning games could allow blind and visually impaired students to learn more easily, just as the use of text-to-speech functionality could allow users to hear mathematical content and resources. Developers should provide customizable content with accessible features that cater to individual needs.

3.7 Concluding Remarks

We have addressed the crucial themes related to mathematics education for visually impaired primary pupils in Chapter 3, and we understand that accessible educational approaches alone are insufficient. Incorporating technology into education can further empower these children by providing extra tools and resources that cater to their individual needs. As we studied pedagogical techniques and inclusive tactics within primary education, it became evident that mobile applications are beneficial in aiding visually impaired learners both within and outside the classroom.

To properly deploy these technical solutions, it is necessary to understand the developmental platforms chapter 4 switches from the pedagogical tactics covered before to the technology issues of producing accessible mobile applications. We have evaluated the accessibility characteristics of several developmental platforms, emphasizing cross-platform capabilities that enable developers to reach a wider audience. By studying these platforms' research problems and opportunities, we intend to provide insights into how accessible educational tools might be suitable. This research bridges the gap between the need for accessible mathematics education highlighted in Chapter 3 and the practical development of technical solutions that can address these needs, ultimately contributing to a more inclusive educational landscape for visually impaired students.

Chapter 4

Accessibility Features of Developmental Platforms

This chapter was published as: Shoaib, M., Fitzpatrick, D., & Pitt, I. (2024). Accessibility features of developmental platforms: Towards developing accessible mobile applications with cross-platform research challenges and opportunities. URI: https://hdl.handle.net/10468/15658.

4.1 Abstract

Mobile application development is a process of designing and developing smartphone-based applications for several platforms i.e., Android, iOS, etc. Mobile application development platforms can be categorized as native and cross-platform, each offering resources, frameworks, and tools to developers so they can develop smartphone-based applications using them. Native platforms concentrate on specific applications designed expressly for a particular platform i.e., Android or iOS. Cross-platform allows developers to develop applications with a single codebase that can work across multiple platforms. Examples include Xamarin and Unity. In this study, we have compared the accessibility features offered by Xamarin and Unity with those offered by native platforms. We analyzed the accessibility features offered by the iOS and Android platforms to determined whether and to what extent Xamarin and Unity offer the same accessibility capabilities. This analysis shows that numerous functionalities are shared by native iOS and Android APIs, however, some of them are not included in Xamarin and Unity. They also do not provide the implementation of fundamental APIs. This will require additional work by developers to write platform-specific code in native APIs to access the unavailable APIs. We have provided a comparative analysis of these platforms. Important accessibility aspects are highlighted that may prove useful for researchers and developers who are working to create accessible apps.

4.2 Introduction and Background Context

Android's popularity has climbed sharply since Google released version 1.0 of the operating system on September 23, 2008. With the release of Android 13 in August 2022, Google claimed to have around 3.6 billion active users worldwide (Turner, 2023). According to Statista's 2023 report, the Google Play Store, the official digital retailer for Android, holds a 71.47% global market share for mobile operating systems. iOS is the other operating system that competes with Android for users. Since its June 2007 release, iOS has increased its market share to 27.6% (Ceci, 2023). This is why developers are keen to create apps that can work on both iOS and Android (Lecomte & Martinez, 2017). Choosing the platforms on which a mobile app will operate is the first step in the development process. Next, using platform-specific toolkits like the Android SDK, developers must create tailored solutions (i.e., native apps) for each selected platform. An app that functions across two or more mobile platforms is known as a cross-platform mobile application. Xamarin and Unity are important cross-platform toolkits that make mobile applications easier and lower development and maintenance expenses (Lecomte & Martinez, 2017).

Xamarin was first introduced in 2011 as a cross-platform app development framework, Microsoft later purchased it, giving it more legitimacy than before. It provides access to native APIs as well as the potential for code reuse and sharing with other platforms. It is one of the most widely used and favored mobile development platforms. This cross-platform uses the C# programming language to produce mobile applications that perform remarkably well across all mobile devices (Toasa et al., 2023). Unity is a cross-platform game engine that was introduced in June 2005. It provides an interface that offers access to all development tools in a single location and is called an Integrated Development Environment (IDE). Developers can drag and drop objects into interfaces with the help of a visual editor and can change their properties. Unity uses an editor of your choice when it comes to coding. Microsoft's Visual Studio, which integrates most of the time, is the most common choice. Unity uses a language known as C#. All of the scripting languages that Unity uses are object-oriented (Uzayr, 2022). Another researcher (Vendome et al., 2019) conducted a large-scale analysis of Android apps and found widespread accessibility violations: their team reported cases where numeric strings were misinterpreted by screen readers (e.g., "555" being read out incorrectly). Similarly, Chen et al. (2021) automated testing on 2,270 apps and identified 86,767 unique accessibility issues. These studies underscore that even mainstream apps often neglect accessibility rules.

Mobile applications are increasingly becoming an integral part of our daily life and the accessibility factor of native and cross-platform apps is essential for disabled people. It means making these apps useful for as many individuals as possible. Applying fairness to all people by granting them the same opportunities regardless of their abilities by adding additional features like scalable texts and screen reader support. Previous studies showed that developers should design the new mobile application by considering the accessibility factor (Balaji & Kuppusamy, 2016; Acosta-Vargas et al., 2021; Korn et al., 2009; Rieger et al., 2020). Based on WHO more than 1.3 billion people worldwide have a disability which means 16% of the world's population, or one in six people (WHO, 2023).

This chapter presents a detailed analysis of mobile application development platforms and discusses their strengths and weaknesses with regard to accessibility. We have demonstrated the functionality of these platforms by exploring their accessibility features, plugins, and extensions. We have listed accessibility APIs, tools, and packages and compared their features. We examined how cross-platform mobile applications wrap native APIs. We demonstrate that two of the most popular mobile cross-platform toolkits, Xamarin and Unity, cover around half and one-third of the screen reader-related iOS and Android APIs, respectively. Finally, we present our findings and talk about how we were able to use them to develop accessible mobile applications. The remaining chapter is organized as Section 4.3, which is named as the most used mobile application development tool. Section 4.4 illustrates native and cross-platform screen reader APIs. Section 4.5 provides a brief discussion and conclusion, and Section 4.6 provides the concluding remarks .

4.3 Most Used Tools for Mobile Applications Development

The quote "the right tools for the right job" has been around forever, and it holds for software development just as much as it does for any other field. These days, there are several mobile app development platforms available. Selecting the appropriate mobile development platform is essential for designing a proper solution to make it scalable, accessible and maintainable. The cost and time of creating a mobile app may be reduced using the right development platform (Charland & Leroux, 2011). This section analyzes all four developmental platforms (Android, iOS, Xamarin, and Unity) and briefly describes them.

4.3.1 Comparative Analysis of Native and Cross-platform Toolkits

Mobile application development through native platforms is very common. Every native platform has its programming language, like Java and Kotlin, the official programming language for the Android platform. On the other hand, having a good grasp of languages like Swift and Objective-C is essential for creating iOS applications. Cross-platform mobile application development can run on multiple platforms, and we can also achieve the performance of Native platforms by using them (Xanthopoulos & Xinogalos, 2013). Here, we compared Native (Android and iOS) and Cross-platform (Xamarin and Unity). Table 4.1 provides detailed information about the strengths and Weaknesses of these platforms.

Table 4.1: Provide information about the strengths and weaknesses of the development platforms.

Platforms Name	**Strengths**	**Weaknesses**
Android Studio	Provide a user-friendly development environment Have excellent support for Android devices Supports various programming languages, including Java, Kotlin, and C++ Provide support to drag-and-drop tools. Previewing the app on different device sizes Better debugging and testing support Support profiling and analyzing tools Support for automated testing frameworks	Resource-intensive Requiring high system requirements Requires prior programming knowledge The size of the app built on Android Studio can be larger compared to other platforms. Development and deployment of apps on Android Studio can be time-consuming Requiring considerable testing and optimization efforts Compatibility issues with some older devices
Xamarin	Write code in C# then compile it to the native language of any platform Provide access to native APIs and libraries for each platform Code Sharing between iOS, Android, and Windows apps Have pre-built UI Controls that can create native user interfaces quickly and easily. Integration with Visual Studio	Steep Learning Curve (requires knowledge of C# and native development environment) Limited Access to Latest Features because it relies on its own version Increased App Size because Xamarin requires additional native APIs Limited Community Support as compared with Android and IOS

Xcode	Integration with Apple Platforms Has robust support for Swift Programming Language Interface Builder allows developers to design interfaces by drag-and-drop Comprehensive Toolset which includes a source code editor, debugging tools, performance analyzers, asset management, version control integration, and testing frameworks Simulator and Emulator App Store Deployment Extensive Documentation and Community Support	Limited Platform Support not for Android or Windows Resource Intensive for large projects or using features like Interface Builder Steep Learning Curve(complex and extensive set of features for new developers) Interface Builder has Limitations in terms of flexibility and customization (manually written code) Code Completion and Indexing Issues in large projects Xcode IDE may occasionally experience stability issues or crashes.
Unity	Cross-Platform Development Visual Editor and Workflow offers drag-and-drop and+D68 visual scripting Asset Store and Community Strong 2D and 3D Capabilities Scripting and customization provide access to Unity's extensive API Provide support to performance and optimization tool Unity Collaborate allows teams to work together.	Performance Challenges because general-purpose design may result in overhead Steep Learning Curve because understanding the various components may take time Scripting Limitations because specific programming paradigms may be more challenging to implement Documentation and Support (some parts of the documentation may be outdated, incomplete, or lack detailed explanations) Asset Store Quality Control because some assets may lack documentation or have compatibility issues Large Build Sizes Software Updates(updating Unity to a new version can sometimes introduce issues)

In Table 4.2, we have mentioned the names of the platforms, types (open-source, not open source or offers free and paid licensing), names of the plugins and extensions, best-suited information (i.e., Native: Android and iOS, Cross-platform: iOS, Android, and Windows) and finally listed the accessibility features.

Table 4.2: Provides information about the type, plugins, extensions, best suitable for and accessibility features of the development platforms.

Platforms Name	**Type**	**Plugins and extensions**	**Best suited for**	**Accessibility features**
Android Studio	Open-source	Firebase Android ButterKnife Zelezny Android Material Design Icon Generator Genymotion Android WiFi ADB CodeGlance Android Lint	Native Android apps	Screen reader compatibility Text-to-speech and speech-to-text conversion Closed captioning High contrast mode Adjustable font size Customizable color schemes Voice recognition
Xamarin	Open-source	Xamarin.Forms Xamarin.Essentials Prism Syncfusion HockeyApp	Cross-platform development iOS, Android, and Windows. Native mobile apps with a shared codebase.	Support for Accessibility APIs Customizable User Interfaces Focus Navigation Accessibility Testing Accessibility Guidelines
Xcode	Not open source	Alcatraz Injection for Xcode SwiftLint ClangFormat XcodeGen KSImageNamed Dash for Xcode GitHub for Xcode Reveal	Apple's platforms, including iOS, macOS, watchOS, and tvOS	VoiceOver Support Keyboard Navigation Voice Control Dynamic Type Support Color Vision Accessibility Accessibility Inspector Documentation Accessibility
Unity	Not open source offers both free and paid licensing.	Rider MonoDevelop-Unity ProBuilder Playmaker Odin Inspector VFX Graph	Cross-platform game development and interactive applications	Text-to-Speech (TTS) Support Screen Reader Compatibility Subtitle Support High Contrast Mode Keyboard and Gamepad Remapping

	UI Scaling and Resolution Independence

Table 4.3 summarizes information about the accessibility API, tools packages and their features (i.e., 1=Event Monitoring, 2=UI Navigation, 3=Content Descriptions, 4= Gesture Detection, 5= Text-to-Speech/Voice Over Support, 6= Event Filtering, 7= Accessibility Settings, 8= Hints and Lables, 9= Screen Reader and 10= Subtitles and Closed Captions).

Table 4.3: Provides information about the accessibility API, tools packages and their features.

Name	**Accessibility APIs, tools and Packages**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Xamarin	AccessibilityDelegate AccessibilityService TalkBack Support Xamarin.Forms Accessibility API Xamarin.Android Accessibility Xamarin.Essentials Xamarin.iOS Accessibility APIs Custom Accessibility Implementations	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Android Studio	AccessibilityService AccessibilityNodeInfo AccessibilityEvent AccessibilityManager ExploreByTouchHelper AccessibilityDelegate AccessibilityAction AccessibilityNodeProvider	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Xcode	UIAccessibility UIAccessibilityElement UIAccessibilityContainer UIAccessibilityCustomAction UIAccessibilityFocus UIAccessibilityIdentification UIAccessibilityTraits	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

	UIAccessibilityZoom										
	NSAccessibility										
Unity	Unity's Accessibility	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Input System										
	Text-to-Speech										
	UIElements										
	EventSystem										
	Unity's UGUI										
	Accessibility Inspector										
	Unity Accessibility Package										

4.4 NATIVE and Cross-platform screen reader APIs

The functionality and capabilities of the screen reader software on a particular platform are directly accessible through native screen reader APIs. These APIs allow programmers to interact with the screen reader, get data from the screen, and create accessible information for their apps. We thoroughly reviewed the screen reader APIs, taking into account our past knowledge as well as the iOS and Android programming development manuals and documentation. Based on the functionality exposed, we developed an API taxonomy. We have listed some API functionalities and their compatibility with the four platforms under consideration (native iOS, native Android, Unity, and Xamarin). APIs that support fundamental screen reader features are also shown in Table 4. We used the accessibility guidelines and best practices listed in Apple and Google's introductory accessibility documentation (Apple, 2023; Google, 2023; Cantù et al., 2018; Gonzalez & Reid, 2005) to identify fundamental features.

4.4.1 Android Studio Accessibility APIs

AccessibilityService and AccessibilityNodeInfo are important accessibility APIs of Android Studio. AccessibilityService API allows programmers to develop services that interact directly with the screen reader to process the accessibility events. On the other hand, AccessibilityNodeInfo will enable developers to adjust accessibility information for their Android applications by providing information about the characteristics and state of UI elements.

4.4.2 iOS Accessibility APIs

UIAccessibility, UIAccessibilityElement and NSAccessibility are important accessibility APIs of XCode. UIAccessibility offers a collection of classes and protocols for improving iOS application accessibility, including VoiceOver support. These APIs allow developers to give UI elements accessibility labels, traits, hints, and other data. UIAccessibilityElement enables the creation of custom accessibility components and sharing this information through VoiceOver in iOS applications. NSAccessibility provides a complete set of classes and protocols for adding accessibility features to macOS apps. These APIs allow developers to handle accessibility events, handle the change in accessibility events and provide accessibility information on these events.

4.4.3 Xamarin Accessibility APIs

AccessibilityService, UIAccessibility and Xamarin.Forms are essential accessibility APIs of Xamarin. AccessibilityService enables programmers to build services that can handle accessibility events. With the help of this API, you may communicate with the screen reader for Android and can customize the UI elements. UIAccessibility offers a collection of classes and protocols for improving the accessibility of iOS applications. Developers can make UI elements more accessible with the VoiceOver screen reader by using these APIs to offer accessibility labels, traits, hints, and other information. Xamarin.Forms ensure accessibility support using the native accessibility APIs on each platform. Developers can use Xamarin to provide accessibility information, manage accessibility events, and create Xamarin forms with accessibility features and characteristics programs that use screen reader-friendly forms.

4.4.4 Unity Accessibility APIs

Unity offers no particular screen reader API. On the other hand, Unity provides some features that allow developers to integrate accessibility features into their Unity apps. The accessibility features can be implemented by making them compatible with screen readers on several platforms. Here are some strategies for integrating accessibility for screen readers in Unity: Text-to-Speech (TTS) Integration, Custom Accessibility Implementation and User Interface (UI) Navigation and Interaction. Table 4.4 indicates which APIs implement basic screen reader functionalities.

We considered the APIs mentioned above and organized them into the following five categories:

Accessibility focus: The ability for the user to select a view, hear a description of it, and then optionally activate it, is a fundamental way of mobile screen reader interaction. Once a view is selected, we can say this is currently in accessibility focus; only one view may be given the focus at once.

Text-to-speech: The screen reader speaks aloud the accompanying text description when a view is under the accessibility focus. The developers can define this description, which we refer to as text-to-speech.

Explicit TTS: Text-to-speech (TTS) software reads the text and speaks aloud. The programmers can also utilize TTS to read aloud content automatically.

Accessibility Hierarchy: The logical hierarchy structure defines the screen elements to enhance the accessibility of the screen contents. The developer has access to change this structure.

Other: Any other accessible features

Table 4.4: indicates which APIs implement basic screen reader functionalities.

ID	Category	API Functionality	XCode	Android	Xamarin	Unity
1	Accessibility Focus	Indicate which view received the accessibility focus	Y	Y	Y	Y
2		State the accessibility focus order.	Y	Y	Y	Y
3		Indicate action connected to accessibility focus-related events (Like toggle view focus)	Y	Y	N	N
4		Determine which view has the accessibility focus	Y	Y	N	Y
5	Text-to-speech	Indicate the position where TTS perform	Y	Y	L	L
6		Mention TTS with the help of a program	N	Y	N	Y
7		One view defines another view.	N	Y	N	N

8		Notice the change even without user interaction	N	Y	N	Y
9	Explicit TTS	Inform when the screen reader finishes reading	Y	N	N	Y
10		Can change TTS features i.e., speech or pitch	Y	Y	N	N
11		Read a text with a non-screen reader TTS	Y	Y	Y	Y
12		Identify when reading performed by a non-screen reader	Y	Y	N	N
13		non-screen reader can change TTS features i.e., speech or pitch	Y	Y	Y	Y
14	Accessibility Hierarchy	Combine various views into a single element that is easily accessible.	N	Y	Y	Y
15		Divide a view into various accessibility components.	Y	Y	N	Y
16		Can access the parent element from the child	Y	Y	N	Y
17	Other	Detection of an active screen reader	Y	Y	N	N
18		Provide implementation on how to respond to a screen reader action	Y	N	Y	Y
19		Take action on the user's behalf.	N	Y	N	N
20		Get arbitrary elements when accessibility-related data you want to view.	N	Y	N	N

4.5 Discussion and Conclusion

The decision to develop Android, iOS, Xamarin, or Unity apps depends on several factors, including the project's requirements, the intended audience, and the developer's experience. Regarding accessibility features and screen reader APIs, every platform has its own advantages and disadvantages. Android can be fragmented but offers diversity and open-source freedom. While limiting customization, iOS promotes consistency and accessibility. Xamarin and Unity offer cross-platform development solutions, with Xamarin giving C# compatibility and Unity being open-source. Both support accessibility and have access to native functionality.

These platforms offer unique approaches to app development, which we have characterized by their strengths, weaknesses, and accessibility features. Android, an open-source platform, boasts many hardware options and incorporates inclusive features such as TalkBack and magnification gestures. Nevertheless, it contends with device fragmentation and potential delays in updates, which may affect the uniformity of the user experience. On the other hand, iOS is renowned for its accessibility-centric approach, delivering a tightly integrated ecosystem complete with VoiceOver and consistent updates, ensuring high accessibility support. However, its closed nature may limit customization options, with the result that apps developed using these tools may present a steep learning curve for users.

Xamarin and Unity, serving as cross-platform development frameworks, provide advantages like code reusability and access to native features, enhancing efficiency. Xamarin, with its compatibility with C# and platform-specific accessibility APIs, empowers developers to create accessible apps. Developers require additional efforts to get familiar with the different platform-specific features to implement the Native APIs. On the other hand, Unity, being open-source, can harness native accessibility features but may encounter delays in adopting new platform features and require developers to acquaint themselves with its framework. Irrespective of the chosen platform or framework, placing accessibility at the forefront of app development is imperative to ensure that all users, including those with disabilities, can fully utilize and benefit from the created applications. Developers should conscientiously evaluate these factors in light of their project prerequisites and available resources when selecting.

Furthermore, native APIs provide a robust and deeply integrated accessibility solution for Android and iOS. Cross-platform solutions like Xamarin and Unity offer the benefit of code reusability and the potential to tap into native features. However, developers must be mindful of potential delays in adopting new platform features and the learning curve associated with cross-platform frameworks. In both platforms, the paramount consideration is accessibility in app development. This ensures that all users, including those with disabilities, can access and utilize apps effectively. Developers should select the best approach with their project requirements, user needs and available resources while keeping accessibility at the forefront during the development of the apps. We also found that the common issues we observed (missing alternate text, low contrast, inaccessible custom controls) are consistent with Vendome's and Chen's findings of pervasive Android accessibility gaps.

This highlights that even specialized apps still suffer from general usability flaws. Our contributions to the debate are that we confirm these problems in the domain of math education apps, and we extend existing work by suggesting domain-specific solutions (e.g. special input methods for mathematical notation). The implications of our analysis are practical and might generalise to other application domains: app developers can use our detailed results to prioritize fixes (for instance, ensuring all buttons have descriptive labels), and researchers can apply our methodology to other subject areas. In short, our analysis strengthens the call to action for accessible design in mobile apps, particularly for users with visual impairments.

4.6 Concluding Remarks

In this chapter, we have looked into the accessibility aspects of several developmental platforms, analyzing how cross-platform capabilities might facilitate the development of accessible mobile applications. We addressed the research challenges and opportunities inherent in exploiting these platforms to produce inclusive and user-friendly solutions for visually impaired individuals. By studying the strengths and limits of platforms like Xamarin, Unity, and native iOS and Android, we understood the technological concerns necessary for designing applications that fulfill accessibility requirements.

Chapter 5 moves from theoretical investigation to practical application based on this technological groundwork. We focus on developing a mobile app to improve visually impaired students' basic mathematics skills. This chapter discusses the application's design, implementation, and evaluation, illustrating how the ideas gathered from our investigation of developmental platforms may be applied to create a practical educational tool. By using auditory and vibrotactile feedback, user-centered design principles, and the accessibility aspects described previously, we seek to demonstrate how technology may directly impact and improve the learning experiences of visually impaired students. This journey from knowing platform capabilities to designing a practical educational application highlights the real-world possibilities of combining technical innovation with accessibility considerations to satisfy the academic needs mentioned in prior chapters.

Chapter 5

Enhancement of Basic Mathematical Skills

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The insights from teacher and student interviews (Chapter 3) identified specific needs (e.g, number writing, or audio descriptions of questions). The exploration of developmental platforms (Chapter 4) showed which existing features helped or hindered access. For example, apps without proper labels for buttons or shapes were unusable by blind. Similarly, low-contrast visuals or small text made content difficult for low-vision users. These findings directly shaped AccessMath's prototype design goals. For example, because teachers reported very limited tactile geometry tools, we ensured the app provides a drawing-based way to input numbers. Since low-vision students mentioned brightness and contrast needs, our UI includes high-contrast, adjustable visuals. Thus, the lessons from our research motivated each design choice.

5.1 Abstract

Although smartphones are equipped with accessibility functions, they still pose significant problems for visually impaired people. Sometimes these functions cannot fulfill the expectations of users. Early mobile devices had physical buttons and a keypad, and visually-impaired users could navigate around the keypad using the tactile markers on the buttons. However, the lack of tactile markers makes it much more difficult to operate a touch-screen device. This paper describes an e-learning platform that is designed to improve the accessibility of smartphone applications for students who are visually impaired but have some useful vision. A User-Centered Design approach was used to develop an effective solution for visually-impaired students. A study was conducted during the development of the described platform, and the results showed that our suggested design improves task completion time as compared to the initial version. Participants also expressed higher levels of satisfaction when using the improved design of this platform. The modified design was also assessed using the Mobile

Application Rating Scale (MARS), and the results indicate that it is quite reliable and rated well among visually impaired children. Furthermore, developers can use our suggested design guidelines such as clear navigation, color contrast, immediate feedback, icon arrangements, button and text size in the development of new applications.

5.2 About the development of the prototype of AccessMath App

AccessMath is a smartphone-based prototype designed specifically for blind and low-vision primary pupils to practice basic mathematics. Its utility is to let students solve arithmetic problems and practice number writing in a multimodal way. The app offers tasks like digit tracing, where a student draws a number on the screen, and the app confirms it audibly and haptically. It provides spoken instructions and feedback, large adjustable-font displays, and a settings panel to personalize contrast and sound levels. Over three iterations, the app evolved: the first prototype (Iteration 1) focused on core functionality using the Android platform's native accessibility features (e.g., support for TalkBack) and a simple UI layout. In later iterations, we added a more refined digit-recognition algorithm, improved the audio cues, and integrated gamification elements (stars and scores) to motivate practice. We explicitly chose Android's standard guidelines for the first iteration to ensure baseline usability; for example, we adhered to Android's recommended touch target sizes and navigation order. This approach gave us a solid foundation before customizing features.

5.3 Introduction

According to the World Health Organization (WHO), there are 285 million people in the world who have some form of visual impairment, ranging from low vision to complete blindness (GHO, 2016). Between 2009 and 2014, mobile usage among visually impaired people increased from 12% to 82% (WebAIM, 2014). Touchscreens provide the primary means of interaction with most mobile electronic products, including smartphones, tablets, smartwatches, etc. Hsinfu Huang (2018) explored the accessible features of touchscreen interfaces on 32 visually impaired participants. Summarize the design guidelines for accessible touchscreen interfaces for visually impaired people and suggest that the operational style of these interfaces should be redesigned. Touchscreens allow direct operation and are an intuitive and effective input device (Dix et al., 2004; Kortum, 2008; Rust et al., 2014), thus providing a usable and convenient interface for most users. Modern smartphones provide various accessibility functions but still pose significant problems for visually impaired people. Rodriguez-Sanchez et al. (2014) noted that, despite considerable research on accessible technology and assessment, visually impaired people find using smartphones challenging because the features currently available are not enough to meet users' expectations and requirements. Since visually impaired people are increasingly using smartphones and similar devices (Senjam et al., 2021; Jayant et al., 2011; Kane et al., 2009), usable and responsive interfaces must be developed to fulfill their needs. Peischl et al. (2014) integrate user-centered design in the early stage of mobile application development. Many studies have been conducted regarding accessibility. Oliveira et al. (2011) evaluated different types of keyboards for blind users to observe and evaluate their difficulties: NavTouch, MultiTap, QWERTY and Braille-Type. Kane et al. (2008) investigated the NavTouch and NavTap for touchscreens that were significantly faster than the button-based system. Yfantidis and Evreinov (2006) developed interactive buttons for touch screens, allowing users to input data by using a single finger swipe in eight basic directions from any position. Several smartphone-based applications are also very useful for visually impaired students. Kuribayashi et al. (2021) developed a smartphone-based system for blind people that enables them to identify and avoid obstacles and thus supports navigation. This system used an RGB camera and a built-in infrared depth sensor to identify the surrounding pedestrians along with their position. This system also provides audio and vibration feedback to notify the user. EyeMath (Dumkasem et al., 2019) is a cloud-based smartphone application that captures images and describes their content. It processes the images by dividing them into smaller segments, then separates mathematical symbols from plain text and presents them as an Abstract Syntax Tree (AST).

There are also several web-based and other solutions that are very helpful for visually impaired students. MyA+ Math (Jariwala et al., 2020) is a web-based prototype that facilitates visually impaired students in learning mathematics. They provided an interactive learning environment by adding speech control and implementing an algorithm to solve mathematical problems. Spinczyk et al. (2019) suggested a method that evaluates computer-aided mathematics teaching and learning for people with visual impairments. This evaluation consists of behavioural, emotional, cognitive, social, distractors, motivational, and modeling factors. They compared the proposed technique with traditional, classroom-based teaching of the same material to visually-impaired people, and observed an improvement. Maćkowski et. al developed a multi-medium method (Maćkowski et al., 2019) that significantly enhances mathematical education in blind people. They assessed the cognitive aspects based on knowledge implementation, self-correction ability and understanding of the correct way to solve the problem. Additionally, they performed a comparison of classic and proposed alternative multimedia methods. Their proposed method significantly enhances the results in the context of knowledge operationalization.

The current chapter set out to explore various issues concerning the design of touchscreen-based mobile devices which might affect people with a visual impairment, such as the arrangement of icons, color combination, auditory feedback and feedback using vibration. Based on this work, a mobile e-learning application was developed that helps visually impaired children to learn mathematical skills easily. The application consists of two modules: "Learn to Draw Digits" and "Perform Basic Mathematics Operation", and provides feedback on both modules.

The remainder of this paper is organized as follows. Section 5.3 reviews related work; Section 5.4 provides the overview of the experimental procedure; Section 5.5 describes the participants and methodology, including the procedure, development of design guidelines and second user study employing the revised application; Section 5.6 presents the results of the user study; Section 5.7 discusses the findings of the study and draws conclusions; Section 5.8 suggests possible future work and Section 5.9 provides the concluding remarks.

5.4 Related Work

Previous studies have shown that a limited number of tools in the field of mathematics are accessible to visually impaired people. For example, studies have shown that haptic technology plays a vital role in improving the learning ability of visually-impaired students in mathematics and science (Wies et al., 2000; Wijntjes et al., 2008). The Lambda System (Nicotra et al., 2010; Bernareggi, 2010) provides a specialized form of mathematical representation using a Braille display, but it uses an 8-dot Braille notation and the necessary hardware is very costly. MathMelodies (Gerino et al., 2014) is an iPad application designed to help primary school children learn mathematics. It uses sophisticated graphics and interaction techniques that are accessible for visually-impaired children. An intelligent tutoring platform called "The Project for Math" (Brzoza & Maćkowski, 2014) offers an interactive system for supporting mathematical education. It is based on a collection of exercises for students who want to study particular mathematics skills independently (i.e., mathematical formulas, structural information of mathematical expressions and equations) and can be used to enhance their knowledge. Microsoft has developed a plug-in for Internet Explorer called MathPlayer which presents MathML (Ausbrooks et al., 2003) visually. It includes several features to make various mathematical expressions easily accessible to visually-impaired people i.e., Fractions, Radicals, Subscript-superscript Pairs, Tables and Matrices. MathPlayer can be used with screen readers such as Window-Eyes and JAWS. It also integrates with various TextHELP! products aimed at students with learning disabilities (Soiffer, 2005). Another approach involves decomposing mathematical exercises into a sequence of non-decomposable sub-exercises (Michał et al., 2017). This makes it possible to resolve mathematics exercises and assess the correctness of solutions interactively at each step. There is also an Android application designed to teach geometry, traditionally a very difficult subject to teach to visually impaired children, which uses vibrotactile feedback (Buzzi et al., 2015).

Researchers have also been working on making e-learning websites accessible for visually impaired users. For example, AudioMath works with material that is already in MathML and renders MathML-coded mathematical expressions into text-to-speech (TTS). This research has the potential to improve the accessibility of e-learning websites and brought huge benefits for visually impaired people (Ferreira & Freitas, 2004). Other researchers (Bernareggi & Archambault, 2007) have developed techniques to make web pages containing scientific documentation more accessible using a mixture of Braille-based devices and speech synthesis. In (Hanakovič & Nagy, 2006), the authors proposed a web-based application that uses speech dialogue to write mathematical expressions. Visually-impaired persons can easily access mathematical materials by using voice controls.

The accessMath prototype uniquely integrates the features that were identified as useful in previous chapters. It extends existing assistive tools (which often lack a cohesive UI) by combining them into one app. For example, while some apps may offer a talking calculator and others offer tactile games, AccessMath prototype "contributes" by delivering structured math practice (e.g. write numbers, perform simple sums) within a single accessible interface. This demonstrator app shows how theory (multisensory learning, usability guidelines) can be embodied in practice, filling a gap in educational technology for the blind.

5.5 The Interface Design and Features

Digit drawing was chosen as a key task because:

Curriculum alignment and inclusion: Young sighted children learn to write numbers and letters at this stage. Enabling VI children to practice the same task promotes inclusion in mainstream math education.

Shape literacy for VI learners: Knowing the shapes of numbers and letters is useful for blind individuals. In past decades, many blind students focused on Braille and did not learn printed shapes. With declining Braille literacy, a blind person may encounter numeric or lettered signs (e.g. a house number or room label) and need to recognize the shape. Our app helps build that non-Braille shape recognition skill.

Foundation for other skills: The ability to create and recognize simple shapes underpins later math and STEM tasks (such as interpreting graphs, charts, and geometry). By practicing drawing shapes now, VI students gain spatial understanding that will benefit them in future subjects.

In this Sections, we now detail each interface element and its design rationale:

Main Menu: Features two large buttons ("Addition", "Subtraction") with high-contrast coloring. The large size and color choice address low-vision users' needs for easy target acquisition. The menu is navigable by swipe gestures, enabling blind users to move between options without requiring fine motor precision. Audio prompts announce each option, following the WCAG principles of perceivable and operable content.

Digit Drawing Task: This is the core feature. A math problem is posed (e.g. "Write the number six"), and the user draws the digit on the touchscreen. This design was chosen because it gives blind students a tactile analog to writing digits, mirroring a Braille or handwriting approach to number learning. In fact, instructional resources recommend that VI learners "write calculations on a Braille typewriter" as a skill; our task mimics that by having children "write" digitally. For the app, each stroke is captured and converted to a number, with immediate feedback.

Feedback Modes: After input, the app provides multimodal feedback: a spoken confirmation ("Six detected, correct!"), a vibration pulse, and a visual highlight. Research shows that "multimodal feedback techniques…improve user interaction and lessen dependency on visual cues". We implemented these because blind children benefit from audio and haptic cues, while low-vision children benefit from visual reinforcement. For example, correct answers cause the device to buzz softly and announce success, fulfilling guidelines for operable and understandable content.

Accessibility Settings: A dedicated settings panel allows adjustment of screen brightness, contrast, font size, and speech rate. We included these controls because our scoping review and design guidelines emphasize their importance: for instance, boosting contrast can "significantly boost content visibility for individuals with low vision". Providing user control over the interface (e.g. selecting preferred voice or tactile intensity) is known to increase user satisfaction and engagement, which is crucial for sustained use.

Throughout, each design decision is mapped back to prior findings. For example, the inclusion of digit drawings addresses the visual content Barrier theme from interviews and aligns with textbook recommendations for tactile shape recognition. The choice of smartphone (versus desktop) is also rationalized: our literature review found that mobile devices are easily accessible and familiar to children, therefore children use them a lot and are therefore very comfortable with them. So a smartphone app maximizes reach and convenience, and supports built-in accessibility features, so focusing on a phone app leverages common hardware that children already have.

5.6 Overview of Experimental Procedure

The work is divided into two parts. In the first part, we set out to identify the most appropriate design guidelines for an application for visually impaired people, concerning matters such as the arrangement of icons, color combinations, auditory feedback and feedback using vibration. In the second part, we employed these guidelines in the development of a mobile e-learning application designed to help visually impaired children acquire mathematical skills easily. Figure 5.1 provides a complete overview of our proposed system.

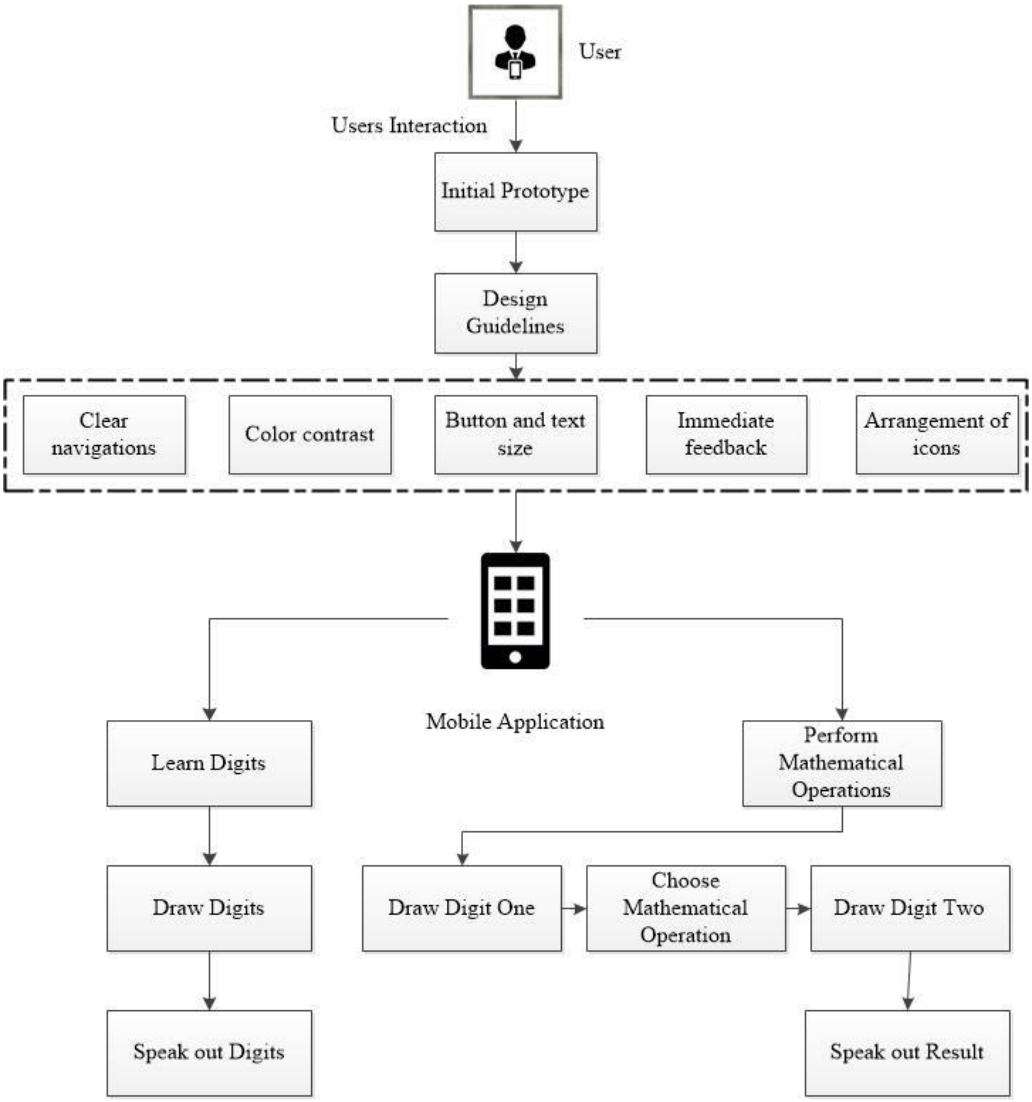

Figure 5.1: Complete overview of the E-learning Platform

5.6.1 Initial Application Design

The application used in the initial user study was developed using standard Android development guidelines, along with some general guidelines dealing with issues such as the contrast between the foreground and background colours. Beyond this, however, no attempt was made to make the application accessible to partially sighted users. The application consists of two main modules "Learn to Draw Digits" and "Perform Basic Mathematical Operations". The first module is designed to help visually-impaired students learn the shapes of the digits and how to draw them. The user is presented with a partially-drawn digit in black and white (black background and white text). Provided the student has sufficient vision to differentiate light and dark, s/he will be able to perceive the shape and draw the digit by moving his/her finger around the touchscreen. If the user deviates from the line which forms the digit, vibration feedback is provided, alerting the user to the error. The second module allows students who have learned how to draw digits to perform basic mathematical operations, such as addition, subtraction, multiplication, and division. The initial design of the app is shown in figure 5.2.

Figure 5.2: Initial design

5.7 Participants and Methodology

The experiment was conducted in a school for blind and visually impaired children. A total of 10 visually-impaired pupils, from 6th grade to 9th grade, took part in the study. Whilst the number of participants is quite small, this is usually unavoidable in research focusing on visually impaired users (Lazar et al., 2010). The age range of participants was between 11 and 16. Three participants were not familiar with the use of smartphones while the remainder were familiar with smartphone devices. We have considered WHO distance vision impairment categories: Mild (visual acuity worse than 6/12 to 6/18), Moderate (visual acuity worse than 6/18 to 6/60) and Severe (visual acuity worse than 6/60 to 3/60) (WHO, 2022). One participant (P1) perceives bright light in the severe category. Five (P2-P6) having a mild impairment and four (P7-P10) having a moderate impairment. The study protocol was assessed and ethically approved by the institute in which the experiments were conducted. Before the study was conducted, each participant completed an informed consent form. Table 5.1 provides detailed information regarding the participants.

Table 5.1: Provide demographic information of participants

Participants	Age	Class	Gender	Type of vision impairment	Familiarity with Mobile	Favourite Color Combinations
P1	11	6th	F	Perceives bright light	Not Familiar	Black and White
P2	12	6th	M	Mild	Familiar	Black and White
P3	11	7th	M	Mild	Familiar	Black and White
P4	13	7th	M	Mild	Familiar	Black and White
P5	12	7th	M	Mild	Not Familiar	Black and Blue
P6	14	7th	M	Mild	Not Familiar	Black and White
P7	14	8th	M	Moderate	Familiar	Black and White
P8	15	8th	F	Moderate	Familiar	Black and Blue
P9	14	8th	F	Moderate	Familiar	Black and White
P10	16	9th	M	Moderate	Familiar	Black and White

5.7.1 Procedure

Before agreeing to take part, potential participants were given a detailed overview of the study and an explanation of its objectives. They were informed of how it may help them to learn the basics of mathematics. After agreeing to take part, participants were given a brief introduction of the tasks and requested to attend all the training sessions. Two separate sessions were conducted to help participants become familiar with the application and understand how to use it, i.e., to learn to draw digits and perform basic mathematical operations. The training sessions lasted 25 minutes each. During the training session, participants were also given information about interaction with smartphone applications. At first, they were not very comfortable interacting with the application, especially those who had less familiarity with smartphones. However, all participants started feeling comfortable after understanding the interaction mechanism.

The study was conducted in the classroom of the school. A task was designed and deployed on Samsung S4 smartphones. The task required each participant to perform a basic mathematical operation, i.e., “Draw the first digit”, “Select mathematical operation”, “Draw the second digit”, “Double-tap on the ‘=’ button”, and “speak out a result”. Auditory feedback was provided for each activity performed by the participant. Speech feedback alerted users if they made errors or ran out of time, e.g. if the time exceeded two minutes, the system would respond with the message “Time is Over”. Table 5.2 below contains all the basic instructions for completing the task.

Table 5.2: instructions pool

Instruction No.	Description
1	Welcome to the accessible math application
2	Draw the first digit.
3	Select mathematical operation.
4	Draw the second digit.
5	Double-tap “=” button
6	Speak out about the result.

5.7.2 First User Study, employing the Initial design.

The first user study was divided into two parts. In the first part of the experiment, participants made use of the app to perform arithmetic operations (addition, subtraction, multiplication, and division) and some other related tasks i.e. drawing of digits on-screen on a smartphone using the shape drawing application. Participants were given a fixed amount of time (2 minutes) for each task, during which they were asked to complete the task repeatedly. Every participant was asked to perform the same task repeatedly until they had completed it 10 times in two minutes or less and without error. Only those attempts that were completed in two minutes or less and without error were included in the calculation of mean task completion time. Participants who were familiar with the use of mobile devices found it quite easy to perform the task, taking less time and making fewer mistakes than participants who were unfamiliar with the use of smartphones, who reported more difficulty while performing the task.

In the second part of the experiment, participants were observed whilst performing the task using different designs. They were asked to perform the tasks using different colour combinations and different font styles and sizes. The intrinsic brightness of colors was taken into account in choosing combinations of colors. Table 5.3 provides detailed information on the intrinsic brightness of the color combination. The colour combinations used in the design were as follows (background and foreground respectively):

- Yellow and Blue
- Black and White

- Red and Green
- Black and Blue

Table 5.3: Information of intrinsic brightness background and foreground colours

Percentage	Achromatic colors	Colors	Intrinsic brightness
100	White		Very high
		Yellow	High
	Medium grey	Red, Green	Medium
		Blue	Low
0	Black		None

Participants used various applications (i.e., Be My Eyes and TapTapSee) as well as the initial version of the application proposed in this paper. Most of them were comfortable with the colour combination of black (background) and white (foreground) along with a large, bold font. It was easily visible to visually-impaired participants, regardless of whether they were familiar with the use of the smartphone or not. Participants reported difficulties in observing text and buttons on the screen using other colour combinations and smaller text sizes. Participants were observed during the performance of the task, and their task completion times were recorded. Participants were also asked to fill in a questionnaire after completing the task.

5.7.3 Development of Design Guidelines

To improve the basic application, relevant research literature was reviewed and a series of guidelines were derived from the findings of key studies and applications. Table 5.4 lists the applications, their important features, the platform on which they run, the target users, research evidence and developer information.

Table 5.4: Describes the features of the application which are considered for finding design guideline

Name of Application	Features	Developers
Seeing AI[8]	▪ This application can be installed on smart glasses. ▪ A blind person wearing smart glasses with See AI installed can just take pictures at run time and the	Microsoft

[8] https://www.microsoft.com/en-us/garage/wall-of-fame/seeing-ai/

	application tells the user what's going on around him/her with good accuracy. ▪ Users in a restaurant can simply take pictures of the menu. The application guides the user to take the correct picture and tells the user what is in the menu. ▪ When the user is sitting with a group of people using smart glasses, the user can find out if they are listening to him/her or (e.g.) sleeping. The application also provides information about their faces and the approximate age of each person. ▪ Users can recognize people with the help of this application using both smartphones and smart glasses. This application narrates the world around visually impaired people	
Eye-D[9]	▪ Eye-D uses the user's mobile camera and identifies objects using speech. ▪ It tells the user the exact location. It does not show a map while telling the user about the location. ▪ Eye-D can read from printed media.	GingerMind Technologies
Be My Eyes[10]	▪ This application automatically connects the user with fully sighted volunteers through video calls, and the volunteers assist users with queries. ▪ It has a feature called "Specialized Help" which connects the user through a live video call to the company customer support representative if the user has any questions or issues. ▪ The app allows users to share personal stories from blind users, volunteers and company agents, describing how they use Be My Eyes.	Be My Eyes
Lazarillo GPS for Blind[11]	▪ It tells the user his/her exact location and offers assistance when travelling on foot or by bus or car, just like google map does. It also connects the user to Uber. ▪ Users can find public transport, banks and ATMs, hospitals, and stores for food and other shopping. ▪ Users can also explore art & entertainment venues, educational establishments (schools, colleges, and universities), public buildings, and pubs and clubs.	Lazarillo Tec SPA

[9] https://play.google.com/store/apps/details?id=in.gingermind.eyedpro&hl=en_IN
[10] https://play.google.com/store/apps/details?id=com.bemyeyes.bemyeyes&hl=en&gl=US
[11] https://play.google.com/store/apps/details?id=com.lazarillo&hl=en&gl=US

TapTapSee[12]	▪ The user opens the camera and taps on the screen, and the app identifies objects using speech. ▪ It uses Android talkback. ▪ Users can import images from the gallery. ▪ Users can also share images.	CloudSight Inc.
Blind Assistant Free[13]	▪ The app alerts the user by generating a sound whenever it detects obstacles near to the user.	Phone Science
AudioBattleShip (Sánchez, 2005)	▪ AudioBattleShip is an interactive version of the board game Battleship, providing different interfaces for sighted and blind people. ▪ It provides a gaming environment to enhance group interaction, abstract memory, spatial abstraction, and haptic perception in blind learners. ▪ The game serves as a platform for collaboration between sighted and blind people. ▪ It provides various playing modes which allow blind people to play with other blind people, with sighted people, or against the computer. The interface options were available depending upon the mode selected by the user.	Department of Computer Science, University of Chile Blanco
AudioMath (Sánchez & Flores, 2005)	▪ Provides different Interfaces for sighted and blind people ▪ The application is integrated with the TTS (text-to-speech) engine. ▪ It converts mathematical expressions from online technical, scientific or even simple documents into speech. ▪ Audiomath is intended to increase the accessibility not only of e-learning websites that use MathML but also to general websites. Therefore, it is an accessibility tool that can bring great benefits to visually impaired persons	LSS - Laboratory of Signals and Systems

[12] https://play.google.com/store/apps/details?id=com.msearcher.taptapsee.android&hl=en&gl=US
[13] www.phonescience.eu/cgi-bin/WEB/index.pl?action=Blind_Assistant_Test_Card

As well as deriving guidelines from earlier research, participants were observed while performing the tasks and the resulting observations were used in the development of guidelines. These observations can be categorized as follows:

1. Issues affecting task performance on the initial version of the app and similar applications
2. Issues regarding adequacy/appropriateness of feedback
3. Issues concerning icons, buttons and text sizes
4. Issues concerning the perception of colour combination for design purposes.

In the light of the literature review and the study findings, the following design guidelines were collected:

1. Use the best possible Colour Contrast between background and foreground (white and black).
2. Ensure sufficient button size and surrounding padding that should range from 32x32 dp to 48x48 dp
3. Provide immediate and consistent feedback.
4. Provide a clear navigation mechanism.
5. Arrange icons around the corners and in the centre of the screen.
6. Do not use colour as the only visual means of conveying information.

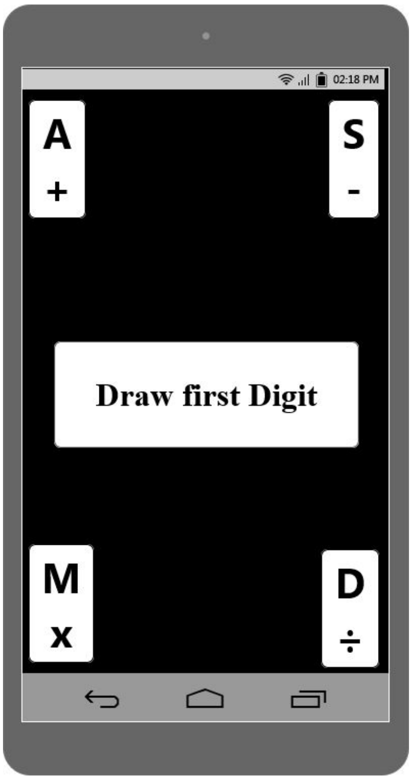

Figure 5.3: Evolutionary design

The feedback from the first study indicated that numerous participants felt comfortable with the colour combination of black (background) and white (foreground). While experimenting it was observed that bold letters/text is more visible to visually impaired participants. The experiments helped in enhancing the design of the application. The final design was drafted after conducting the experiments and using the guidelines established after completing the experiments. The revised design is shown in figure 5.3.

5.7.4 Second User Study, employing the Revised Application

The user study was repeated, but this time using the revised application. The same participants took part, and they were asked to perform the same task as in the first part of the initial study, under the same conditions.

5.8 Results

The mean task completion time was measured for both the initial version of the application and the revised version. The mean task completion times for participants P1-P10 using the initial version were 80, 76, 72, 75, 79, 83, 73, 77, 71, and 70 in seconds. When using the revised design, the task completion times were 56, 50, 49, 48, 55, 54, 48, 49, 45, and 46 in seconds. These results are shown in figure 5.4.

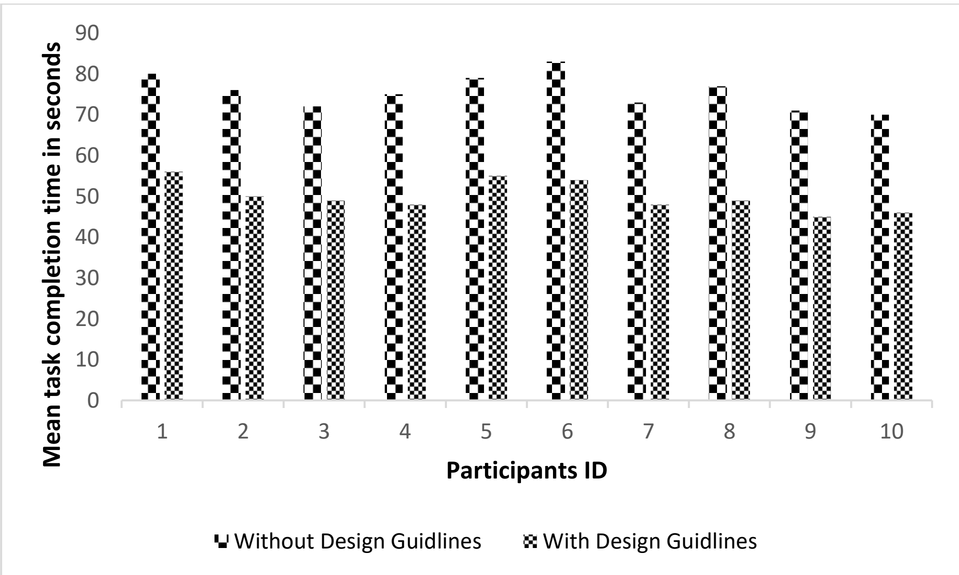

Figure 5.4: Mean task completion time

After both the first and second user studies, participants were asked to fill in a questionnaire that contained four questions designed to assess satisfaction/ dissatisfaction with the app.

Each question required a response on a 5-point Likert scale (1=Disagree strongly, 5=Agree strongly).

The questionnaire data were analyzed using a Wilcoxon signed-rank test, the results for which show that the participants reported higher levels of satisfaction when using the modified version of the app. The result of the Wilcoxon signed-rank test expressed that z value is 2.395, the p-value is 0.016, W value is 4 and the critical value for W at $N = 10$ ($p < .05$) is 8. Results show that participants feel more satisfied at $p < 0.05$.

After each user study, participants were also asked to complete a questionnaire that contained five questions designed to assess how meaningful they found the feedback provided by the app. A one-tailed paired t-test was used to compare the results when using the original version of the app with those obtained when using the modified version of the app. The results show that the modified app (developed using the design guidelines) provided more meaningful information to participants ($T_{cal} = 4.8503$, $t= 1.671$, $df = 9$, $p < 0.05$).

After completing the second user study, participants were shown five-word pairs and asked to indicate their feelings about the modified app by selecting one or the other words in each pair. The responses were: feeling Satisfied (8)–Unsatisfied (2), Like (8)–Dislike (2), Fun (7)–Hatred (3), Joyful (8)–Painful (2) and Comfortable (8)–Uncomfortable (2).

Finally, a Mobile Application Rating Scale (MARS) was used to rate the quality of the modified application. The MARS scale has 23 items, grouped under five headings: engagement, functionality, aesthetics, information and subjective quality. Each MARS item uses a 5-point scale (1-Inadequate, 2-Poor, 3-Acceptable, 4-Good, 5-Excellent). Table 5.5 shows the MARS subcategories and the mean scores obtained under each subcategory.

Table 5.5: MARS items with a mean score of the apps.

No.	**Subscale/Item**	**Mean**
Engagement		
1	Entertainment	3.1
2	Interest	2.9
3	Customization	3
4	Interactivity	3.2
5	Target group	3.8
Functionality		
6	Performance	4.4
7	Ease of use	4.4

8	Navigation	3.8
9	Gestural design	4.3
Aesthetics		
10	Layout	3.4
11	Graphics	2.7
12	Visual appeal: How good does the app look?	2.4
Information		
13	Accuracy of app description	3.6
14	Goals	4.2
15	Quality of information	4.4
16	Quantity of information	4.2
17	Visual information	2.3
18	Credibility	3.2
19	Evidence base	1.7
Subjective quality		
20	Would you recommend this app?	3.9
21	How many times do you think you would use this app?	4.1
22	Would you pay for this app?	1
23	What is your overall star rating of the app?	4.2

Table 5.6 provides independent ratings on the overall MARS total score of the application which demonstrated an excellent level of inter-rater reliability (2-way mixed ICC = 0.53, 95% CI 0.007-0.134). The MARS total score had excellent internal consistency (Cronbach alpha = 0.37) and was highly correlated with the MARS star rating item (#23), r (1) = 0.53, P<.001.

Table 5.6: Results of ICC Calculation Using Absolute-Agreement, 2-Way Mixed-Effects Model

Intraclass Correlation Coefficient						
	Intraclass Correlation	95% Confidence Interval	F Test with True Value 0			
		Upper Bound	Value	df1	df2	Sig
Single Measures	.007	.048	1.585	9	198	.122

Average Measures	.134	.536	1.585	9	198	.122

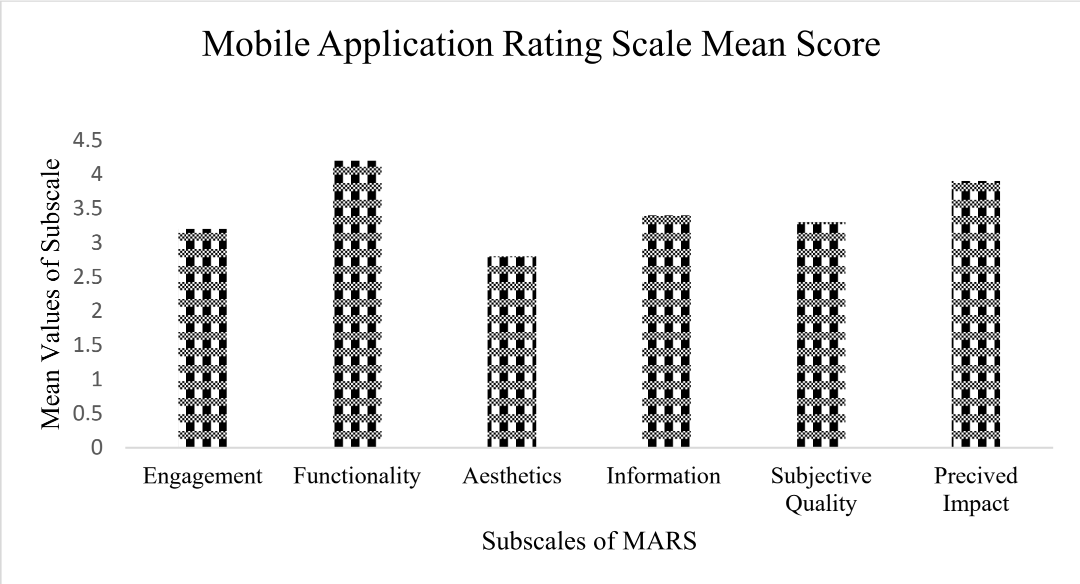

Figure 5.5: Mean values of MARS Subscales

Figure 5.5 demonstrates the mean score of each subscale of the Mobile Application Rating Scale. The mean score of the Engagement subscale is 3.2, Functionality subscale has 4.2 mean value, Aesthetics subscale has 2.8 mean value, Information subscale has 3.4 mean value, Subjective quality has 3.3 mean score and lastly Perceived Impact was determined as 3.9. Perceived Impact is another subsection of the MARS questionnaire that evaluates the impact of the app on users' awareness, knowledge, attitude, intention to change, help-seeking and behaviour change.

5.9 Discussion and Conclusion

In the absence of vision, hearing becomes the primary channel for communication among people with visual impairments. Keeping this principle in mind, the researchers set out to develop an accessible system for visually impaired people. The proposed application helps visually impaired children to learn basic math skills by using an auditory feedback mechanism. This application is specifically designed for moderately visually impaired children from grade 6 to grade 9. Traditionally, visually-impaired students have relied on Braille for learning, but this presents its own problems. Only a small percentage of visually impaired people can read braille (Lazar et al., 2010). Our proposed application enables visually-impaired students to learn and draw digits along with basic mathematics operations by using auditory feedback.

After conducting the experiments, it is concluded that using a smartphone for learning is much easier as compared to other traditional ways of learning because smartphone-based learning solutions are cheaper and more widely available. Auditory and touch feedback (using vibration) is a better medium for conveying meaningful information. During the experiment, it was found that most of the participants were comfortable with the colour combination of black (background) and white (foreground). Bold letters/text is more accessible for moderately visually impaired participants.

The mean task completion time was lower when participants used our enhanced application than it was when they used the initial version of the application. The results also show that our application provides meaningful information to the participants, which improves their awareness of the actions taken during the use of the application. The participants also expressed higher levels of satisfaction when using the enhanced version of the application. Furthermore, the MARS results indicate that the proposed application is quite reliable for visually impaired children. The proposed application has a sufficient rating among participants. It can also be used to provide a checklist for the design and development of new high-quality health apps. Finally, the MARS results show that the participants were comfortable with the feedback provided by the application.

5.10 Evaluation Reflection

We note how our chosen metrics (task completion time, 5-point Likert scale, Wilcoxon signed-rank test, A one-tailed paired t-test, and Mobile Application Rating Scale (MARS)) capture important usability aspects, but also consider complementary methods. For instance, observing student behavior during tasks or using qualitative feedback yields deeper insights into engagement and strategy use. We refer back to the multisensory learning literature to suggest that adding more interactive, game-based assessments may reveal additional strengths or weaknesses of the interface. This reflection acknowledges that while our evaluation metrics were appropriate, a full mixed-methods approach could further validate and refine the app. Such as a full mixed-methods evaluation would combine quantitative data (e.g., SUS, task times) with qualitative insights (e.g., interviews, observations). This could enable triangulation of results, also explains why certain usability patterns occur, and could help to understand more robust and generalizable design recommendations.

5.11 Future Work

The proposed application only supports basic mathematical operations. The application can be enhanced by adding voice-based input while using the calculator module for better accessibility. Currently, the proposed method is designed for 6th to 9th-grade students with visual impairments. However, the intention is to extend the application by adding further mathematical operations such as percentage, decimal point, square root, pi, power (i.e. square, cube) and to make it accessible for students in higher grades. Incorrect attempts by users were not considered in this study. In future studies, it might be of value to investigate the nature and frequency of errors.

The current application focuses on mathematical skills only and does not cover other educational areas. In the future, the application could be extended with new and advanced features related to English reading for children. These features will be based on Artificial Intelligence, Machine Learning and Natural Language Processing. This will make the application smarter by allowing it to analyze the speech of a child/user reading text from a book, and provide feedback and assistance if the user reads incorrectly. These features could be used by anyone, whether visually impaired or not.

5.12 Concluding Remarks

This chapter is about designing, developing, and evaluating a mobile e-learning application to enhance the basic mathematical skills of visually impaired children. The change from creating a specialized mobile application to developing AccessMath, an accessible interactive learning platform designed to overcome the various challenges that blind and visually impaired students face in learning mathematics. Building upon the insights and successes of the mobile application, AccessMath seeks to provide an accessible educational environment that supports a more extensive range of mathematical topics and ability levels. This platform combines advanced features like interactive problem-solving tasks, real-time feedback, and swipe controls. In developing AccessMath, we have overcome the limitations described in earlier chapters by merging cutting-edge technologies and educational methodologies. This illustrates our dedication to enhancing the accessibility and quality of math education for visually impaired students. Chapter 6 provides designing development and evaluation of AccessMath, revealing how it builds upon past work and satisfies the broader educational requirements indicated throughout this dissertation.

Chapter 6

AccessMath

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6.1 Abstract

Smartphone-based apps and games can provide an enjoyable and inspiring atmosphere for learning mathematics. They potentially offer an engaging and exciting way to help students utilize their previously acquired abilities. Implementing such platforms has become increasingly significant in the rapidly evolving educational technology landscape. However, the integration of such technologies poses unique challenges and opportunities, particularly when it comes to catering to the needs of blind and visually impaired primary school students. This article is based upon a survey designed to investigate the needs of blind and visually impaired students and identify enablers that improve the effectiveness of interactive learning platforms specifically for learning mathematics. Nineteen people participated in this study: five blind and visually impaired students, nine teachers, and five professional experts. Participants highlighted important functionalities which would help them address their needs in primary education settings. Using the findings from this study, the authors aim to develop an interactive learning game to fulfill the participants' needs. This interactive game focuses on enhancing numbering skills, performing basic mathematics operations, and learning about shapes and digits because most school children struggle to learn these topics. This game can engage blind and visually impaired students and help them quickly understand these topics. The aim has been to introduce educational aspects in a way that does not compromise game enjoyment.

6.2 Introduction

The popularity of smartphones and other mobile devices in our daily lives keeps increasing. These devices add novel features with each new version, improving ease and affordability. New applications are regularly developed to simplify numerous aspects of our lives. This technological advancement has motivated researchers and developers to take advantage of these devices within the educational sector to move from traditional classrooms to more dynamic and engaging learning environments (Shen et al., 2008). It allows teachers to educate students without being confined by location or time. It also encourages learning inside and outside the classroom, during or after classes (Huang et al., 2010). These devices also allow teachers to interact with their students more efficiently and enhance their student's concept-building (Ward et al., 2013). Chiong and Shuler analyzed the impact of smart mobile devices and their applications on preschool- and early-elementary-aged children. They found that children can use these devices easily, and the apps can boost their learning skills (Chiong & Shuler, 2010).

Based on these and similar findings, the idea of developing a learning game has emerged. Educational games entertain students and help them learn several subjects, including mathematics. Mathematics is compulsory for primary school students in Ireland and many other countries. This subject is constructive for developing problem-solving skills in students, but sometimes it's very confusing and challenging (Amirali, 2010). Blind and visually impaired students face particular challenges when accessing visual mathematics content, i.e., graphs, formulas, and mathematical notations. The UN Convention on the Rights of Persons with Disabilities states that persons with visual disabilities should not be overlooked or left behind in terms of quality of life (CRPD, 2024). Similarly, the World Health Organization requires that implementation of its Sustainable Development Goals "leaves no one behind", including those with a visual disability (LNOB, 2024).

The continual improvement in digital assistive technologies offers novel opportunities to overcome many barriers faced by people with visual disability (Phillips & Proulx, 2018). Smartphones are one of them, and they include several accessible features and applications for blind and visually impaired students. For example, MathMelodies is an iPad application developed for primary school students, including those with vision difficulties. The developers examined the problems that occur during the design of an accessible learning environment by using a user-centered design. They evaluated the usability of this application with professionals, blind students, and sighted students. They found that the inclusion of object-based interactions, audio cues, and text-to-speech enhanced user engagement (Gerino et al., 2014). AudioMath, introduced by Jaime and Hector, is another example. It supports blind children in learning mathematics using audio-based interactions. The developers focused on improving short-term memory and arithmetic knowledge using an interactive auditory interface. The application was built with input from blind students and was tested for its efficiency in increasing memorization and learning skills. The study reveals that audio can be a powerful aid for boosting memory and learning maths in visually impaired children (Sánchez & Flores, 2005).

This chapter is based upon a study conducted among domain experts, teachers, and blind and visually impaired students in order to identify design guidelines for developing an accessible solution for learning mathematics. This research aims to design and develop a mobile-device-based mathematics learning game called AccesMath. Students can use this learning application from anywhere. Using and playing this game can enhance the children's understanding of mathematics. The remainder of this article is organized as follows: Section 6.3 explains the related work; Section 6.4 illustrates the study's procedures; Section 6.5 describes the proposed learning game architecture; Section 6.6 provides the participants' comments and information; Section 6.7 has the discussion and concludes of the article and Section 6.8 provides recommendations for future work.

6.3 Related Work

Previous research has revealed several software tools available for blind and visually impaired students to access mathematical content. Mejia et al. (2021) provided an extensive survey of software tools available for visually impaired persons to access, create, and manipulate mathematical material. They analyzed the issues visually impaired persons faced when accessing mathematical resources. They categorized the tools into two groups: those for accessing mathematical content and those that enable them to execute mathematical operations. The report also examined the advantages and disadvantages of essential technologies for interacting with mathematics material. Audio Games (Balan et al., 2014) was a novel technique that analyzed the impact of audio games on visually impaired individuals' learning and cognitive skills development. They showed how audio-based teaching aids and combining user-centered design can significantly boost visual representation, memory, and problem-solving skills among blind students. The research evaluated the audio games developed for teaching, focusing on the potential for improving learning skills in blind and visually impaired learners. Shoiab et al. (2021) investigated the development of a mobile e-learning application designed to aid visually impaired children in learning basic mathematics. The aim of the research was to enhance smartphone application accessibility through a user-centered design approach. The study focused on a prototype application that was modified in the light of user feedback. The modified version yielded reduced task completion time and greater user satisfaction. The modifications were designed to simplify navigation, improve color contrast, and provide more rapid feedback, and user testing confirmed the usefulness and reliability of the application for visually impaired students.

Song et al. (2011) examined the design and execution of mobile learning games for visually challenged children. They focused on increasing spatial skills using two audio mobile games: "Cardinal Direction and a modified Tower of London". The study comprised both quantitative and qualitative evaluation, with results indicating enhanced enjoyment among participants. The results provided insights into building more efficient and interactive smartphone games for visually impaired users. Sánchez and Sáenz (2009) analyzed the usage of "The Natomy's Journey Games" an audio-based video game. It demonstrated the game's design and implementation by emphasizing an interactive environment among blind and sighted students. The study examined the game's accessibility and its influence on integrating blind students into mainstream classrooms, highlighting considerable improvements regarding learning and integration into society. Arlinwibowo et al. (2021) focused on constructing an Android application to aid visually impaired students in learning mathematics. The project involved specialists from several sectors to produce a realistic, feasible, and practical app. They highlight the need to establish accessible educational technologies that respond to the special needs of blind and visually impaired students, enhancing their capacity to learn and test skills effectively. Ramos Aguiar et al. (2023) discussed two case studies employing gamification approaches for blind and autistic individuals. The first study offers an application teaching Mexican currency to blind persons using interactive interfaces and gamification. The second study explored an app for autistic children, enabling them to better navigate and engage through a virtual reality game. Both studies indicated the beneficial use of technology and gaming in teaching for those with disabilities.

6.4 The Procedure of the Study

This research study was carried out with blind and visually impaired students, teachers, and professionals working in accessibility. A group of nineteen users took part in the research, including five blind and visually impaired students, nine teachers, and five domain specialists. The thirteen female and six male participants in this study were 9 to 58 years old. The research was organized in two phases. In the first phase, we conducted a study with students, teachers, and domain experts to explore several themes. In the second phase, we gathered their opinions and suggestions for developing a smartphone-based accessible solution. Table 6.1 offers comprehensive details about each participant.

Table 6.1: Demographic information of the Users

User ID	Age	Gender	Type
U1	12	Female	Student
U2	10	Male	Student
U3	11	Female	Student
U4	9	Male	Student
U5	12	Female	Student
U6	52	Female	Teacher
U7	42	Female	Teacher
U8	26	Female	Teacher
U9	29	Female	Teacher
U10	45	Male	Teacher
U11	37	Male	Teacher
U12	43	Female	Teacher
U13	54	Female	Teacher
U14	44	Female	Teacher
U15	43	Female	Professional
U16	58	Male	Professional
U17	40	Male	Professional
U18	57	Female	Professional
U19	41	Female	Professional

6.4.1 The interviews for this study

The study was conducted from August to November 2023, and interviews were conducted via video call (on Teams). The semi-structured interviews were conducted with students, teachers, and domain experts. Most questions were open-ended, allowing participants to explore the topic comprehensively. Towards the end, participants had the chance to express any views they felt were not addressed during the interview.

6.4.2 The analysis process and general findings

From the collected interview data, we have explored the challenges of blind and visually impaired students and the experiences of teachers and experts. Using thematic analysis, we identified several essential themes, i.e., "Mathematics Topics," "Challenges, Obstacles, and Issues", "Digital and Non-digital Resources", and "Ways to make learning mathematics easy" etc. A full description of the study and the thematic analysis will be published as a separate paper. Moreover, information was gathered from blind and visually impaired students about what kind of applications might help them to learn mathematics. The opinions of teachers and domain experts regarding the design of smartphone-based solutions for these students were also noted. This article focuses on the design guidelines for an accessible solution resulting from the study i.e., independence, font and color contrast, proper labeling, clear navigation, etc. These guidelines were used in the design of a game called "AccessMath".

6.4.3 Ethical Considerations

Permission was obtained from the University, school management, and the participants for the conduct of this study. All participants were given an information sheet and fully briefed on the study's purposes. All participants signed informed consent forms. They were told that the entire experiment would be recorded for evaluation purposes. The respondents were assured that no harm was involved either before their participation or during the study to extract information. It was emphasized that the participant's involvement in the study was voluntary. Additionally, the participants received assurances about the confidentiality of their identity, with explicit instruction that real names and addresses would not be used in the final report. To uphold ethical standards, we followed the guidelines outlined by Bogdan and Biklen (1998), encompassing informed consent and protecting participants from any potential psychological harm or danger.

6.5 Design Choice of Gamification

Gamification was included to increase motivation and engagement. Research indicates (Luo, 2023) that gamified math exercises can highly engage students and create an inclusive learning environment. Even though it's about general math education, the principle applies here: children are more motivated when learning feels like play. In AccessMath, we implemented positive audio feedback, which encourages students to persist through the math tasks.

The core tasks in Chapters 5–6 revolve around writing numbers on the device. Writing numbers explicitly was chosen because it reinforces numeral formation and spatial understanding, which are foundational math skills. The following are a few more details about the choice of digit drawing:

• It is what mainstream children are learning at this stage, so enabling blind and VI children to learn and perform the same task aids inclusion

• It is useful for blind children to know the shapes of letters, numbers, etc. Previous generations of blind children learned Braille, but often did not learn the shapes of numbers, letters, etc., and thus could not read tactile representations unless the characters were rendered in Braille (which was not always the case). For example, a blind person attempting to identify a house might not be able to recognize the house number displayed on a raised sign on the front door or gate. The need for blind children to be able to recognize non-Braille representations has increased as levels of Braille literacy have fallen in recent decades.

• Creating and recognizing simple shapes is a useful skill that can later be employed for other tasks, e.g., reading and creating graphs.

6.6 Proposed Learning Game (AccessMath)

This chapter highlights essential guidelines and opportunities for developers: independence, font and color contrast, proper labeling and clear navigation, multimodal approach, easy access, and no internet dependency. See below the details about these guidelines:

Independence: Support blind and visually impaired students to work without supervision. Provide them with straightforward game rules and motivate them with the game's entertainment factor that can keep them focused on the task.
Font and color contrast: Make it easy for them to adjust font size and color contrast based on their needs.
Proper labeling and clear navigation: Ensure proper labeling of the interface elements, i.e., buttons, etc., and clear navigation between screens to make the app more accessible.
Multimodal approach: Make appropriate use of text-to-speech, vibro-tactile, and auditory feedback.
Easy access: Students should be able to access and use the app from anywhere. It also refers to obtaining the app (e.g., free of charge, simple download and installation).

No Internet dependency: Students should be able to use the app without Internet availability.

Subsequently, we applied these recommendations and guidelines in developing a game named AccessMath to help the blind and visually impaired. This game has three main modules named "Basic Operations", "Shapes and Digits," and "Numbering". There details are mentioned below:

Basic operations: Through interactive challenges, the game presents addition, subtraction, multiplication, and division concepts to blind and visually impaired students. We have utilized audio narratives, swipe functions, audio, and vibro feedback. Students can solve the questions and learn more about basic operations using them.

Shapes and digits: Using a multimodal approach, teach geometry shapes, lines, symbols, and digits drawing to blind and visually impaired students. Users can draw the shapes by touching the screen, and audio explanations illustrate them more appropriately for them. It can be useful for designing games where players can recognize and classify shapes using their touch and auditory perception.

Numbering: Start with basic counting activities using auditory cues for numbers where blind and visually impaired users can learn counting skills. Also, a comparison of numbers using sound-based activities could help them learn.

Figure 6.1 presents a detailed overview of our proposed game. All these activities are interactive, engaging, and accessible for blind and visually impaired students. Frequent feedback, encouragement, and progressively challenging levels can enhance their learning experience.

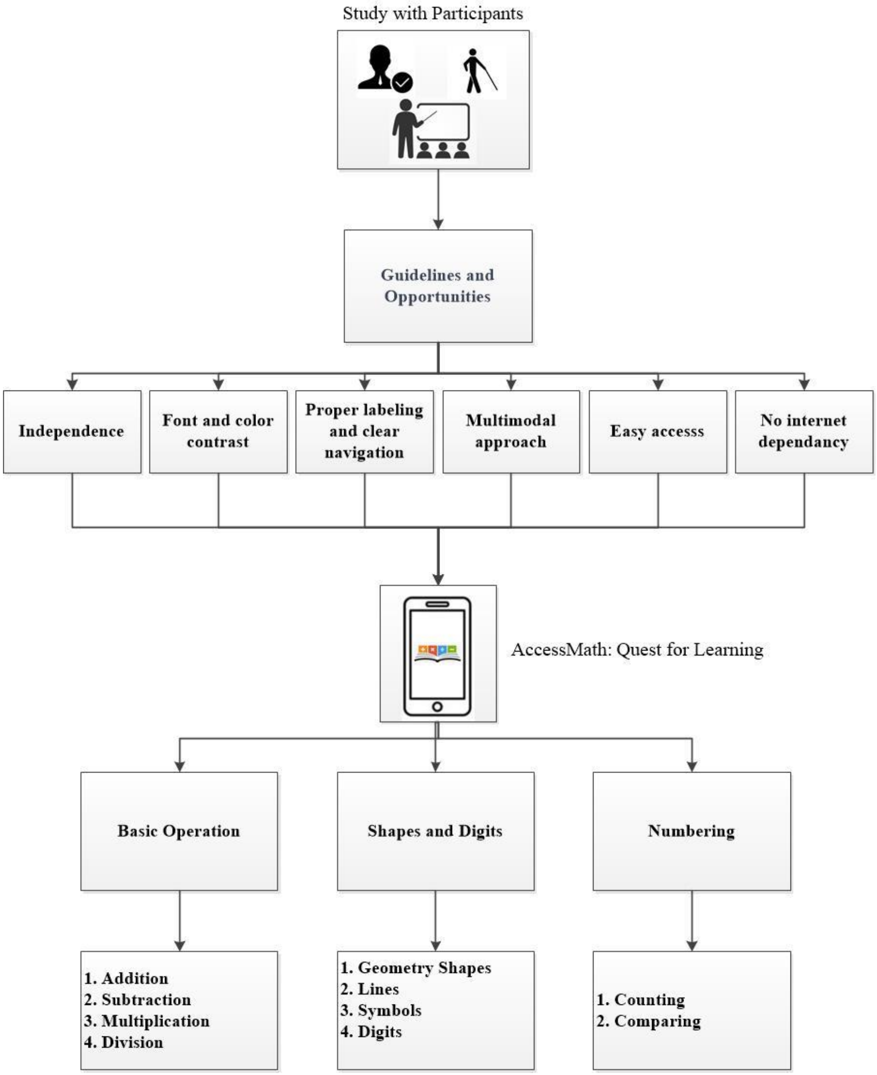

Figure 6.1: Proposed methodology for this research study

6.7 Interesting guidelines/suggestions/opportunities suggested by participants.

As described above, the study comprised two parts. The first part involved a thematic analysis of survey results concerning inclusive learning. The second part focused on the design of an inclusive learning platform, and some of the resulting guidelines and suggestions for researchers and developers are listed below:

"Blind and visually impaired students like games. But for my blind students, unless somebody sits beside them all the time and explains exactly what's happening in the game or helps them manage it. So, I think the independence of students is essential."

"Games can be quite useful because using them on the tablet or other mobile device makes students happy. They can use screens if the interface elements and fonts of the apps are big enough to see."

"Measuring skills-based solutions and devices we need. Some of these resources are available in America but not in Ireland. England is also making resources that will make measuring more accessible."

"I think a possible solution might be something like preparation for leaving CERT. Students can prepare math for Leaving Cert with the help of a learning app, which helps them learn different topics like measuring and graphs."

"Anything they will do with speech and students can use from anywhere."

"There were a lot of topics that they could learn through playing games like understanding the numbers and quantity of numbers, graphs, basic math operations etc."

"For a developer developing a tool to support them, I think the first thing is to use co-design, so they have to work with these individuals to have a live experience. For example, if you are working with students, try to recruit one or two nine-year-old students to be a part of your team; I think they'd take great pride and ownership, and they really appreciate being invited onto something like that to be a part of building the solutions to support themselves."

"The best platform all depends on the end users. You know what I mean? And it depends on what's available to them. So a lot of them will have smartphones, but maybe what you're building is not going to necessarily if it's in this classroom environment, you know, smartphones and now being banned everywhere and all this kind of stuff, especially if it's a mainstream classroom and the school of no bond smartphones, it kind of rules out the opportunity of having that tool on the smartphone, which is a bit crazy. I think the smartphone is the most accessible as it's the one the kids will engage in the most, but this is good for their home. If you're actually talking practicality, I'd probably go down the tablet route, as in that's what if you look at the broader scale of things, if you look at how like big screens, how they will work really well and integrate really well with systems, I think a lot of that is built for tablets. If it's something that's actually going to be educational, then a tablet could be a good choice."

"If the audience is primary school kids, then gamification will be really important, and games will be a motivation. Another thing, it's better that the game does not have internet dependency. And if it's an older cohort of students, like secondary school students who are just trying to pass the Leaving Cert, they will have a different motivation. And so, in their case, it will be the

laptop because when they walk into that leaving CERT exam, it's a laptop they will be in front of.".
“I have to spend extra time converting diagrams to tactile form for my blind students.”
"If you are designing a solution, you must see the curriculum. Considering the end users like the persons with the disability and their needs, his teachers, and his family members views."
"I think taking a universal approach to learning is really important, and using a multimodal approach to integrate the solution is more beneficial if possible."
"The work we're finding on sites is to do with poorly labeled or unlabeled things. Developers should avoid this; proper labeling, clear navigation, and color contrast matter a lot."
"I've heard about games and even the VR experiences where you can learn about different subjects. VR-based solutions could help people in their learning."
"During the planning stage of an app, you should engage with the audience. Also, it's important to include people with disability in the research."
"I suppose providing audio and vibro feedback to understand the number sequence, numbering lines, 1, 2, 5, getting vibrational feedback on doing something, even moving from one cell to another, anything like that will help them."
"I have never used a screen reader. I like easy things that I can easily access and use from anywhere, for example, a scanning pen; I want to scan text, giving me audio information about this. So, it is something that gives me information in voice, or I can learn it through play again. Something provides me with feedback in speech and vibration, I like it."

6.8 Discussion and Conclusion

Educational and assistive technology are evolving day by day. Because of this, providing equal opportunity for learning for blind and visually impaired primary school students is very important. We have conducted a study with blind and visually impaired students, their teachers, and domain experts to introduce an inclusive learning solution for them. The results of this study illustrated that providing them with an independent learning environment, proper opportunities for font and color contrast settings, adequate labeling of user interface elements, straightforward navigation between screens, the introduction of a multimodal approach, easy access to the learning platform, and running of the application without internet dependency can make the solution more accessible for them.
We have developed a learning game, "AccesMath", for these students by keeping these guidelines in mind. This math learning game provides inclusive education for blind and

visually impaired primary school students. This game involves basic mathematical operations, shapes and digits, and numbering skills. Our game consists of special accessibility features by keeping a range of learning requirements in mind and considering the influence of mobile devices on blind and visually impaired student's educational experience. We have attempted to understand the nature of learning for blind and visually impaired students and to develop an interactive and user-friendly platform. This platform introduced a multimodal approach for feedback and user setting based on their needs that enhance the accessibility nature of this app. In a follow-up study, we plan to investigate the usefulness and effectiveness of this mobile application for the learning enhancement of blind and visually impaired students. We will examine whether blind and visually impaired students use this to improve their learning skills.

6.8.1 Comparison with Existing Literature

We compare our app's performance and design to prior educational tools. For instance, our findings that audio and haptic feedback help VI learners are consistent with guidance in Paths to Literacy and with experts' emphasis on multisensory materials. It support a wide range of mathematical tasks, including basic arithmetic, numbering, shapes, and digits. It provide multimodal interaction (auditory, tactile, and visual), interactive feedback and swipe function to navigate the interface without visual dependency. It have the accessibility features like touch-based interactions, flexible interface where users can choose how they interact with the help of a setting panel, and interface design considers cognitive load, ensuring that the app remains easy. Adheres to universal design guidelines, it ensuring that it is accessible to all users and WCAG Guidelines in the context of smartphones stress the need for accessible navigation, readable content, and flexibility in how users interact with the system. These interfaces and interaction techniques are refined based on Users and Experts opinions. However, AccessMath goes further by integrating these cues into interactive math tasks. We also note that existing apps, tactile and Braille-based math tools were largely static, whereas our app offers a dynamic, digital approach. By discussing these similarities and differences, we contextualize how this work builds on and extends the literature on VI math education.

6.9 Future work

Future researchers can introduce machine learning-based algorithms that customize the game to each player's learning preferences and skill level. These customizations could be based on each student's strengths and weaknesses. Furthermore, the game's features could be expanded to include more complex topics appropriate for elementary school grades. This expansion might cover more advanced geometric shapes, fractions, and decimals, offering a more extensive mathematical education. Moreover, we suggest that researchers and developers should work together with experts and organizations that specialize in accessibility to carry out comprehensive studies on the efficacy of the game in various educational settings. Maximizing the game's impact and obtaining insights might involve collaborating with academic institutions, accessibility specialists, and teachers. Finally, we should explore other ways to use the game to involve parents in their children's education and provide them with possibilities to engage in educational opportunities at home with their children.

6.10 Concluding Remarks

This chapter is about designing and developing AccessMath to enhance visually impaired children's basic mathematical skills. AccessMath, is an accessible interactive learning platform designed to overcome the various challenges that blind and visually impaired students face in learning mathematics. This platform combines advanced features like interactive problem-solving tasks, real-time feedback, and swipe controls. Chapter 7 provides the details about the evaluation of an Accessible Smartphone-Based App for Blind and Visually Impaired Students for Learning Mathematics, revealing how it builds upon past work and satisfies the broader educational requirements indicated throughout this dissertation. Through this platform, we intend to enable design guidelines for smartphone-based applications. We have provided an overview of existing design guidelines and extended them for smartphone applications, especially for visually challenged users.

Chapter 7

Designing and Evaluating

This chapter was accepted as: Shoaib, M., Minghim, & Pitt, I. (2024, June). Designing and Evaluating an Accessible Smartphone-Based App for Blind and Visually Impaired Students for Learning Mathematics. Accepted in 19th annual International Technology, Education and Development Conference.

7.1 Abstract

The design and development of educational applications to enhance the learning experiences of blind and visually impaired people have improved considerably in recent years. Still, research suggests there is a need for further improvement. Despite the increasing prominence of accessibility features in mobile devices, barriers remain in providing efficient learning resources for these students, especially in STEM topics like mathematics. This paper discusses the design and usability evaluation of AccessMath, a mobile application designed to help blind and visually impaired primary school pupils learn mathematics. The application was developed using accessibility design guidelines, offering adjustable intrinsic brightness, multimodal feedback, a comprehensive settings panel, and intuitive swipe control functions. A usability test was carried out with five blind and visually impaired students employing a variety of metrics, such as task completion time, Usability Metric for User Experience (UMUX), NASA Task Load Index (NASA-TLX), and the System Usability Scale (SUS). The results revealed improved usability, lower cognitive load, and satisfactory user experiences, highlighting the usefulness of the implemented guidelines for designing and developing accessible mobile applications for blind and visually impaired users.

7.2 Introduction and Background

Mobile technology has changed the way users obtain information and learn new skills. Smartphone apps offer unique opportunities for students to have interactive and personalized learning experiences. However, for blind and visually impaired students, the accessibility of these apps remains a considerable barrier. Traditional mobile apps rely primarily on visual interfaces, which makes them difficult for those with visual impairments to use. This gap in accessibility impedes the educational development of these students, who need more inclusive design approaches.

Accessibility standards like the Web Content Accessibility Guidelines (WCAG) provide a framework for generating accessible digital information (W3C, 2018). The UXBERT lab introduced ten mobile UX design principles that are important for creating good mobile user experiences (UXBERT, 2017). These standards highlight ideas about making content perceivable, operable, understandable, and robust for all users. Although the WCAG guidelines have been instrumental in improving web accessibility, implementing these principles in mobile applications requires extra considerations due to the specific interaction patterns and restrictions of mobile devices (Vigo et al., 2013; Power et al., 2012).

Previous studies have highlighted the need for accessible mobile interfaces to fulfill the needs of visually impaired users. For instance, contrast and brightness settings can significantly boost content visibility for individuals with low vision (Kane et al., 2008). Multimodal feedback techniques have been shown to improve user interaction and lessen dependency on visual cues (Giudice et al., 2012; Yu et al., 2000). Giving users control over interface settings empowers them to modify their experience according to their preferences, increasing their satisfaction and engagement (Yesilada et al., 2004). Intuitive navigation with gesture-based controls can also promote better app browsing for blind and visually impaired users (Branje et al., 2014).

Despite these features, educational mobile apps lack appropriate mathematics learning materials. Mathematics material provides unique problems for visually impaired learners due to its visual and symbolic nature (Jayant et al., 2010). Existing solutions typically do not adequately address these problems, resulting in a lack of resources to support efficient mathematical education for these students (Buzzi et al., 2008, 2011).

This study reviews existing guidelines for accessible application development and seeks to refine and extend them through the development and assessment of a mobile application aimed at helping blind children learn mathematics. We used the refined guidelines to develop AccessMath, which promotes mathematical learning for blind and visually impaired students. We also conducted a usability study with blind and visually impaired individuals in order to analyze the effectiveness of the design decisions and provide insights into improving accessibility in mobile educational applications. The remaining article is organized into sections addressing various aspects of our research. Section 7.3 elaborates on the design guidelines for mobile applications. Section 7.4 provides details about the participants and the methodology used. Section 7.5 describes the evaluation results of the study, and Section 7.6 provides information about the discussion and conclusion.

7.3 Overview of Existing Design Guidelines and Extending Them for Visually Challenged Users

We have briefly mentioned the WCAG guidelines and the UXBERT guidelines, which are critical ones with regard to accessible mobile app development. Implementing the WCAG guidelines into our study helps us to benefit from a globally accepted framework that assures comprehensive accessibility. By focusing our design and evaluation on these guidelines, we seek to produce a smartphone application that is compatible with international standards and accessible and simple to operate for blind and visually impaired users. This strategy improves the effectiveness of our work and adds to the more significant objective of making digital materials accessible to all. We also looked at general usability principles (e.g., Norman's design principles and Nielsen's heuristics) to ensure good user experience (clear feedback, consistency, etc.). WCAG (Web Content Accessibility Guidelines) are international standards for making digital content accessible. They are ISO-approved and widely adopted; following WCAG helps ensure broad accessibility. The UXBERT guidelines (a set of ten mobile UX principles) complement WCAG by focusing on mobile-specific design (e.g., ease of use on small screens). We cite how UXBERT emphasizes perceivability, operability, etc., in mobile contexts. Together, WCAG and UXBERT cover global accessibility principles and mobile usability best practices. We chose these because WCAG's core concepts (provide text alternatives, ensure sufficient contrast, etc.) are essential, and UXBERT adds recommendations like consistent gesture design, which are crucial on smartphones.

7.3.1 Web Content Accessibility Guidelines (WCAG)

WCAG guideline 1.3 focuses on developing content that may be displayed in numerous ways without losing information or structure. Information, structure, and relationships presented visually should be programmatically determinable or available in text, ensuring interoperability with assistive devices like screen readers. When content sequencing impacts its meaning, the proper order has to be maintained. Instructions should not rely exclusively on sensory features such as shape, size, visual position, orientation, or sound. For example, presenting tabular data like a calendar using speech can cause issues, as individual dates lack context without their matching row or column headings. To alleviate this, developers could give additional context (e.g., announcing 'Friday the 17th' instead of just '17').

WCAG guideline 1.4 emphasizes making it easier for users to see and hear content by correctly separating foreground from background elements and providing audio separation. It highlights that color should not be utilized as the sole visual means of transmitting information, signaling actions, prompting responses, or differentiating visual elements; such dependencies can disadvantage color-blind users or those utilizing monochrome displays. To maintain accessibility, colors should only improve visual appeal or reinforce information supplied through other means. Foreground and background color choices must give sufficient contrast to be immediately distinguishable, which can be tested by examining the material in black and white.

WCAG Guideline 2.1 ensures that each of the features of an application or website needs to be accessible via a keyboard interface. Particularly, it is crucial for blind users who cannot depend on visual cues such as cursor position or other on-screen features, and may have difficulty manipulating objects. Interfaces should allow for suitable keyboard navigation—for instance, utilizing the Tab key to navigate among form elements in a logical sequence. It is crucial to avoid creating keyboard traps, circumstances in which a user cannot exit a form field without inputting the necessary information, as this can be very unpleasant and difficult for blind users who may not have access to help text.

WCAG Guideline 2.4 emphasizes providing users with effective ways to navigate and find content. This guideline includes implementing mechanisms that allow users to bypass blocks of content repeated across multiple web pages, such as headers and footers, which can be cumbersome for blind users who rely on screen readers. Each web page should have a descriptive title that clearly reflects its topic or purpose. When content is navigated sequentially, the focus order of interactive elements must preserve the meaning and functionality of the page, ensuring logical and intuitive navigation. Links should be clearly labeled so their purpose is understandable from the link text alone or in conjunction with their programmatically determined context. Proper use of page markup according to standards like HTML5 enables assistive technologies to identify and navigate different sections—such as headers, footers, and navigation bars—allowing users who are blind or visually impaired to skip repetitive content and efficiently locate unique content on the page.

7.3.2 UXBERT lab Mobile UX Design Principles

The 2nd principle from UXBERT's lab underlines the necessity of making navigation intuitive in mobile app design. A well-designed interface needs to be highly accessible, allowing users to easily navigate around the app without requiring explanations. Users may lack patience and can leave an app if it requires too much effort or time to find out where to navigate or execute tasks. So, user journeys must be clear and simplified, ensuring that tasks can be completed within the app without needing to hop between pages or other apps. Simplifying processes and having all relevant information easily available keeps people interested.

The 4th principle from UXBERT lab highlights the necessity of offering users control over their interactions in an app. Users value being able to personalize their experiences. Therefore, designers should allow users to make decisions such as altering settings, regulating notifications, and canceling actions. Keeping users informed by adding status updates and feedback to the interface promotes transparency without disrupting their workflow.

The 6th principle from UXBERT's lab stresses the importance of clearly visible interface elements. Since people use their mobile devices in various settings—indoors, outdoors, on public transport, and even in bright sunlight—designs must ensure sufficient contrast between content and background to maintain legibility in any environment. Achieving the right amount of contrast isn't always straightforward, because it needs a comprehensive evaluation of technological guidelines, user diversity, situational factors, and design principles. Designers must balance these aspects to develop interfaces that are both visually attractive and accessible to all users. It's appropriate for designers to consult the W3C's Web Content Accessibility Guidelines for recommended contrast ratios for images and text. Ultimately, the most critical step is to test text and background combinations with users to ensure readability across different conditions.

The 8th principle from UXBERT's lab focuses on minimizing data input to optimize the mobile user experience. Typing on tiny screens can be tedious and lead to errors. Therefore, designers should attempt to decrease the necessity of entering information by hand. The desired effect might be achieved through simplifying forms, deleting unnecessary fields, and including 'remember me' choices for future usage. Implementing tools like autocomplete, recent search history, and location awareness can further lower typing needs and speed up interactions.

7.3.3 Refined Design Guidelines

By refining the design improvements with specific WCAG guidelines and UX design principles, we have strengthened the design of accessible smartphone-based applications for blind and visually impaired users by applying them in practice and then evaluating the usability of the resulting application.

1. Adjustable Intrinsic Brightness for Enhanced Visibility

Incorporate customizable intrinsic brightness settings in mobile applications to improve accessibility for blind and visually impaired students. This allows users to alter brightness levels, improves visual clarity and contrast between text and background, and improves interaction with the application's content. Higher brightness settings can enhance the contrast of text, buttons, and images, making them easier to differentiate for people with limited vision. Additionally, providing alternatives for high-contrast modes and configurable color schemes to cater to the individual needs of users. This strategy aligns with WCAG 1.4 (Distinguishable), which focuses on making content more straightforward by separating foreground from background and supports the UX principle of having interface elements readily identifiable across different environments.

2. Incorporating Multimodal Feedback to Minimize Data Input

Employing multimodal feedback mechanisms in mobile applications by integrating audio cues, tactile feedback, and gestural inputs to offer a more valuable and accessible learning environment for blind and visually impaired students. By offering content using auditory and tactile channels, users can interact with the application more efficiently without relying mainly on visual or extensive data inputs. This lowers the need for typing, which can be onerous on mobile devices, and promotes usability by enabling users to utilize intuitive gestures. This technique aligns with WCAG 1.3 (Adaptable) and WCAG 2.1 (Keyboard Accessible), promoting material that can be displayed in many ways without losing information or structure and assuring all functionality is available through alternative input methods.

3. Empowering Users Through a Comprehensive Settings Panel

Offering a comprehensive settings panel inside the mobile application to give users complete control over its function and appearance. Allowing users to personalize their experience by adapting settings such as speech speed, volume control, color contrast, text size, and notification preferences—not only promotes accessibility but also empowers users with a sense of independence and transparency. This correlates with the UX principle of enabling user control, ensuring that users may adjust the app to their unique needs and preferences.

4. Implementing Swipe Controls for Intuitive Navigation

Providing simple swipe control functionalities and standard gesture-based navigation within the smartphone application enables a simple and predictable way for visually impaired students to explore the app. Utilizing consistent swipe moves helps users to apply learned controls across various applications, reducing the learning curve and improving usability. Providing tactile interaction options minimizes the need for visual cues, enabling visually impaired students to explore the application independently and confidently. This empowerment correlates with WCAG 2.4 (Navigable), which offers means to assist users in navigation and finding content, and supports the UX principles of making navigation intuitive.

7.4 METHODOLOGY

7.4.1 Design and Development of AccessMath (Shoaib et al., 2024)

The AccessMath app was designed to focus on four essential accessibility features: changeable intrinsic brightness, multimodal feedback, user settings panel, and swipe controls. These features enable them to better use their visual skills by changing brightness and contrast to minimize dependency on visual information by audio cues. Auditory and vibro feedback for output and gestural inputs help them navigate the app easily. With the help of a user-controlled setting panel, users can customize the app extensively to their preferences.

7.4.2 Usability Evaluation

A usability test was conducted with five blind and visually impaired users to examine the app's usability, cognitive load, and user experience. The study utilized measurements, i.e., task completion time to measure efficiency, the UMUX for perceived usability, NASA-TLX to evaluate cognitive workload, and the SUS for overall user satisfaction. Participants interacted with the app to perform the task and access the mathematical information. Later, they provided valuable feedback on the effectiveness and accessibility features of the application.

7.4.3 Participant Information

Five blind and visually impaired students were involved in this study, two males and three females. Their ages ranged from 9 to 12 years. All students had experience using mobile applications with assistive features. Ethical considerations were observed carefully, and all students were given informed consent before the study. This study has highlighted the Usability Evaluation. First, it expands existing accessibility guidelines to better suit the mobile context for blind and visually impaired users. Second, it presents empirical information on the usability and user experience of AccessMath, giving valuable insights for developers and researchers in accessible educational technology. Table 7.1 offers comprehensive details about each participant.

Table 7.1: Demographic information of the Users

User ID	*Age*	*Gender*	*Type*
U1	12	Female	Blind
U2	10	Male	Blind
U3	11	Female	Low Vision
U4	9	Male	Blind
U5	12	Female	Low Vision

7.5 RESULTS

In this study, participants were assigned a structured task designed to evaluate the usability and accessibility of the AccessMath application. The core task objective was to assess how effectively blind and visually impaired users could identify, draw, and receive feedback on basic geometrical shapes using the multimodal interface. Each participant was asked to complete a guided activity that involved drawing shapes and interacting with commands within the app. Each participant was asked to draw the geometrical shapes, i.e., "Click on the app Icon," "Swipe down for Shapes and Digits," "Swipe up for Geometry Shapes," "Draw the shape," "Speak out correct/wrong Answer" "Double tap for repeat" and "Triple tap for application quit" Auditory feedback was provided for each activity performed by the participant. Speech feedback alerted users if they made errors. Each participant completed the task three times, while we recorded the time to completion. We logged each answer to compute accuracy. We explicitly defined accuracy in our tasks as successful completion of the drawing task: i.e. the participant correctly drew the target shape. In practice, this meant the shape drawn on-screen matched the required digit or figure. Thus, a higher accuracy score simply indicated more correct drawings.The data collection included a task completion time of the accurate attempt, to verify interactions. We calculated average task completion times per user. Each participant completed the task three times, with a maximum allotted time of 150 seconds per task. The mean task completion times for participants ranged between 130 to 148 seconds, indicating that all participants were able to complete the tasks within the required time. However, the variation in completion times suggests that some participants may have found certain aspects of the task more challenging than others. Figure 7.1 outlines the task completion time of each participant.

Figure 7.1: The task completion time of the participants

The UMUX scores for the participants ranged from 75.0 to 91.67, with an average score of 83.33. This score indicates high perceived usability. A score above 80 on the UMUX scale reflects that participants generally found the system easy to use and capable of meeting their needs, which correlates with a positive user experience. Figure 7.2. illustrates the UMUX (Usability Metric for User Experience) score of each of the participants.

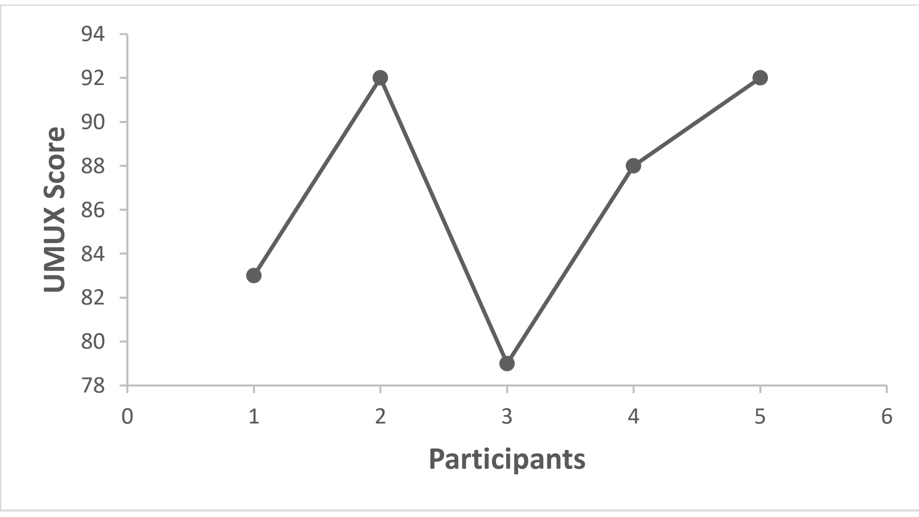

Figure 7.2: The UMUX (Usability Metric for User Experience) score of the participants

The NASA-TLX measures the perceived workload across six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. The average workload score across all participants was 49.83, indicating a moderate perceived workload. Some participants reported high mental demand, effort, and frustration, especially during complex or time-sensitive tasks. Figure 7.3. demonstrates the participants' NASA Task Load Index (NASA-TLX) scores.

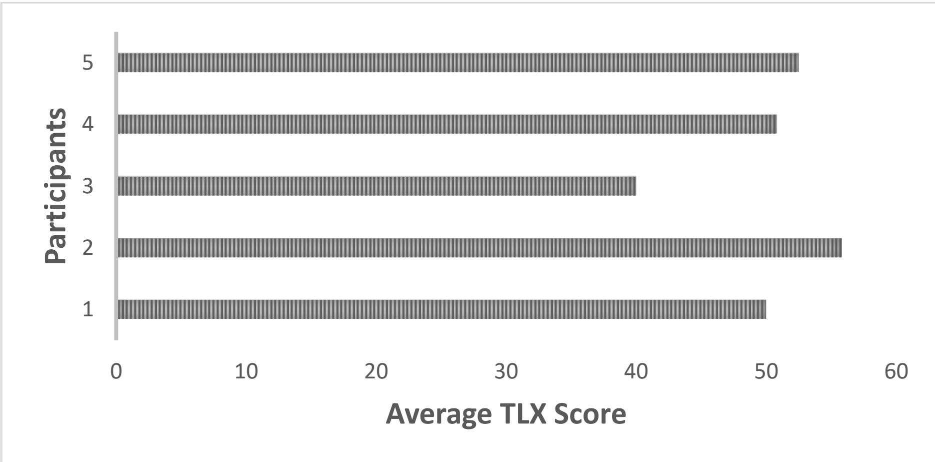

Figure 7.3: Demonstrated the NASA Task Load Index (NASA-TLX) score of the participants

The SUS scores ranged from 75.0 to 92.5, with an average score of 83.5. A score above 80 counts as excellent, indicating that users found the application highly usable. Many participants evaluated the application positively, believing in their ability to learn and manage it quickly while seeing that it was not excessively complex or challenging. Figure 7.4. shows the System Usability Scale (SUS) scores of the participants.

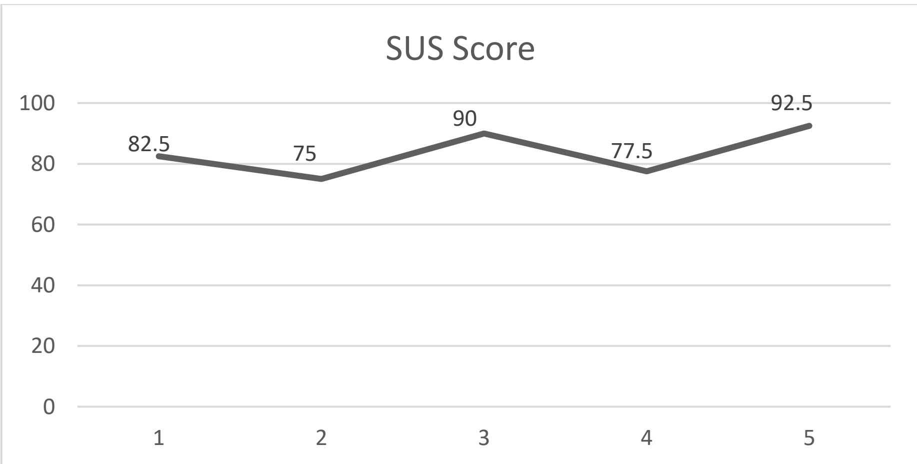

Figure 7.4: Shown the System Usability Scale (SUS) score of the participants.

7.6 Discussion and Conclusion

The development and evaluation of AccessMath illustrate the usefulness of implementing specific accessibility guidelines in the design of an app for blind and visually impaired users. The positive usability evaluation results suggest that features like user-selectable brightness, multimodal feedback, user-controlled settings, and clear swipe navigation greatly enhance the user experience.

The work described here highlights the value of extending existing guidelines, expands the knowledge of accessible mobile application design, and provides practical guidance for developers hoping to develop inclusive educational tools. By integrating our extended design guidelines with specific WCAG principles and UX design concepts, we strengthened the importance and usefulness of our suggestions for creating accessible mobile apps for blind and visually impaired users. In particular, we looked at WCAG guidelines concerning: brightness and contrast settings, with the help of intrinsic brightness, to create more distinguishable content (1.4 Distinguishable); including multimodal feedback like audio and tactile cues to make content adaptable (1.3 Adaptable); guaranteeing all functionalities are accessible using alternative input methods like introducing gestural controls (2.1 Keyboard Accessible); and introducing simple swipe gestures to enhance navigability (2.4 Navigable). Consequently, we adopted UX principles by improving visibility through customized brightness and contrast, decreasing data input requirements through gesture controls, empowering users through a customizable settings panel, and permitting simple and predictable navigation using intuitive swipe gestures.

Furthermore, during the evaluation, the task completion times reveal that the application is accessible and effective for blind and visually impaired users. Slight differences in intervals during usability testing could indicate specific usability changes that may help to minimize cognitive or operational pressure for some users. The UMUX scores imply that the smartphone app is well-received in terms of usability, with users perceiving it as beneficial, simple to use, and effective in helping them achieve their tasks. Furthermore, the moderate workload scores signal that while the technology is helpful, certain aspects may inflict cognitive and emotional pressure on users. Efforts to streamline task workflows, simplify interactions, or lessen physical and mental demands might reduce workload and improve user satisfaction. Finally, the SUS scores coincide with the favorable UMUX findings, demonstrating that users consider the smartphone application intuitive and effective. An overall SUS score of 83.5 shows that the application provides a solid user experience, while a few minor changes in areas such as consistency or support might further boost usability.

The guidelines we derived and generalize beyond our app: any developer of accessible educational software can apply them. For example, our refined guideline to "provide redundant feedback (audio + haptic) for each interaction" would benefit other accessibility-focused tools. Academically, these guidelines suggest new criteria for evaluating mobile apps for disabled users. We critique our guidelines by noting that, while tailored to math learning, many principles are applicable to other domains (e.g. adjusting text display benefits all low-vision users). For instance, facilitate independent navigation for blind and visually impaired users in mobile applications by implementing accessible swipe controls complemented by keyboard and voice navigation options. Ensure that navigation elements are consistent and simplified across the mobile interface.

Finally, we addressed differences between blind and low-vision users (formerly brief, now expanded). In our results, blind users generally took longer to complete tasks than low-vision users, likely due to relying on audio/haptic cues instead of visual scanning. Conversely, low-vision users preferred a higher contrast mode (e.g. dark text on light background, or vice versa) to improve legibility. This indicates that when designing the UI, providing adjustable contrast or high-contrast themes is important. Regarding usability questionnaires, both groups rated the app favorably, but blind students reported slightly higher mental demand for the NASA-TLX, reflecting the cognitive effort of processing non-visual feedback. These quantitative and qualitative observations highlight that blind students benefit most from clear haptic and audio cues, while low-vision students benefit from maximized visual clarity. In future designs, we recommend features like an optional Braille display output or alternate input modes to better support blind users, and even larger fonts or color themes for low-vision users. Thus, the evaluation illuminates group-specific needs and informs tailored design improvements.

7.7 Concluding Remarks

This chapter describes the usability evaluation of AccessMath and discusses the design guidelines for mobile application developments specifically for visually challenged users. Chapter 8 provides the conclusion and future directions for researchers and developers.

Chapter 8

Conclusion and Future Directions

8.1 Conclusion

This dissertation has explored the vital role of Assistive Technology (AT) in facilitating the mathematics education of visually impaired and blind students. The prototype solutions are aimed solely at users with visual impairments, thus making Assistive Technology appropriate in these instances. Throughout the chapters, we have combined findings from various sources to give a unified understanding of the issues and solutions in this study area, demonstrating how one section of research builds upon previous background and informs the next developments.

A systematic review

We started by identifying the unique obstacles that visually impaired students encounter with the rise of e-learning-based solutions. While available solutions and technologies have extended education opportunities, they also introduced challenges such as difficulty obtaining graphical information, fostering independent learning, dealing with high color contrast, and reading large print numbers. Recognizing these challenges laid the groundwork for exploring AT-based solutions, stressing the need for specialized mathematics teaching methods for visually impaired learners. AT advancements have revolutionized how visually impaired students receive specialized education, making learning more inclusive and adapted to their needs.

Building on this foundation, we observed that multimodal learning systems integrating approaches like speech, vibro-tactile (convey information through the skin), tactile displays (surface-based or pin-based devices), tangible user interfaces, and Braille are more efficient than unimodal systems. Innovative technology, including Graphical User Interface (GUI) calculators and virtual learning platforms, have been developed to support these students. We provided a conceptual framework for learning mathematics using AT, emphasizing how these technologies empower visually challenged users. Our categorization of available solutions into multimodal, Braille, desktop, and smartphone-based provides significant insights for readers, developers, and researchers.

A multi-stakeholder qualitative analysis

A comprehensive study was conducted with visually impaired students, their teachers, and expert professionals to delve deeper into the practical challenges and needs of the stakeholders. The study emphasizes the need for instructors to motivate students to take advantage of digital textbooks, which can be more effective than traditional methods of instruction. Key aspects such as the learning environment, technology-based training, student motivation, and instructor expertise were found to play pivotal roles in the academic success of visually impaired individuals. Academic, technological, and specialist support is also recommended to aid their learning further. Collaborative efforts among students, instructors, parents, institutions, and legislators are vital in creating an atmosphere conducive to educational success.

Guide for Mobile Accessibility Platforms

Armed with this comprehensive understanding, we evaluated developmental platforms for smartphone applications in the context of accessibility; we evaluated Android, iOS, Xamarin, and Unity, each presenting various advantages and problems related to accessibility features. Our analysis highlights the need to emphasize accessibility in the development process, ensuring that applications are entirely usable by those with impairments. By using available platforms, developers are urged to evaluate project requirements, user needs, and available resources when adopting a development strategy, ultimately supporting the production of more inclusive and effective educational tools.

Empirical Validation Through User-Centered Prototypes

Methodological Rigor and Diverse Research Approaches

Methodologically, in our research, we employed various study designs, data collection methods, and analysis approaches, including interviews, focus groups, questionnaires, thematic analysis, the Lens tool, Wilcoxon signed-rank test, one-tailed paired t-test, MARS, UCD, usability studies, exploratory studies, word clouds, UMUX, NASA-TLX, and SUS. Previous studies have shown that interviews, questionnaires, and participant observation are compelling for assessment. Pre-study training sessions gradually enhanced the skills of visually impaired and blind individuals, proving helpful for their learning interventions.

Application of Accessibility Guidelines to Mobile Development

In addition to practical solutions, we have looked at established guidelines, most of which relate to web applications. What we have learned from the literature and our work on mobile development tools shows how these guidelines can be applied effectively to the environment of smartphone applications. We described how the WCAG can be used more effectively in mobile apps for blind and visually impaired users. It highlights practical ways for applying established principles, such as providing text equivalents and assuring navigability on small displays and touch-based interfaces. These recommendations aim to bridge the gap between web-centric accessibility standards and the unique design needs of mobile environments (e.g., touchscreen interfaces, small screen sizes, and gesture-based interaction). These involve improving perceptibility via adjustable contrast and audio controls and developing flexible content structures that adapt to different presentation styles—offering alternative input methods, such as swipe gestures, to enhance navigational independence. These adaptations comply with the original WCAG objective and provide enhancements such as user-driven customization, adaptive content rendering, and context-aware navigational aids designed for mobile contexts. Part of the work also underlines the need to revise accessibility guidelines to fit the growing needs of users, enabling the creation of more inclusive and prosperous mobile applications for visually impaired and blind individuals.

Development of Accessible Mathematics Applications

We have developed smartphone-based accessible solutions that help students who are blind or visually impaired to improve their math skills. Research has demonstrated that smartphones are beneficial for education due to their accessibility and low cost. Instructional information on mathematics was successfully communicated by combining multiple modes of interaction (speech output, haptic feedback, and visual contrast). That effectively assists blind and visually impaired students in learning and performing mathematical tasks. The main objectives of these accessible solutions are providing auditory feedback for accessing mathematics instructions, offering them better ways of interaction with the help of user-friendly swipe gestures, audio prompts for explanations of mathematical problems, layout schemes that minimize cognitive load, and transforming visual and mathematical concepts into auditory formats. These solutions help blind and visually impaired individuals to make mathematics material accessible and understandable for them.

Positive Outcomes and User Satisfaction

Our proposed solutions resulted in quicker mean task completion times, revealing better efficiency. Participants noted that the applications helped them to increase their action awareness and provided helpful information. The solutions have been well received and may be used as a guide for designing new apps. Notably, blind and visually impaired students mathematics learning ability, as measured by the task completion time, increased significantly, and they expressed great satisfaction with the proposed solutions. The findings also revealed improved usability and lower cognitive load, highlighting the usefulness of the implemented guidelines for designing and developing accessible mobile applications for blind and visually impaired users. The positive reception of these solutions suggests they enhance mathematical proficiency and contribute to a more engaging and satisfying educational experience. Audio feedback proved to be the most efficient and immediate prompt for actions, but swipe gestures should be designed to be simple and consistent to prevent user confusion. These results can guide the development of future applications, emphasizing the importance of user feedback and iterative design processes. Through comprehensive research and analysis, we concluded that AT increases educational opportunities and effectively minimizes the unique problems of learning mathematics faced by blind and visually impaired students.

8.2 Proposed Directions for Future Research

Limitations: Recruiting primary school participants was challenging: obtaining consent, and conducting engaging sessions within children's attention spans, limited the depth of data collected. In qualitative studies, keeping questions simple (as noted in the viva) sometimes restricted the detail of responses. These factors are common in research with young participants, but they mean the results should be interpreted cautiously. Additionally, the AccessMath app is currently a prototype; its long-term impact ("legacy") depends on future development and dissemination. For instance, further work could involve making the app freely available to schools. The classification of accessible libraries (Ch4) we provided is also tied to the specific platforms examined – as technology evolves, new libraries may emerge, so our analysis may need updating. Lastly, the modified guidelines we propose are derived from this particular context (math learning); applying them to other domains might require validation.

Based on the findings of this research, various potential paths and recommendations emerge for developing smartphone-based apps to assist visually challenged individuals in learning maths.

Legacy of the AccessMath app: The AccessMath app has played an important role in supporting inclusive mathematics education, particularly for visually impaired and blind learners. It offers flexibility for future adaptation, allowing educators, developers, and researchers to build on its foundation and apply it in a variety of learning contexts. Its features have already attracted interest from accessibility-focused educational communities and have been mentioned in discussions around the development of future inclusive STEM platforms.

As part of this work, a comparative overview of accessible libraries across major platforms was conducted and is presented in Chapter 4. This includes options for Android, such as custom MathView with TalkBack support; for iOS, VoiceOver-compatible LaTeX renderers; and for web, tools like MathJax enhanced with ARIA attributes. These libraries were assessed for their accuracy in rendering mathematical content, screen reader support, and ease of interaction. This comparison serves as a useful reference point for developers working on accessible math content across different platforms.

Additionally, the thesis led to proposing refinements/clarifications to existing accessibility guidelines for presenting mathematical content, as detailed in Chapter 5. Key recommendations include the use of background color combinations, facilitating independent navigation by using swipe control, minimizing text input by allowing gesture selection, clear labeling of interactive elements, and user-driven customization features. These updated guidelines informed the design of AccessMath and can also serve as a practical resource for others aiming to create accessible educational tools that align with evolving accessibility standards.

To improve the user control, future apps can contain adjustable swipe controls and additional accessibility capabilities, such as altering the sensitivity or speed of swipe gestures. Customized swipe gestures such as double-swiping or holding after a swipe can be manipulated to trigger specific actions like going to the home screen or opening the settings panel. These changes can make navigation easier and lessen the cognitive load on people using it. Currently, a lack of standardized guidelines for gesture design might result in uneven experiences for visually impaired individuals across different apps. This lack of standardized guidelines could be a starting point for future researchers to overcome app navigational and cognitive load issues.

A separate study could be conducted to determine the optimal button size alongside layout, user interaction patterns, proper padding, and spacing, significantly improving accessibility for visually impaired students. Some research suggests that precision and accuracy vary across different screen areas. In this case, button size should adapt to different interaction zones that may enhance the usability of the interfaces. By focusing on the tactile aspects of the user interface, developers can create more accessible and user-friendly applications that cater to the specific needs of this demographic.

Technological advancements have shifted the focus from vision to other senses in eyes-free environments (Chen 2023; Bala 2023; Fallah, 2010; Ran et al., 2004; Loomis et al., 2005). Recent innovative technologies utilize hearing, haptic feedback, and multimodal combinations to facilitate mathematical learning for visually impaired and blind people. While many existing solutions predominantly support the English language, future developments should aim for language-adapted interfaces. This approach would enable individuals whose first language is not English to develop their mathematical skills more easily, thereby broadening the accessibility of these educational tools.

Implementation of voice recognition technology in apps can allow for hands-free interaction, further enhancing accessibility. Voice commands can ease navigation and control inside the app, making it more user-friendly for blind and visually impaired users who may have problems with touch-based interaction. This function can also assist blind and visually impaired users in entering mathematics expressions and obtaining auditory feedback.

Collaborations with professionals and organizations specialized in accessibility are recommended to undertake detailed studies to check the impact on various educational contexts. Promoting a collaborative approach involving educators, developers, policymakers, blind and visually impaired individuals is crucial for effective and sustainable assistive technology-based solutions. This collaborative approach could address real needs, should be user-friendly, and promote the necessary support for widespread adoption. Collaborative efforts can also contribute to developing standardized guidelines and best practices in designing accessible educational technologies. Moreover, discovering ways to involve parents in their children's education can create chances for academic engagement at home.

Investigating the possibility of implementing AI-driven features that offer personalized feedback and adjust to each user's learning pace and style. These programs can assess a user's strengths and weaknesses by applying machine learning algorithms and adapting the material and difficulty level accordingly. This adaptive learning method ensures that each student receives the education that matches their particular needs, boosting engagement and efficacy.

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Appendix A

Interactive Learning Platform

This study was published as: Shoaib, M., Jiang, S., Jin, L., Fitzpatrick, D., & Pitt, I. (2023, July). An Artificial Intelligence-Based Interactive Learning Platform to Assist Visually Impaired Children in Learning Mathematics. In International Conference on Human-Computer Interaction (pp. 366-373). Cham: Springer Nature Switzerland. DOI: https://doi.org/10.1007/978-3-031-35992-7_51.

1 Abstract

Visually impaired children mainly depend upon hearing and touch in the absence of vision. Smartphones are now relatively cheap and are in widespread use in almost all parts of the world, including by many people who do not have access to laptops or desktop machines. Smartphone-based applications provide a learning environment in which visually impaired children can enhance their educational skills in a similar way to other students. This paper introduces an artificial intelligence-based interactive learning platform that can enhance the mathematical skills of visually impaired children. This platform can assist teachers in the classroom to provide accessible and interactive materials to their visually impaired students. The proposed platform uses text-to-speech along with vibrotactile and auditory feedback to help visually impaired students arrive at a better understanding of mathematical material. Four participants were recruited to evaluate the prototype of this interactive learning platform. The results showed that understanding of mathematical content in visually impaired children was significantly improved. Furthermore, problem-solving skills and action awareness were enhanced with the help of a multimodal feedback approach. Participants also reported high levels of satisfaction with the proposed design. The paper concludes with a discussion of possible directions for future research aimed at overcoming barriers to learning faced by visually impaired children.

1.2 Introduction

Visually impaired students have difficulties in perceiving graphical information. They normally use the senses of hearing and touch to obtain information from their surrounding environment. With the help of technological advancement, many techniques and solutions have been introduced that could assist them to improve their learning skills. Smartphone-based and computer-based solutions are prominent areas of solutions for visually impaired people and provide effective assistance to them in accessing information. In these solutions, artificial intelligence-based techniques are quite useful for visually impaired students. Felix et al. (2018) proposed a smart personal assistance by using the artificial intelligence technique that provided better access to the surrounding environment of visually impaired people. They used image recognization, text recognization and machine learning techniques together in form of a mobile application. This application helped visually impaired people in certain tasks i.e., accessing books electronically, currency and image recognization. Some tutoring applications are also available for visually impaired people that provide better ways to access and manipulate information during their learning process. The i-Math is an automatic math reader application which was designed for Thai Blind people and is quite useful for them to access mathematics material. It can read the mathematics content from documents in audio form with the help of a screen reader. Teachers also have the facility to prepare their assessments for students in the audio form (Wongkia et al., 2012). Computer Haptics provided a new way to access information by touch, auditory and visual means. In this approach computer and haptic feedback controller were used by students to explore the 3D shapes (Darrah, 2013) virtually

Interactive learning platforms are also becoming popular in education, especially for visually impaired students. Visually impaired students can easily use them in learning mathematics. These platforms used various technologies such as screen readers, braille displays, and audio instructions to present mathematical concepts in a way that was accessible to visually impaired students. One such platform is MathTrax (Nguyen, 2011), which was designed to offer accessible math materials to students with visual impairments. MathTrax used screen reader technology to read mathematical expressions aloud and allows students to navigate through equations using their keyboards. Another platform, MathSpeak (Sauer, 2020), was a browser-based tool that can be used by both sighted and visually impaired students to learn math concepts through a combination of text, audio, and video instruction.

This chapter introduced an Artificial Intelligence-Based Interactive Learning Platform for math tutoring of visually impaired children. This platform helped visually impaired children in learning mathematics by using text-to-speech and vibrotactile feedback. Visually impaired children can learn and practice linear and quadratic equations of mathematics by using this platform. The remainder of this article is organized as follows: Section 1.3 which defines previous work associated with visually impaired children learning mathematics. Section 1.4 describes the proposed methodology of the interactive learning platform. Section 1.5 presents the participants and results information. Lastly, section 1.6 has a discussion and conclusion based on the results of this study.

1.3 Related Work

Ávila-Soto et al. (2017) designed a tangible user interface by using a multimodal method. This method used auditory feedback and tangible numbers to enhance the basic arithmetic skills of visually impaired students. Bouck et al. (2011) proposed a computer-based Voice Input and Speech Output (VISO) calculator to help visually impaired students to solve basic mathematic calculations. Results showed that the VISO calculator reduced the time to perform the calculations. It also has some accuracy issues in the recognition of speech. Bier & Sroczyński (2019) designed and implemented a multi-purpose math-to-speech translation system based on Lua script, which allows users to manually adjust translation rules, i.e., language change and focusing on the relevant requirements. Results illustrated that the overall success rate of the correct answers was about 83%. This system can be used for several purposes i.e., e-learning platforms for auditory representation and as an educational tool for non-native visually impaired users.

Buzzi et al. (2015) developed an accessible vibro-tactile-based android application to solve geometry problems. The design of this application is more accessible for visually impaired children because they can make freehand drawings and recognize geometry shapes based on vibration and touch senses. Gulley et al. (2017) introduced an auditory approach to guide and evaluate mathematics learning named Process-Driven Math. It facilitates the visually impaired students who do not have enough experience in Braille to learn mathematics. Audio rendering of the algebraic expression was used to significantly reduce the complexity of mathematical expression. It also helped the visually impaired students to improve their understanding of mathematical expressions.

Murphy et al. (2010) designed auditory cues by using synthetic speech, non-speech and spearons. These newly designed cues were used to eliminate the ambiguity of mathematical formulas. They designed an online survey to evaluate the effectiveness of these auditory cues on 56 participants. Results demonstrated that visually impaired users better understand mathematical equations with the help of synthetic speech Their listing time is reduced with the help of modified speech (spearcons). MathPlayer is also an important platform for learning mathematics. It can read aloud mathematical formulas and has support for Internet Explorer, Mozilla Firefox and screen readers (Sorge et al., 2014). Furthermore, researchers have also proposed some theoretical methods for visually impaired students to learn specific kinds of mathematical problems i.e, algebra and calculus. Elkabani & Zantout (2015) proposed a framework that helped visually impaired people in learning linear algebra. There is another framework that has been proposed to solve some simple calculus problems and achieve successful outcomes by (Maćkowski et al., 2018).

1.4 Proposed Methodology

In this chapter, a prototype was introduced that can enhance the learning skills of visually impaired students more effectively. This prototype used a multimodal feedback approach that facilitates visually impaired students. This prototype has two main modules "interactive learning module" and "Practice module". In the interactive learning module, students can practice linear and quadratic equations. They can choose one type of mathematical question, and the proposed system automatically searches the related questions from the question bank. they can interact with the system through their voice. During the interaction, the user can explore all relevant information about the selected questions. Shown below is a step-by-step example for solving a linear equation with one variable in this module:

Solve for y, $y^2 + 4(y + 1) = 1$

$y^2 + 4y + 4 = 1$	Multiply small parenthesis by 4
$y^2 + 4y + 4 - 1 = 0$	Move the right constant to the left side
$y^2 + 4y + 3 = 0$	Subtract both constant values
$y^2 + 3y + y + 3 = 0$	Factor the equation
$y (y + 3) + y + 3 = 0$	Take y value common from equation
$(y + 3)(y + 1)$	Splitting the equation for the solution
$y = -3, y = -1$	Final solution

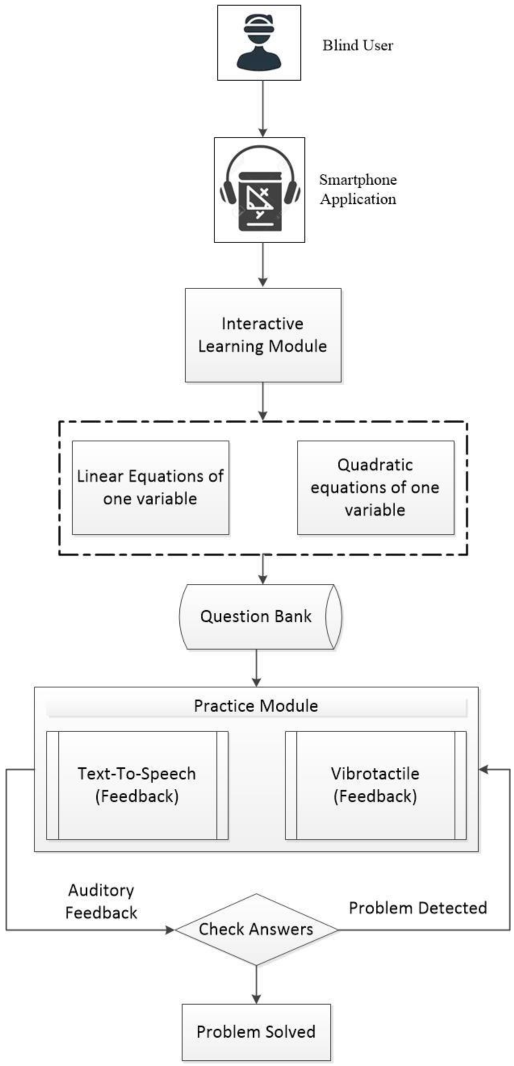

Figure 1.0.1: Provides a basic overview of the proposed framework.

Once students have a proper understanding of the selected topic then they can proceed with the practice module to check their learning skills. Students can attempt to solve the questions in this module. They can acquire the information by using multimodal feedback which is the composition of text-to-speech and vibrotactile feedback. They have to select a question from the question bank. After selection, the text-to-speech function reads the selected question aloud which indicates the user is ready to solve the question. Users can give the step-by-step solution by speaking and the system can validate the solution. If there is something wrong then it generates vibrotactile feedback. Vibrotactile feedback indicates that something went wrong and the user can request a hint in this situation. If the student solved the question accurately then it generates a message that "problem solved". Figure 1.1 provides a complete overview of the proposed framework.

1.5 Participants and Results

Four participants 3 male and 1 female, aged between 12 and 14 years old (M=12.5 and SD=0.84), were involved in this study. All participants were desktop computer and smartphone users. Table 1.1 provides the demographic information of the participants. Self-assessed scores in the table expressed the expertise level of the participants with desktop computers and smartphones. On average self-assessed expertise level with desktop is 5.25 and smartphone is 6.75. Year of usage represents the number of years that a participant has been using a desktop and smartphone. On average, participants have been using a desktop for 3 years, and a smartphone for 5 years.

Table 1.0.1: Participants' demographic information.

PID	Age	Impairment Type	Self-Assessed Expertise Level with		Years of Usage	
			Desktop	Smartphone	Desktop	Smartphone
P1	12	Blind	5	6	2	4
P2	13	Visually Impaired	6	7	3	5
P3	12	Blind	5	7	3	5
P4	14	Visually Impaired	5	7	4	6

The study's goal was clearly explained to the participants. The details of application usage were thoroughly explained to them. Participants were told that in order to participate in this study, they must first attend a training session. All participants were informed that the entire study would be recorded on video for analysis purposes. Signed informed consent forms were also collected by participants.

Each participant responded to a survey after the experiment. The scores for this survey were reported as feeling pleasant (3)-unpleasant (1), like (4)-Dislike (0), enjoyable (4)-hurting (0), happy (4)-painful (0), and pleased (3)-irritating (1).

Figure 1.0.2: Extracted word clouds from the comments of our participants (Designed from: https://www.wordclouds.com)

Figure 1.2 displayed word clouds made from a total of 24 words that our participants believed best captured their experience with our proposed application. Mostly the words were positive i.e., “helpful”, "pleasant," "enjoyable" "useful," and "interesting". As well as there were some words with negative responses i.e., "disturbing," "painful" "useless" and "irritation”.

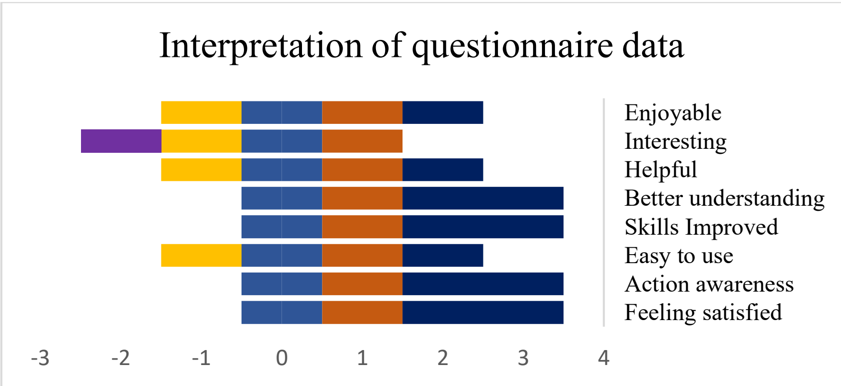

Figure 1.0.3: Interpretation of participants behaviour after the experiments

After the experiments, we conducted a study with participants in which they had to fill out a questionnaire. We designed this questionnaire using the 5-Point Likert Scale (values as Strongly Agree, Agree, Neutral, Disagree, Strongly disagree). Questions were designed to measure several aspects of the participants i.e., satisfaction, action awareness, ease, skills improvement, understanding, helpful, interesting and enjoyable. Figure 1.3 provided an overview of the participants' behaviour after the experiments. Blue indicates that participants strongly agree, maroon indicates that they agree, cyan color indicates that they were neutral, light purple indicates that they disagree and dark purple indicates that they strongly disagree with this study. It was clearly illustrated that participants mostly agreed or strongly agreed with the proposed prototype.

1.6 Discussion and Conclusion

Teaching mathematics to visually impaired students is a very difficult task due to the rich visual information i.e., graphs, formulas and notations. With the help of advanced technology, visually impaired students can now access a more inclusive and personalized learning experience that caters to their requirements and adjusts to their learning styles. Previous studies showed that auditory and vibrotactile feedbacks were very useful for visually impaired students in learning mathematics. In this study, we have combined both feedbacks to provide better interaction and action awareness to visually impaired students. Our main focus was to solve linear and quadratic equations of one variable. The proposed prototype was mainly designed for visually impaired students who want to gain better mathematics skills.

Our proposed prototype plays an important role in making mathematics material accessible to visually impaired students. With the help of auditory and vibrotactile feedback, visually impaired students can receive audio descriptions of math problems, interact with the platform using voice commands, and access visual representations of math concepts through an audio form. This prototype can track the student's progress and provides personalized feedback, enabling them to learn at their own pace and adapt to their individual learning styles. Results from the questionnaire data and face-to-face interviews showed that the proposed prototype helped visually impaired students to improve their learning skills in mathematics. Visually impaired students feel satisfied with multimodal feedback. Words clouds showed that visually impaired students felt enjoyable, pleasant and happy with the proposed prototype. 5 Point Likert Scale data represented that mostly participants agreed on better action awareness and understanding of the proposed prototype.

This prototype has the potential to significantly improve the accessibility of math education for visually impaired students. It was also effective in helping students to learn and understand mathematical concepts. However, further research is needed to introduce future improvements. Such as, we have recruited only four participants. In future, we can recruit more participants to better assess the application's usability and effectiveness to add a future enhancement. The final release of this application will be open-source and available for anyone to use for free to learn mathematical skills. We are also planning to link a parent and teacher account with the student, therefore, they can easily monitor the learning activities of the student.

Appendix B

Remote Learning during COVID-19

This chapter was published as: Shoaib, M., Fitzpatrick, D., & Pitt, I. (2023, September). Remote Learning of Mathematics for Visually Impaired Students During COVID-19: Exploring Online Intervention, Resources, Challenges and Issues. In Intelligent Systems Conference (pp. 145-156). Cham: Springer Nature Switzerland. DOI: https://doi.org/10.1007/978-3-031-47715-7_11.

2.1 Abstract

Due to COVID-19, several dramatic changes have appeared all over the world i.e., travel restrictions, healthcare shortages, self-isolation, economic crises, social distancing, increases in food demand, job losses and closure of educational institutions. This led to a rapid transition from face-to-face to remote teaching. Most remote learning platforms are designed primarily for sighted students and are less useful for visually-impaired students. Especially in mathematics, it's quite difficult for visually-impaired students to access rich visual information, such as graphs, algebraic notations, geometric shapes and statistical formulas. This article provides an overview of mathematics learning resources during the COVID-19 pandemic. It explores assistive technology-based interventions which enable visually-impaired and blind students to actively participate in remote teaching and enhance their learning skills. It was noted that solutions are available for various platforms (i.e., smartphones, tablets, laptops & desktop PCs) to support visually-impaired students. Assistive Technology in remote learning also plays a key role in enhancing the mathematical skills of visually-impaired students. Furthermore, we have investigated the important COVID-19-related resources of different institutes which are very beneficial for the online education of visually-impaired students. Moreover, some challenges and issues are discovered such as internet connectivity, lack of interaction, inadequate support, one-way communication and less effective learning. Finally, some future directions are suggested for research i.e., parents should be a part of remote learning.

2.2 Introduction

Coronavirus was identified in 2019 in Wuhan, China. This virus was recognized globally as a pandemic in early 2020 when confirmed cases significantly increased. The World Health Organization recognized this coronavirus disease as COVID-19 on 11 February 2020 (WHO, 2020). The global mortality rate peaked in January 2021 and the number of newly diagnosed cases peaked in April 2021 (CRC, 2021). Due to COVID-19, educational institutions were closed and traditional teaching methods shifted to remote learning to reduce the pandemic effects on education (Bozkurt & Sharma, 2020). Teachers and students both had to learn to use remote teaching platforms. Teachers had to prepare the lecture material according to the student's expectations and in addition had their own requirements i.e., interactive virtual environments, strong collaborative environments, online support for special education, and easy content management (Assunção Flores & Gago, 2020). Mathematics has its peculiar characteristics i.e., symbols, equations, formulas, language, shapes and abstraction in its concepts. Mathematics develops reasoning capabilities in the human mind and is also very important for the foundation of other science subjects (Iqbal & Shams, 2019). Visually-impaired students face several issues when learning mathematics, such as working with graphs and diagrams (Beal & Rosenblum, 2018; Morash & McKerracher, 2014). Visually-impaired students can access information about basic math operations (i.e., addition, subtraction, multiplication and division), geometry, numbers, algebra, graphs and statistics with the help of mathematics teaching. Several instructors of visually-impaired students have reported that their students face problems in accessing mathematics graphics independently (Zebehazy & Wilton, 2014). There is a need for tools, techniques, systems and web-based platforms that provide easy interaction, full encouragement and motivation to the disabled student (Diane et al., 2012). In the CoVID-19 situation, digital learning provided better opportunities to deal with challenges (Dhawan, 2020). Numerous computer-based applications integrated with different software and web-based packages offer virtual educational environments to empower the students learning skills (Kleanthous & Meletiou-Mavrotheris, 2016; Merchant et al., 2014). Assistive Technology is also very useful for exploring a variety of mathematics topics. Visually-impaired students can learn many areas of mathematics with the help of assistive programs (Asebriy et al., 2018). Assistive Technology provides hardware and software-based solutions which are free or commercially available for visually-impaired students and used to enhance learning and functional capabilities (Wong & Cohen, 2011). In mathematics, there is always a need to design and develop learning programs that could be useful for enhancing mathematical skills (Godino & Batanero, 2007). The National Council of Teachers of Mathematics (NCTM) in the USA has issued some principles and standards (i.e., Content standards, Process standards) for mathematics institutes. The six principles are Teaching, Learning, Curriculum, Assessment, Equity and Technology. Five important process standards are connection, reasoning, representation, communication and problem-solving skills. Five core topics in mathematics are probability, number, geometry, data analysis and algebra (NCTM, 2000). Researchers and developers who wish to introduce a new solution for visually impaired people can bear in mind these principles and standards to optimize the learning ability of students.

The goal of the study is to investigate the challenges and issues faced by those working in this area, the resources available, and the potential for online intervention. This study suggests ways to address the current challenges and increase the inclusivity and accessibility of online mathematics education for students who are visually impaired. This article also explores the use of remote learning tools and techniques for teaching mathematics during the COVID-19 pandemic. Also, to explores freely-available COVID-19 resources and discusses challenges and issues faced by visually-impaired students during the Covid-19 pandemic. The remaining sections are organized as follows: Section 3.3 reviews related work in the area of remote learning of mathematics. Section 3.4 illustrates the remote learning model for visually-impaired students. Section 3.5 describes some COVID-19 Resources and tips for visually impaired learners. Section 3.6 defines the overall educational experience from different perspectives (i.e, Teaching perspective, Social perspective, Cognitive perspective and Student perspective). This section also provides an analysis of online learning during COVID-19 and discusses strengths, weaknesses, opportunities and challenges associated with this. Section 3.7 presents a discussion based on previous sections. Section 3.8 concludes the article, whereas Section 3.9 provides the future directions for upcoming researchers and developers, and Section 3.10 provides the concluding remarks.

2.3Related work

This section provides a detailed review of the previous literature on remote learning of the visually impaired student. Researchers have introduced technology-based solutions to help visually-impaired students learn mathematics. Reddy (2017), noted that mathematics is a very challenging subject. With the help of assistive technology, students can easily access the material and interact more effectively with the platforms to support their learning process.

Sokhulu (2021) provided a case study-based analysis of five masters-degree students and discussed the impact of digital technology on their learning during the COVID-19 pandemic. The findings suggested that some students were familiar with digital technologies and able to select technologies that were appropriate for them, whereas other participants did not have this awareness and faced challenges in selecting and using technology-based solutions. They also concluded that a combination of social and professional experience can address the research needs of students individually. Recently, assistive technology-based solutions have proven very useful in helping visually-impaired students to acquire mathematical skills (i.e., Abacus Media, Mathematical Braille, ViewPlus Accessible Graphing Calculator, MathTalk, and MathPad Plus) (Reddy et al., 2021; Bouck & Satsangi, 2020; Sharma et al., 2015).

Children with special needs required extra attention during the COVID situation. Kadarisma & Juandi proposed a qualitative approach to describe the mathematics learning process for visually-impaired children during the pandemic. They conducted interviews with teachers to obtain information on teaching materials used by them during the COVID pandemic. The results demonstrated that at the beginning of the pandemic, Alam Bandung School implemented online learning but students faced issues during video lectures. Mutiara Bunda School also used online learning through Google Meetings and assessment collection by Google Classroom. Some teachers use their learning platform (i.e., home learning guides) to provide support to the children. Overall, student learning capabilities are decreased especially in mathematics as compared to traditional teaching methods before the pandemic (Kadarisma & Juandi, 2021).

Rett Mcbride has discussed the finding of two articles, one of which is related to the preparation of Teachers while the second is associated with the impact of the COVID-19 pandemic on the educational experiences of students. In the first study, forty-two teachers participated, half of whom reported that they have better abilities and experience to support mathematics students. Some reported that at the start they were not well prepared but slowly they increased their skills through self-study and professional development opportunities provided by their institutions. For the most part, they used large print or braille materials in the teaching and guidance of visually-impaired students. The second study investigated the impact of COVID-19 on different dimensions (i.e., parents concerns, access to material through technology and contacting teachers). The parents of visually impaired children are concerned about the education of their children because they lack the skills and training to educate their children at home. Parents also reported that they did not have adequate knowledge to access Braille material and mathematics educational tools. Some parents are satisfied with the teachers and instructors of their children, but others reported that the teachers don't have enough skills to understand the needs of their children (McBride, 2020).

2.4Remote Learning-based Educational Model for Visually-impaired Students

Before the COVID-19 pandemic, visually-impaired students could easily access teaching resources, lab facilities, and classroom environments. They could also have direct communication with their teachers during the classes. Unfortunately, during the pandemic, their learning process was changed.

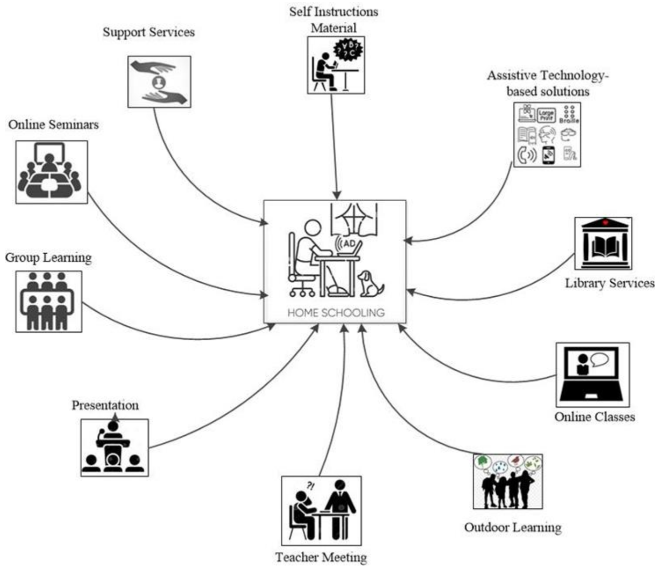

Figure 2.0.4: Remote Learning-based educational model

Figure 2.0.1 provides an overview of the remote learning-based educational model for visually-impaired students. In this model, the focus is shifted from classroom to homeschooling. Students can connect with educational facilities through the Internet. These educational facilities are online classes, assistive technology-based solutions, library services, outdoor learning, self-instruction material, support services, online seminars, group learning, presentations and meetings with teachers.

*2.5*COVID-19 resources and tips for remote learning

Table 2.0.1 provides a list of useful learning resources for visually-impaired students. These resources are available on the web portals of several institutes i.e., Michigan Department of Education, The California School for the Blind, Training and Technical Assistance Centers, National Council for Special Education, Paths to Literacy for students who are blind or visually impaired and Special educational needs and disabilities. Visually-impaired students normally use these resources at their homes during the pandemic.

Table 2.0.2: Resources along with the short description

Name	Description
Michigan Department of Education[14]	These resources are collected by MDE staff members. These are very useful for families of visually-impaired students and school personnel.
The California School for the Blind[15]	These are very useful resources for remote, virtual and home learning.
Training and Technical Assistance Centers(TTAC) Online[16]	These resources have a lot of stay-at-home activities that are very useful for visually-impaired children.
National Council for Special Education(NCSE)[17]	They provide many online resources i.e., curriculum, outdoor and active learning. These resources are also very useful for visually-impaired children.
Paths to Literacy | for students who are blind or visually impaired[18]	They provide several online resources for educators and students i.e math games & activities for home.
Special educational needs and disabilities (SEND)[19]	They provide very convenient COVID-19 related resources.

Table 2.0.2 provides a list of important remote and virtual learning-based tips that are very beneficial for visually-impaired students. These tips are listed from different electronic sources and articles that are part of our study.

[1] https://mdelio.org/blind-visually-impaired/other-resources/covid-19-resources

[2] https://www.csb-cde.ca.gov/resources/covid-19/parentvirtualresources.aspx

[3] https://ttaconline.org/Resource/JWHaEa5BS741JNaLDkgnuA/Resource-stay-at-home-activities-for-children-with-visual-impairments-paths-to-literacy-for-students-who-are

[17] https://ncse.ie/all-online-resources

[5] https://www.pathstoliteracy.org/resources/online-learning-opportunities-schools-blind-and-related-organizations

[6] https://www.sthelens.gov.uk/send/support-services/visual-impairment-service/covid-19-useful-resources-for-children-with-a-visual-impairment/

Table 2.0.2: Virtual Learning Tips for Visually Impaired Learners

Sr. No	Virtual Learning Tips
1	Proper Training for the online classroom.
2	Use communication options properly i.e., Zoom and Microsoft.
3	Proper use of assistive technology on top of the online classes i.e., use JAWAS
4	Online tools should be compatible with screen-reading software.
5	Use printed/magnified worksheets for braille users.
6	The whole print material should be clear and dark.
7	In colour contrast, black and white is the best option.
8	Provide a clear verbal explanation.
9	Introduce more oral activities and exercises.
10	A time limit should be more to complete the tasks.
11	Call the student's name when requires his/her attention.
12	Provide proper training to students.
13	Introduce peer tutoring to support the students.

*2.6*Overall Educational Experience with Remote Learning

Figure 2.0.2 provides a complete overview of the educational experience through remote learning. Firstly, to obtain the desired learning outcomes from any online platform, it is important to consider the teaching perspective. Several important aspects should be kept in mind when designing a better online learning platform i.e., effective pedagogical approach, suitable use of technology, flexible learning environment and providing better assessment opportunities (Ducan & Barnett, 2009; Jin, 2005; Chieu et al., 2011; Uribe et al., 2017). Secondly, some studies suggest that several aspects of social presence are important in remote learning, i.e., teacher and student involvement, belongingness, community, and participation during online sessions (Hramiak, 2010; Komninou, 2018; Li, 2011; Satar & Akcan, 2018; Yeh, 2010). Thirdly, some articles addressed issues relating to cognitive skills, such as students need good cognitive skills to benefit from the teaching, critical reflection, where learning is based upon watching, listening and engaging students by practising, doing, and thinking (Ryan & Scott, 2008; Sing & Khime, 2006; Jones & Ryan, 2014; Dyment & Downing, 2018). Fourthly, some studies examined the concerns of students, and these included enhanced collaboration between student and teacher, creating interpersonal relationships, and enhancing engagement during online learning (Mumford & Dikilitaş, 2020; Farr & Riordan, 2015; Jones, 2010). Moreover, once the institutes switched their educational structure from face-to-face to online during COVID-19 then the parents of the students also faced issues with this transition. Some countries researched this such as the government of Luxembourg, which switched to online instruction in response to the COVID-19 pandemic. Their Ministry of Education ran a survey which revealed that more than half of the parents had issues using remote teaching with their children. To address this issue Haas et al., used augmented reality, digital and physical-mathematical models in online learning of mathematics for primary schools. They focused on how parents can help their children access various educational instructions remotely. They suggested in online teaching parent perspective is important to enhance learning designs and associated pedagogical approaches (Haas, 2023).

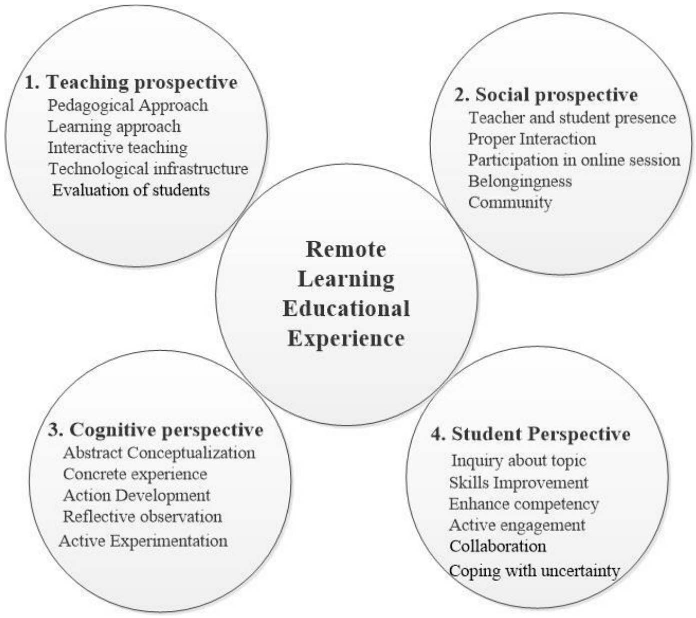

Figure 2.0.2: Educational Experience with Remote Learning

2.6.1 Analysis of Remote Learning During COVID

Nowadays, the educational sector faces many challenges due to the COVID-19 pandemic. Remote learning is quite useful to address these challenges. Mathematics is a very important domain of education because students have to acquire essential knowledge and skills i.e., geometry, calculus, graphs, numbers and algebra. Visually impaired students can access this information through digital and assistive technologies.

The main strength of online learning is to provide better opportunities and address the challenges faced during this time by enabling learners to customize procedures and processes.

Remote learning has several weaknesses i.e., technical issues, time management and lack of personal attention. Remote learning provides many opportunities to various educational institutes in a smooth transition from traditional education methods to online educational platforms. Teachers and students can communicate better with one another through assistive technologies. Due to this paradigm shift, a lot of new opportunities are available for researchers and developers to introduce new solutions. Many challenges are also associated with online education. These challenges can be faced by students, teachers and developers. There are different kinds of challenges i.e., lack of digital knowledge, changing the teaching methodologies, engaging students and technological costs. Figure 2.0.3 provides an analysis of remote learning during the pandemic and demonstrates the strengths, weaknesses, opportunities, and challenges associated with this situation.

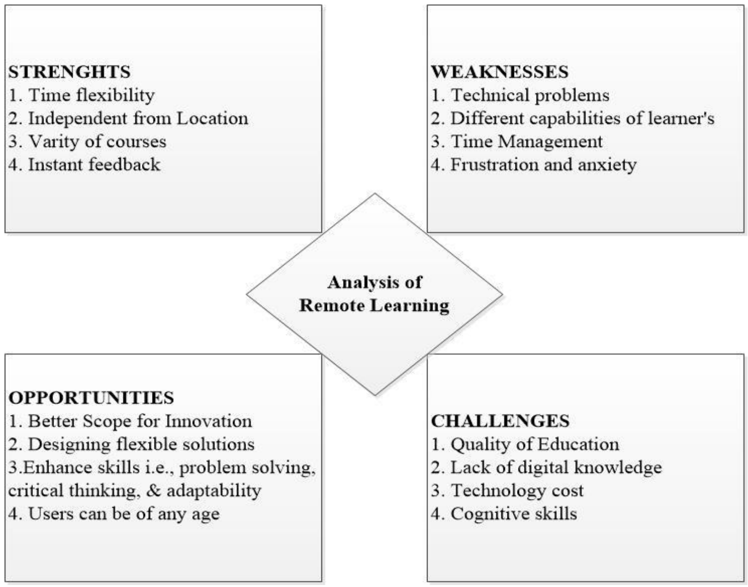

Figure 2.0.3: Analysis of Remote Learning

2.7Discussion

Many nations around the globe have adopted remote learning instead of face-to-face classes during the COVID-19 pandemic. This transition is very challenging for visually impaired students because they have special needs to access and learn mathematics. Teachers of visually impaired students played an important role during this challenging time. They have utilised a variety of resources and methods, such as screen readers, Braille materials, audiobooks and online math applications to facilitate visually impaired students through remote learning. This study has provided a remote learning-based educational model for visually impaired students.

This model illustrated that the focus shifted toward homeschooling during the pandemic situation. Visually impaired students can attend online classes, access various services (i.e., library and support services) and use different assistive technology-based solutions whilst studying remotely.

We have carefully reviewed and considered the particular requirements and challenges of visually impaired students during remote learning. We have also explored the important resources and tips that were useful for visually impaired students during COVID-19. Visually impaired students have accessed the mathematical content with the help of accessible materials i.e., screen readers, audiobooks, text-to-speech and magnification software. Visually impaired students have regularly maintained communication with their peers and teachers by using smartphones and video conferencing tools. Teachers were also able to provide them with clearer feedback on assignments to ensure that they were on track. This process helped them all to enhance their collaboration with each other. It was also noted that schools, colleges and universities also provided additional training and support to both teachers and students. This training and support helped them in understanding of remote learning platform. After that training, their abilities to use assistive technology-based solutions and accessible materials were enhanced.

In the context of earlier studies, a comprehensive model was designed to demonstrate the overall educational experience with remote learning. Four important aspects (i.e., teaching, social, cognitive and student perspective) were considered for effective online teaching and learning. Teaching perspective is very important during the designing of a remote learning platform. Better integration of technology and appropriate pedagogical approach are the key factors determining the effectiveness of the e-learning platform in teaching and learning. Social and cognitive perspectives enable teachers and students to maintain a better interpersonal relationship, trust and perceive knowledge development (according to the cognitive skills of the students). According to the student perspective, the learning process can be maximized by providing better support and interaction mechanisms to the students.

2.8Conclusion

Remote learning of mathematics for visually impaired students during COVID-19 has highlighted a significant number of new issues. To cover them in this study, a remote learning-based educational model was introduced that showed the focus shifted toward homeschooling during COVID-19. This study also highlighted some important pandemic resources and tips to enhance the learning skills of visually impaired students. Moreover, a comprehensive model was developed to demonstrate the overall educational experience of visually impaired students with remote learning in mathematics.

Furthermore, a detailed analysis was conducted to examine the strengths, weaknesses, opportunities, and challenges of remote learning during the COVID-19 pandemic. Remote learning was a powerful tool in the pandemic situation. It's quite a flexible approach in the context of location and time. It's a student-centred approach and can be customized according to their needs. Remote learning platforms provide a very interactive environment by using several functionalities i.e., audio, video, touch and vibrotactile feedback. Students can easily raise queries, ask questions of their instructors and access course material from anywhere by connecting through the internet.

Some weaknesses are also associated with remote learning i.e., a communication gap between student and teacher, lack of face-to-face interaction, discipline behaviour due to time flexibility, lack of technical skills, and different cognitive and confidence levels of students. Additionally, numerous opportunities are also available for remote learning i.e., innovation in e-learning, digital solutions development, introducing flexible solutions, effective management of the critical situation, increasing market demand and providing effective ways of teaching, learning, evaluation, assessment and so on.

Lastly, there are many challenges in remote education for students, teachers, parents, institutions, government, developers and researchers. Students require quality education, teachers want to implement their teaching methodologies, parents wish to be a part of remote learning, institutions aim to provide a better platform for learning, the government wants to implement their educational policies, developers want to tackle the concerns of stakeholders and researchers always try to find an innovative solution of the problems. These are the key areas where researchers and developers can work and design efficient educational systems for visually impaired students.

2.9 Future Work

Currently, lack of direct interaction with teachers is a major issue in remote learning. Researchers can introduce new innovative ways of interaction to overcome this issue. Specialized tools and applications are expensive and not readily available for visually impaired students. Developers can introduce easily accessible and cheaper solutions for visually impaired students. Furthermore, providing teachers with professional training and promoting a collaborative learning environment among visually impaired students can also facilitate remote learning in visually impaired students.

Appendix C: Information Sheets and Concent Forms

INFORMATION SHEET STUDENT

UCC

University College Cork, Ireland

Coláiste na hOllscoile Corcaigh

Purpose of the Study. This study aims to explore the experiences of mathematics students in primary education with a particular focus on the problems faced by blind and visually impaired students learning numbering skills in mathematics. We hope to gain a greater understanding of the barriers involved, the strategies currently used to tackle these barriers, and the types of enablers that may be helpful. This knowledge will then be used in the development of appropriate technology-based solutions.

What will the study involve? This study involves asking visually impaired and blind students to fill in a questionnaire and take part in an interview.

Why have you been asked to take part? You have been asked because the study concerns the teaching and learning of mathematics in primary schools.

Do you have to take part? Participation is voluntary. If you choose to take part, you can change your mind and withdraw at any stage, either before the study begins or during the study procedure. If you decide to withdraw part-way through a trial, all information gathered from you will be discarded. If you decide after taking part that you do not want your data used, you can ask that all data gathered from you be destroyed. You can do this anytime up to two-weeks after the study has taken place.

Will your participation in the study be kept confidential? Yes. Only summary data from the study will be presented in a thesis or other publication, and there will be nothing to identify individual participants. Any extracts from what you say that are quoted will be entirely anonymous.

What will happen to the information which you give? It will be stored in a secure UCC computer server. On completion of the research project, the data will be retained for a minimum of a further ten years and then destroyed.

What will happen to the results? The results may be published in a research journal. They may also be presented at conferences on educational practice, eLearning, etc. However, the identity of the individuals taking part, and any data gathered during the study which might allow them to be identified, will only be available to the experimenters and will not be published in any form.

What are the possible disadvantages of taking part? I don't envisage any negative consequences for you in taking part.

What if there is a problem? At the end of the procedure, the experimenter will discuss with you how you found the experience and how you are feeling. If you subsequently feeldistressed, you should contact Muhammad Shoaib (see below).

Who has reviewed this study? Approval must be given by the Social Research Ethics Committee of UCC before studies like this can take place.

Any further queries? If you need any further information, you can contact the following persons: Ian Pitt, School of Computer Science & Information Technology, University College Cork; email: ianp@cs.ucc.ie; telephone (021) 420 5904. Muhammad Shoaib, School of Computer Science & Information Technology, University College Cork; email: muhammad.shoaib@cs.ucc.ie; telephone (089) 9785378.

If you agree to take part in the study, please sign the consent form overleaf. [Ove

INFORMATION SHEET TEACHER

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Purpose of the Study. This study aims to explore the experiences of mathematics teachers in primary education with a particular focus on the problems faced when teaching blind and visually impaired students. We hope to gain a greater understanding of the barriers involved, the strategies currently used to tackle these barriers, and the types of enablers that may be helpful. This knowledge will then be used in the development of appropriate technology-based solutions.

What will the study involve? This study involves asking teachers of visually impaired and blind students to fill in a questionnaire and take part in an interview.

Why have you been asked to take part? You have been asked because the study concerns the teaching and learning of mathematics in primary schools.

Do you have to take part? Participation is voluntary. If you choose to take part, you can change your mind and withdraw at any stage, either before the study begins or during the study procedure. If you decide to withdraw part-way through a trial, all information gathered from you will be discarded. If you decide after taking part that you do not want your data used, you can ask that all data gathered from you be destroyed. You can do this anytime up to two weeks after the study has taken place.

Will your participation in the study be kept confidential? Yes. Only summary data from the study will be presented in a thesis or other publication, and there will be nothing to identify individual participants. Any extracts from what you say that are quoted will be entirely anonymous.

What will happen to the information which you give? It will be stored in a secure UCC computer server. On completion of the research project, the data will be retained for a minimum of a further ten years and then destroyed.

What will happen to the results? The results may be published in a research journal. They may also be presented at conferences on educational practice, eLearning, etc. However, the identity of the individuals taking part, and any data gathered during the study which might allow them to be identified, will only be available to the experimenters and will not be published in any form.

What are the possible disadvantages of taking part? I don't envisage any negative consequences for you in taking part.

What if there is a problem? At the end of the procedure, the experimenter will discuss with you how you found the experience and how you are feeling. If you subsequently feeldistressed, you should contact Muhammad Shoaib (see below).

Who has reviewed this study? Approval must be given by the Social Research Ethics Committee of UCC before studies like this can take place.

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If you agree to take part in the study, please sign the consent form overleaf. [Over.

INFORMATION SHEET DOMAIN EXPERTS

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Purpose of the Study. This study aims to explore the experiences of people working in organizations concerned with the teaching of mathematics to blind and visually impaired students. We hope to gain a greater understanding of the barriers involved, the strategies currently used to tackle these barriers, and the types of enablers that may be helpful. This knowledge will then be used in the development of appropriate technology-based solutions.

What will the study involve? This study involves asking domain experts to fill in a questionnaire and take part in an interview.

Why have you been asked to take part? You have been asked because the study concerns the teaching and learning of mathematics in primary schools.

Do you have to take part? Participation is voluntary. If you choose to take part, you can change your mind and withdraw at any stage, either before the study begins or during the study procedure. If you decide to withdraw part-way through a trial, all information gathered from you will be discarded. If you decide after taking part that you do not want your data used,you can ask that all data gathered from you be destroyed. You can do this anytime up to twoweeks after the study has taken place.

Will your participation in the study be kept confidential? Yes. Only summary data from the study will be presented in a thesis or other publication, and there will be nothing to identify individual participants. Any extracts from what you say that are quoted will be entirely anonymous.

What will happen to the information which you give? It will be stored in a secure UCC computer server. On completion of the research project, the data will be retained for a minimum of a further ten years and then destroyed.

What will happen to the results? The results may be published in a research journal. They may also be presented at conferences on educational practice, eLearning, etc. However, the identity of the individuals taking part, and any data gathered during the study which might allowthem to be identified, will only be available to the experimenters and will not be published in any form.

What are the possible disadvantages of taking part? I don't envisage any negative consequences for you in taking part.

What if there is a problem? At the end of the procedure, the experimenter will discuss with you how you found the experience and how you are feeling. If you subsequently feeldistressed, you should contact Muhammad Shoaib (see below).

Who has reviewed this study? Approval must be given by the Social Research Ethics Committee of UCC before studies like this can take place.

Any further queries? If you need any further information, you can contact the following persons: Ian Pitt, School of Computer Science & Information Technology, University College Cork; email: ianp@cs.ucc.ie; telephone (021) 420 5904. Muhammad Shoaib, School of Computer Science & Information Technology, University College Cork; email: muhammad.shoaib@cs.ucc.ie; telephone (089) 9785378.

If you agree to take part in the study, please sign the consent form overleaf. [Over

CONSENT FORM

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

I ....agree to participate in Muhammad Shoaib's research study.

The purpose and nature of the study have been explained to me in writing. I am participating voluntarily.

I am aware that the researchers would like to record my responses, and have indicated whether or not I consent to this below.

I understand that I can withdraw from the study, without repercussions, at any time, whether before it starts or while I am participating.

I understand that I can withdraw permission to use the data within two weeks of the interview, in which case the material will be deleted.

I understand that anonymity will be ensured in the write-up by disguising my identity.

I understand that disguised extracts from my interview may be quoted in the thesis and any subsequent publications if I give permission below:

I agree to the quotation/publication of extracts from my interview.	☐ yes	☐ no
I agree that the interview may be recorded (recordings will be deleted once the transcription is complete)	☐ yes	☐ no

Signed: ……………………………………. Date: ……………….. PRINT

NAME: …………………………………….

CHILD ASSENT FORM

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

I………………………… [name in CAPS] agree to take part in the research study.

I understand what the study is about, and it has been clearly explained to me.

I am participating voluntarily.

I undertake to maintain the confidentiality of the interview /.

It's fine if I drop out of the study, and I do not have to give any reasons for this.

I understand that the information collected are for research and teaching purposes only for the project. I have the right to see these data, change them, or ask that they be deleted and not used.

•I can withdraw permission to use the data from the study at any time up to within two weeks after the interview / focus group / survey is completed, in which case the material will be deleted.

•For a focus group, I understand that no guarantees can be offered to withdraw my information as it may be hard to pick out my voice on the audio.

•I understand that with anonymised survey's it will not be possible to delete my data if I change my mind.

•If I change my mind and want to withdraw after a report has been published, my material cannot be removed from the reports, but the research team will not use it in any future work or analysis.

I understand that nobody will know it's me in the results or report because my name or any other identifying information will not be linked to my survey answers. I understand that my parent(s) / legal guardian(s) must also consent before I can take part in the study.

Signed: ……………………………………. Date: ……………….. PRINT

NAME: …………………………………….

☐ Yes, I consent to take part in this study.

☐ No, I do not consent to take part in this study.

CONSENT FORM(Participants and guardians)

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

I --hereby consent to participate in Muhammad Shoaib's research study.

I have received a written explanation regarding the purpose and nature of the study, and I am participating voluntarily.

I am aware that the researchers may wish to record my responses, and I have indicated below whether I consent to this:

[ ] I consent to the recording of my responses.

[ ] I do not consent to the recording of my responses.

I understand that I have the right to withdraw from the study at any time, without facing any repercussions, whether before it commences or while participating.

I acknowledge that I have the option to revoke permission to use my data within two weeks of the interview, after which the material will be deleted.

I understand that my identity will be kept anonymous in any written reports or publications.

I hereby grant permission for disguised extracts from my interview to be quoted in the thesis and any subsequent publications:

☐ yes ☐ no

I also give consent for the interview to be recorded, with the understanding that recordings will be deleted once transcription is complete:

☐ yes ☐ no

Signed: ……………………………………. Date: ……………….. PRINT

NAME: …………………………………….

Appendix D: Questions asked for each stakeholder group in qualitative interviews

a. Experience of primary students with mathematics education

1. Tell me about your most favourite topic in mathematics and why you like it.
2. Tell me about your least favourite topic in mathematics and why it's your least favourite.
3. Do you receive any additional assistance during learning mathematics at school?
4. If yes, tell me what kind of assistance you receive.
5. Tell me about how you would like to participate in the math class (i.e., raise your hand, do group work or ask questions?
6. What kind of activities do your teachers use to engage their students in the classroom?
7. Does working with other people in your class help you in learning mathematics?
8. Do your family members help you in doing your homework in mathematics?
9. What makes learning mathematics challenging for you?
10. What challenges have you faced when seeking assistance from your mathematics teacher?
11. Do you feel learning mathematics is difficult for you?
12. If yes, then tell me what kind of things makes it difficult for you.
13. What kind of technology platform do you prefer to have for you?
14. What kind of technology solutions do you prefer to use (please tick all that apply)?
15. Please list the names of the applications which you find most helpful when learning mathematics.
16. Tell me about things you like in applications.
17. How effective is each functionality for you?
18. Have you found any simple techniques or methods that help you fulfil your mathematics learning needs? If so, please describe them.
19. Some people say mathematics is a difficult subject, what do you think?

b. Experience of primary teachers with mathematics education

1. What type of non-digital teaching-learning resources are available to help in

learning mathematics at your school for visually impaired students?

2. What type of digital teaching-learning resources are available to help in learning mathematics at your school for visually impaired students?
3. In your opinion, what are the main problems for visually impaired students in learning mathematics during their primary level?
4. What barriers, obstacles, and challenges do you face during teaching mathematics to visually impaired students?
5. How do you deal with the barriers, obstacles, and challenges?
6. Do you find that have to make additional effort to enable blind and visually-impaired students to understand numbering topics in mathematics (compared with teaching the same topics to other students)?
7. Could you suggest possible ways that are helpful to make the learning of numbering skills more accessible for visually impaired students?
8. What kind of technology platform do you prefer to have for your students?
9. What kind of technology solutions do you prefer to have for your student (please select the appropriate options below)?
10. What specific features or functionalities would you find helpful in mathematics solutions to enhance your students learning experience?
11. What forms of assessment do you use to assess students' mathematical skills?
12. How do you support students with visual impairments in building relationships with their peers?
13. Would you like to share some useful strategies which better support students in learning mathematics?
14. In your opinion, what support is most helpful?
15. Can you suggest any creative approaches for designing mathematics solutions that could cater to the specific needs of learning numbering skills for visually impaired students?

c. Experience of focus group domain experts with mathematics education

1. Some people say mathematics is a difficult subject, what do you think?
2. What type of non-digital resources does your organization have or recommend for visually impaired students, specifically for learning mathematical skills?
3. What type of digital and technology-based solutions does your organization have or recommend for visually impaired students specifically for learning

mathematical skills?

4. Do you feel that the teaching and learning of mathematics has changed since your childhood (e.g., did you find it difficult when you were at school, but feel it is easier now because new technologies have changed the nature/focus of mathematics teaching)?
5. In your opinion, what are the main challenges for visually impaired students in learning numbering skills during their primary level?
6. Would you like to suggest some important guidelines/methods for developers that could make learning mathematics more accessible for visually impaired students?
7. What kind of technology platform do you prefer to have for your students?
8. What kind of technology solutions do you prefer?
9. What specific features or functionalities would you find helpful in mathematics solutions to enhance your student's learning experience?
10. Would you like to share some useful strategies which better support students mathematics education in visually impaired students?
11. In your opinion, which kind of support is required by visually impaired students during learning mathematics?
12. In your opinion, what do you feel is missing from the currently available solution for visually impaired students?
13. Can you suggest any creative approaches for designing mathematics solutions that could cater for the specific needs of visually impaired students?

Appendix E: Transcript of Experience of primary student A with mathematics education

1. Tell me about your most favourite topic in mathematics and why you like it.

Comparing, Ordering and Matching are my favourite topic. I like to adding up tens of gigs and done the symmetry, some money. Okay. There are some topics we haven't come across yet. Like geometry Yeah.

2. Tell me about your least favourite topic in mathematics and why it's your least favourite.

Reading graphs is my favourite topic

3. Do you receive any additional assistance during learning mathematics at school?

Yes

4. If yes, tell me what kind of assistance you receive.

Sometimes I'm read questions. Sometimes Mr T1 when doing basic math. Help during shapes. Mr T1 call the name of the shap and I have to pick the shape like like a cube, if I pick a different share the Mr T1 Help me. I learn the numbers, addition and subtractions by using the coins as well. Mr T1 try to makes the things tangible to learn them easily.

5. Tell me about how you would like to participate in the math class (i.e., raise your hand, do group work or ask questions?

Just shouts the name of the teacher, I also like to work in groups. I enjoy solving math problems with my friends because they describe the shapes for me.

6. What kind of activities do your teachers use to engage their students in the classroom?

He do like Coins (numbers greater than less than), shapes, measuring, reading text books

7. Does working with other people in your class help you in learning mathematics?

Yes, I like to work with my friends

8. Do your family members help you in doing your homework in mathematics?

Yes, help me in reading books. Help me in learning tables every night like 3 and 3 6, 5 and 5 10, 7 and 7 14, 8 and 8 16 , 9 and 9 18 and 101 and 10 20,. Everybody gets more homework and I have a bit less from others. I also do my homework during after school.

9. What makes learning mathematics challenging for you?

Yeah, I like it. This is interesting subject, but maybe sometime it's challenging like learning graphs. Sometimes I can't keep up when the teacher writes on the board, I miss what was drawn and I fall behind

10. What challenges have you faced when seeking assistance from your mathematics teacher?

Looking to read the question for me. If I am holding a shape then I need assistance to know how many sides and edges it has.

11. Do you feel learning mathematics is difficult for you?

Yes

12. If yes, then tell me what kind of things makes it difficult for you.

I don’t have electronic equipment’s. I feel without the tangible objects learning mathematics is very difficult.

13. What kind of technology platform do you prefer to have for you?

Smartphone and Tablet

14. What kind of technology solutions do you prefer to use (please tick all that apply)?

Games

15. Please list the names of the applications which you find most helpful when learning mathematics.

A scan pen that can read the text for me. I like 3D printers and Braille Embossers. Playing the game on a smartphone, so once you use the headphones and listen to the sound, this feedback is good, as I also have the speech.

16. Tell me about things you like in applications.

Speech feedback, VibroTactile feedback and Voice command input

17. How effective is each functionality for you?

Speech Feedback, vibro-tactile feedback, and Voice command input are very effective.

18. Have you found any simple techniques or methods that help you fulfil your mathematics learning needs? If so, please describe them.

I have never used a screen reader. Like a scan pen I want to scan the picture and it will give me information about this in audio form. So something that gives me information in voice or I can learn it through play again. Something provides you the feedback in vibration.

19. Some people say mathematics is a difficult subject, what do you think?

Sometimes its easy when I use 100 Square (Hundred Square) sometimes it difficult when I was doing graph and large number addition.

Thematic Analysis of the Student A Interview

We applied Braun and Clarke's six-phase reflexive thematic analysis (RTA) to the student interview. In **Phase 1** (Familiarisation), we read the transcript repeatedly, noting our initial impressions (e.g., the student emphasizes the use of tactile aids and social support). According to Braun & Clarke, familiarisation involves "reading through each data item and making a note of things of potential interest". For example, we repeatedly observed that the student mentions coins, shapes, and tangible objects, suggesting a focus on non-visual learning methods.

Phase 2 (Generating Initial Codes) involved systematically coding the data. We labeled meaningful features of the text (quotations or ideas) with concise codes. For instance, we coded “using the coins… learn them easily” as Tactile aids/objects, and “I like to work in groups… friends describe the shapes” as Peer collaborative support. We noted both semantic codes (surface meanings) and latent codes (underlying concepts). Some initial codes included:

Tactile learning aids (coins, shapes, 3D printer, Braille tools),

Teacher support (reading questions, naming shapes),

Peer/family support (group work, friends describing shapes, family reading homework),

Visual accessibility challenges (difficulty with graphs, missing board content),

Assistive tech preferences (scan pen, speech/vibrational feedback, voice commands),

Attitudes towards topics (enjoys ordering/money, dislikes graphs).

These codes were collated with their data extracts in preparation for theme development.

Phase 3 (Searching for Themes) involved clustering codes into preliminary themes. We examined connections among codes and proposed candidate themes. For example, codes related to coins, shapes, and 3D printers clustered under a tentative theme, “Techniques and Methods to Fulfill Learning Needs,” reflecting the use of tactile tools. Codes related to group work, friends, and family fell under the category of “Collaborative Support and Engagement.” Codes related to graphs and missing board information suggested “Visual Access Barriers.” Codes about tech devices (scan pen, Braille embosser, speech feedback) formed a preliminary “Assistive Technology Use.” We also noted a theme centered on “Math Learning Attitudes” (enjoyment vs. challenge). This step “organizes the codes into initial themes,” clustering similar concepts to tell a coherent story.

Phase 4 (Reviewing and Developing Themes) required critically examining these candidate themes for coherence and depth. We reviewed each theme against the coded extracts and the whole transcript, as Braun & Clarke advise, to ensure we captured the data well. For example, we verified that “Techniques and Methods to Fulfill Learning Needs” was distinct from “Assistive Technology” or whether they should be merged. We interpreted the latent meanings: for instance, grouping “coins,” “Braille,” and “vibration feedback” into one theme reflects the student’s reliance on sensory-based supports due to visual impairment. In doing so, we moved beyond mere description to interpretation (latent coding), asking why these codes cluster. We also considered the researchers’ perspective, noticing that, as sighted analysts, we were drawn to the student’s emphasis on touch and sound as compensations for vision. Reflecting this, we refined theme boundaries. Themes were redefined only if they fully represented the data. For example, “Visual Access Barriers” was broadened to include not only graphs but also “board writing” and “lack of electronic equipment,” capturing any inaccessible visual content the student mentioned. Braun & Clarke emphasize checking if candidate themes make “a coherent pattern” and working for the entire dataset, which guided these refinements. Through this iterative review, we ensured that each theme was meaningfully represented in the data and removed or reworked any vague categories.

Phase 5 (Defining and Naming Themes) involved articulating the essence of each theme. We condensed our refined themes into clear, descriptive labels and definitions. For example:

Techniques and Methods to Fulfill Learning Needs: captures how the student utilizes physical, auditory, and tactile tools (such as coins, shapes, Braille embossers, and vibrotactile feedback) to learn math. We interpret this theme as the student’s active use of non-visual sensory inputs to access content, an insight supported by multiple quotes (e.g. “Mr T1… makes things tangible to learn them easily” and listing of tactile devices). This theme reflects a latent understanding that sensory aids mediate the student’s learning.

Class Collaboration Activities: encompasses codes about group work, peers describing shapes, and family help. We define it as the student’s reliance on social support teachers, friends, and family to understand math. For instance, the student says “I enjoy solving math problems with my friends because they describe the shapes for me,” indicating a deeper theme of community-based learning. This theme implies that, for this student, math understanding is co-constructed with others.

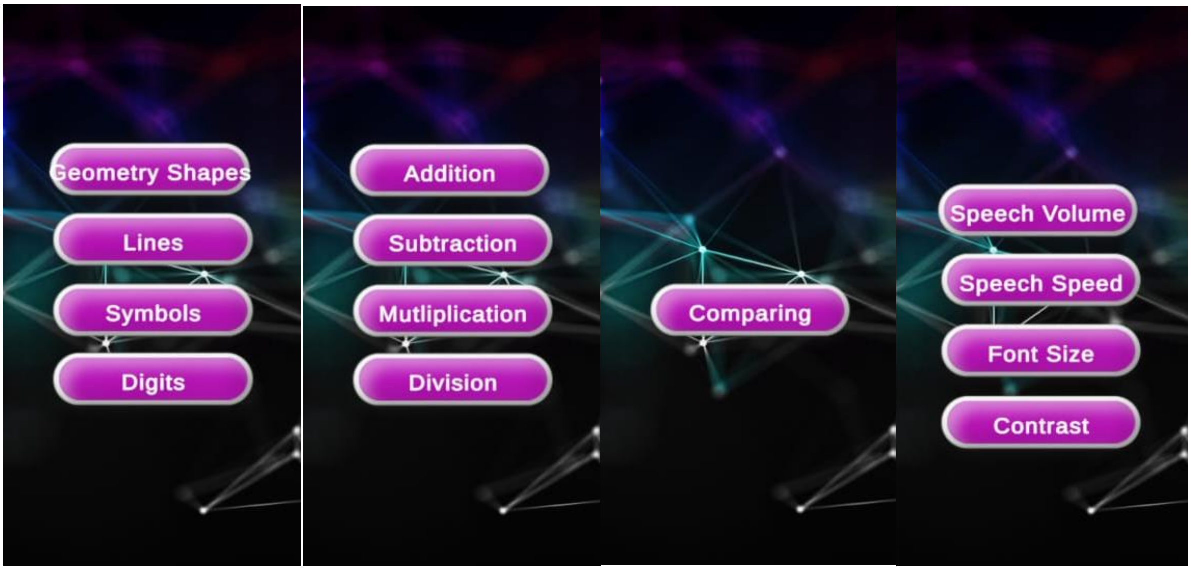
Challenges, Obstacles, and Issues: covers difficulty with graphs/board content and technology preferences. It reflects both the challenges the student faces (e.g. “Sometimes I can’t keep up when the teacher writes on the board”) and the desired solutions (e.g. preferring smartphones, voice feedback). We interpret this theme to mean that the student perceives math as difficult when it is presented visually, and therefore emphasizes specific tech or strategies to bridge that gap.

Techniques and methods to fulfill learning needs: (if considered separate) encapsulates mention of specific tech tools (scan pen, 3D printer, voice command). Defined as the student’s active preference for digital and assistive tech, it highlights a latent theme of empowerment through technology. Speech and tactile feedback are not just liked but are reported as “very effective,” suggesting they form an essential part of the student’s learning strategy.

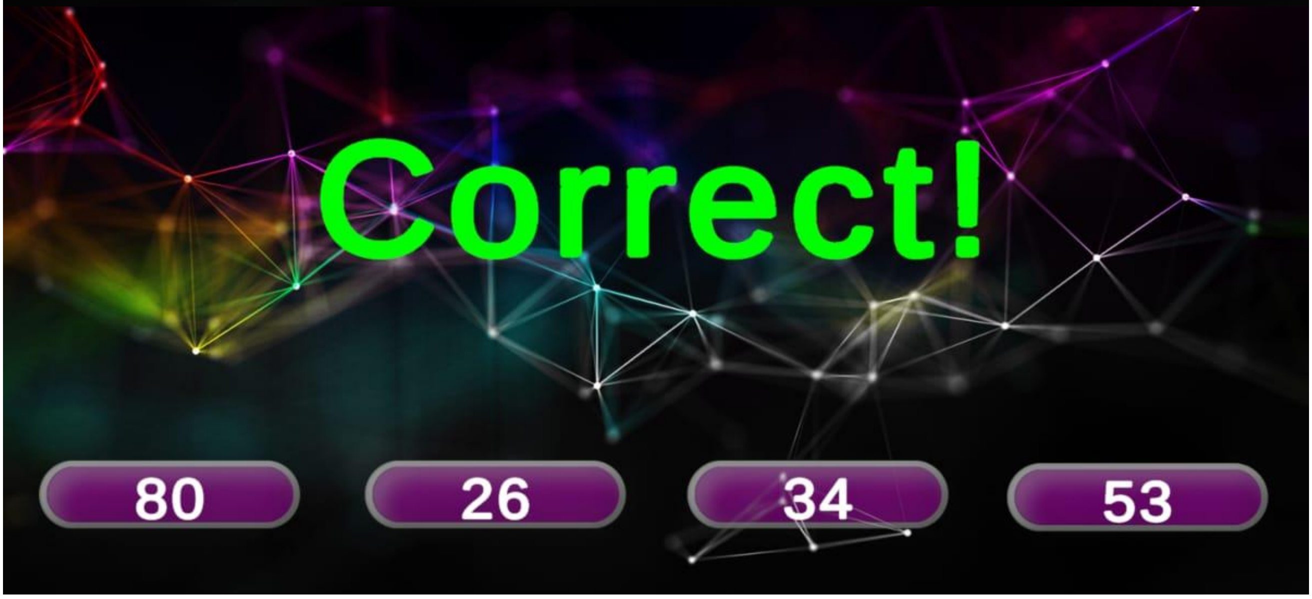
Phase 6 (Producing the Report) involves weaving these themes into a coherent narrative. In practice, we would illustrate each theme with selected quotes (e.g., the student's own words about tactile learning and group work) and embed our analysis within the context. For instance, under the Class Collaboration Activities theme, we would discuss the student's quote about friends describing shapes and analyze its implications for peer-assisted learning. Throughout, we ensure the analysis addresses the research focus (accessible math learning) and reflects on how the data answers the research questions, as recommended for the final write-up

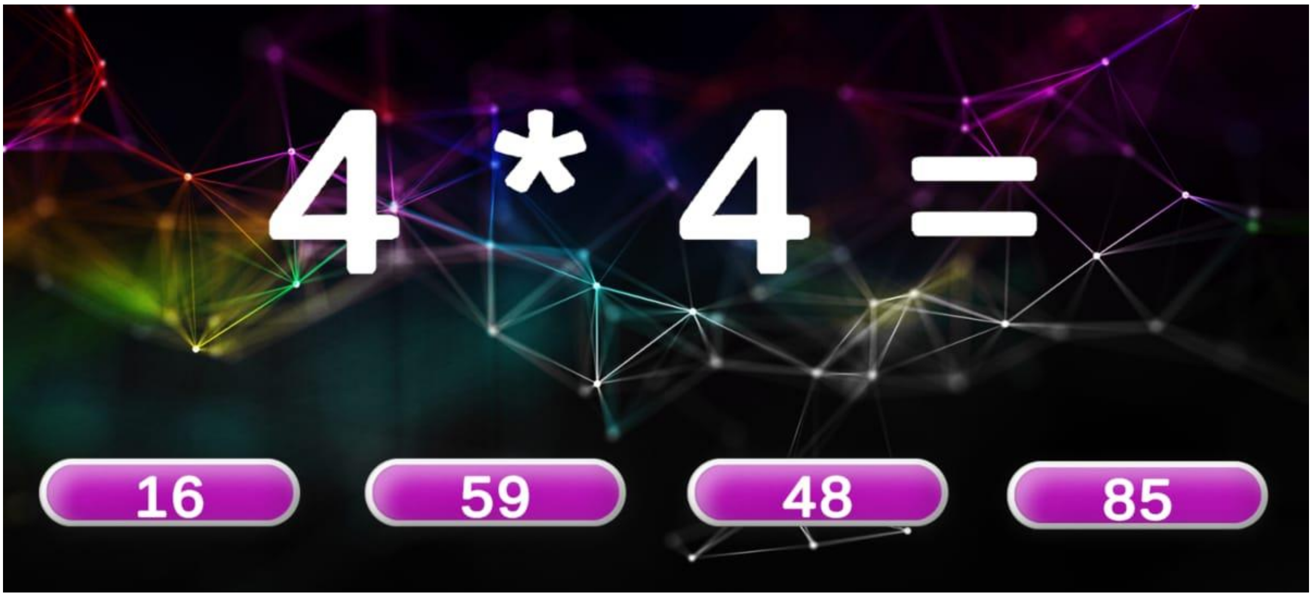
Appendix F: Screenshots of the AccessMath application

I have designed an application called AccessMath. On the Main Screen, we have Basic Operations (swipe up to open), Shapes & Digits (swipe down to open), Numbering (swipe left to open), and Settings (swipe right to open). A double-tap repeats the option, a triple-tap quits the application, and audio feedback is provided. On the Basic Operations Screen, we have Addition (swipe up to open), Subtraction (swipe down to open), Multiplication (swipe left to open), and Division (swipe right to open). A double-tap repeats the option, a triple-tap quits the application, and audio feedback is provided. On the Shapes & Digits Screen, we have Geometry Shapes (swipe up to open), Line (swipe down to open), Symbols (swipe left to open), and Digits (swipe right to open). A double-tap repeats the option, a triple-tap quits the application, and audio feedback is provided. On the Numbering Screen, we have Comparing (swipe up to open). A double-tap repeats the option, a triple-tap quits the application, and audio feedback is provided. On the Settings Screen, we have Speech Volume (swipe up to open), Speech Speed (swipe down to open), Font Size (swipe left to open), and Contrast (swipe right to open). A double-tap repeats the option, a triple-tap quits the application, and audio feedback is provided. Please see below the AccessMath Main Screen, Basic Operations Screen, Shapes & Digits Screen, Numbering Screen, Settings Screen and there funtionalaties.




40 + 40 =
80
26
34
53

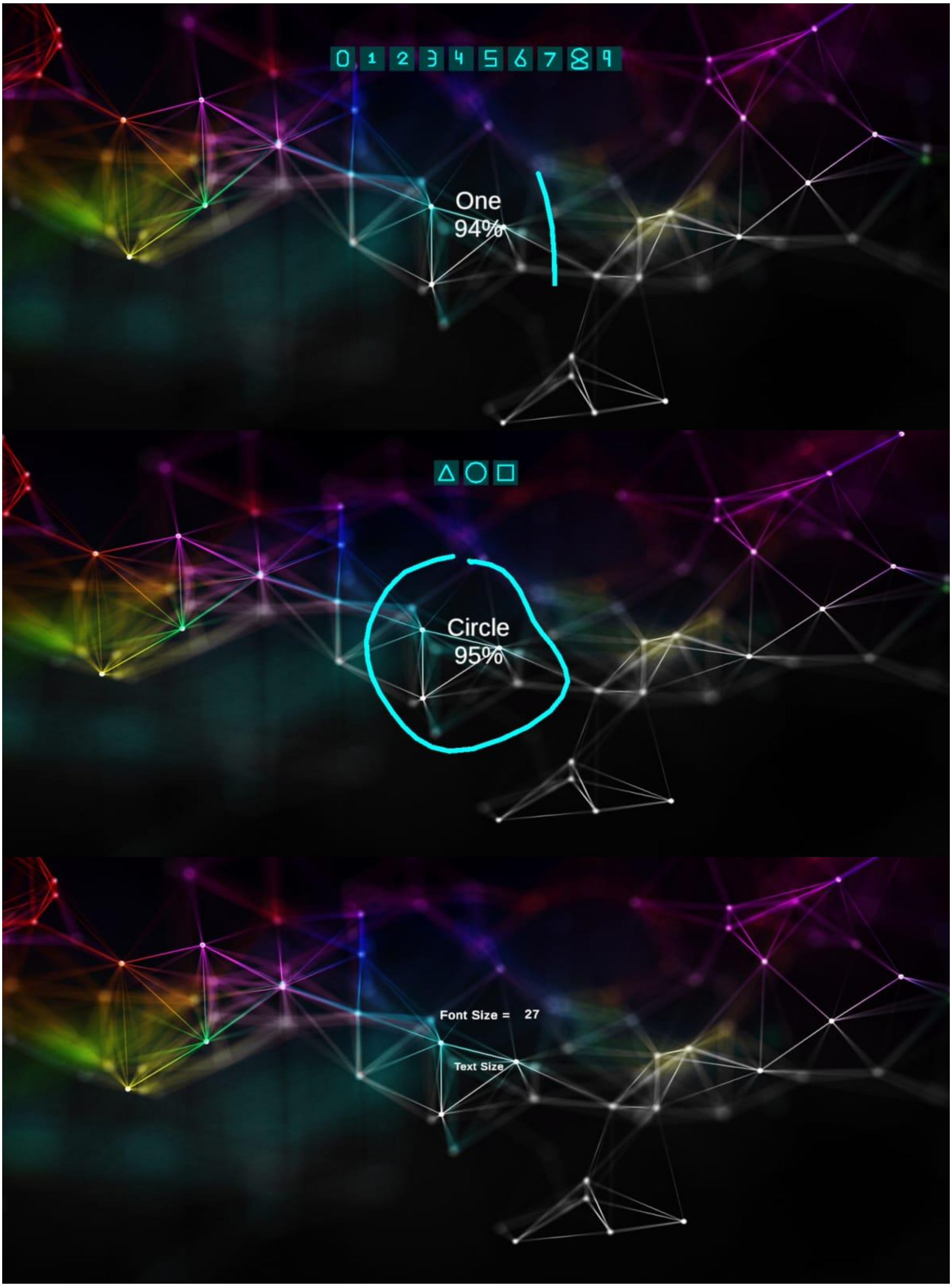

Correct!
80
26
34
53

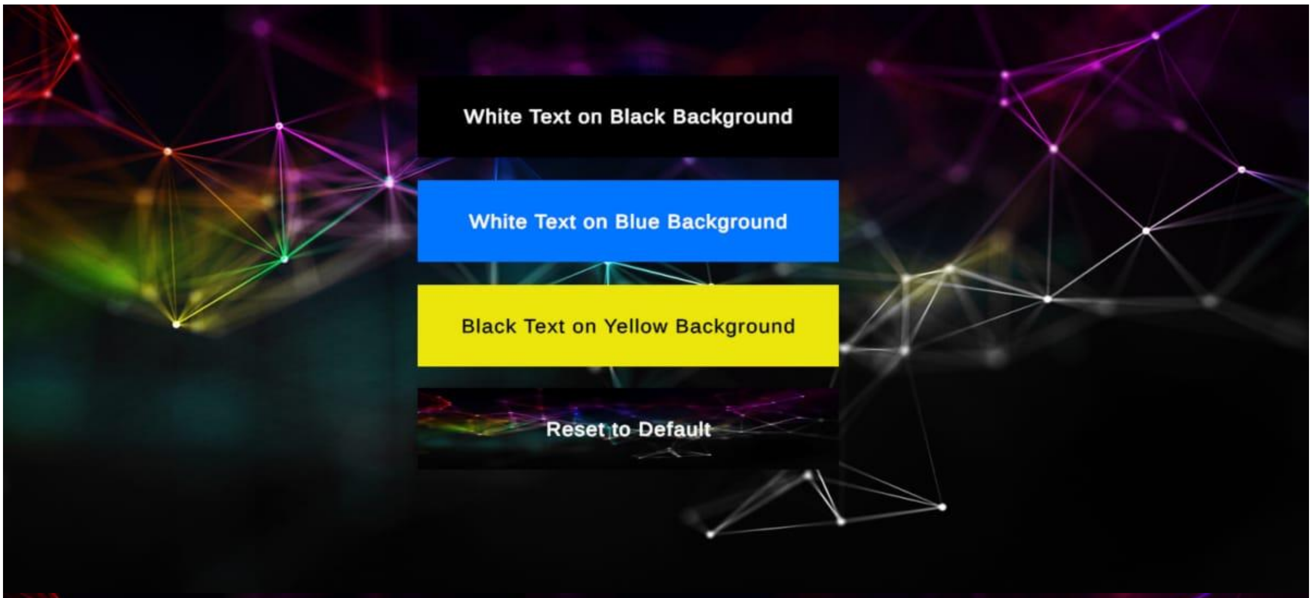

4 * 4 =
16
59
48
85

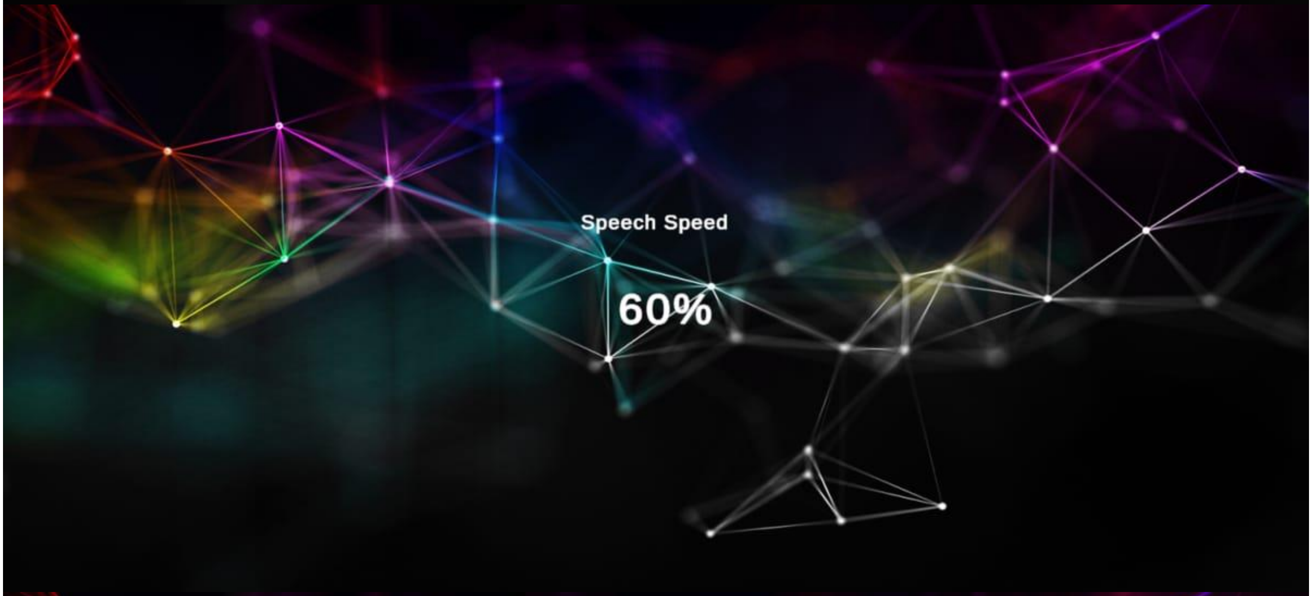

16 / 8 =
35
2
67
33

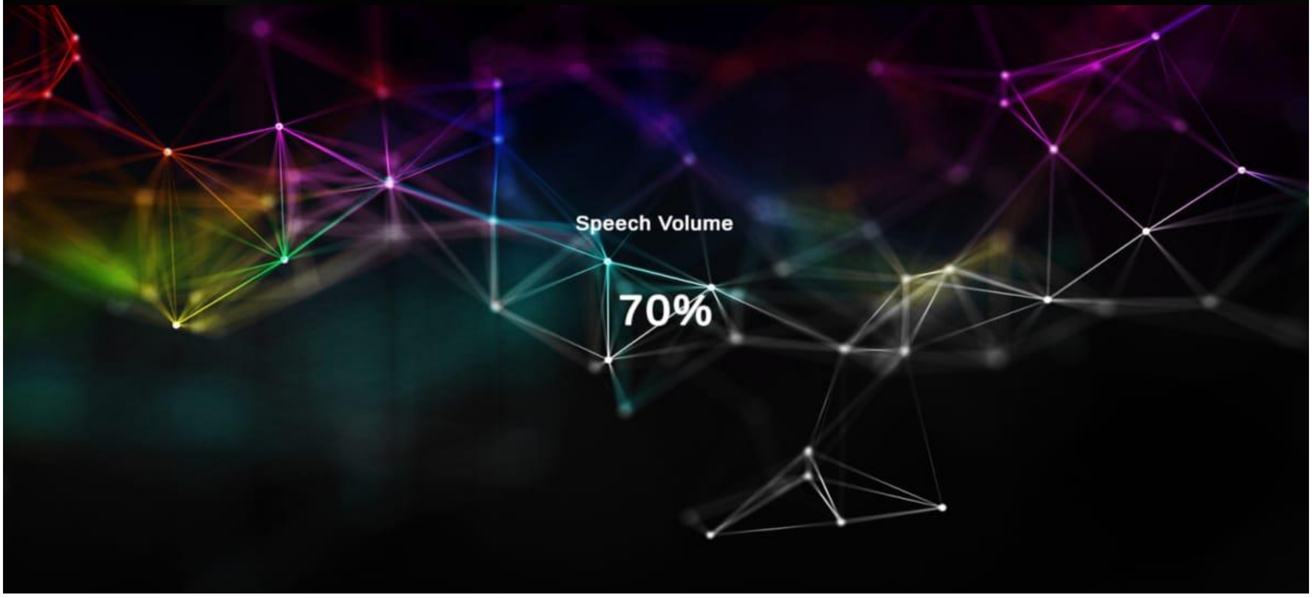

37 - 13 =
24
96
52
83


+ − × ⁄
Plus
89%


0 1 2 3 4 5 6 7 8 9
One
94%
Circle
95%
Font Size = 27
Text Size


White Text on Black Background
White Text on Blue Background
Black Text on Yellow Background
Reset to Default


Speech Speed
60%


Speech Volume
70%