Mathematics Learning Technologies for Students with Visual Impairments: A Literature Review

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***Abstract*—Students with Visual Impairment (VI) face many challenges in learning mathematics due to its visual nature. Digital-based learning technologies have reformed the mathematics learning experience for VI students. We collected, analyzed, and critiqued mathematics learning technologies for VI students developed between January 2010 and December 2020. We further classified apps by the domain, interactive features, and accessibility approaches to examine the teaching, learning, and assessment. We found that the audio-based and interactive e-learning technology may be helpful to improve the mathematical skills of VI students.**

***Index Terms*—Visually impaired students; Mathematics learning; Assistive technologies**

I. Introduction

The innovation of new learning technologies, recent improvements in Information and Communication Technologies (ICT), and digital resources has promoted self-directed learning for students. With the growing interest in self-directed learning, many developers, researchers, and universities have launched creative, flexible, and easy-to-learn programs to improve students' productivity.

Mathematics has been recognized as a formidable roadblock for students with visual impairment [1]. High-school mathematics acts as a baseline for students to learn and persevere in social and professional worlds. With technological advancements, ICT has provided many resources and educational tools such as graphics calculators, computers equipped with dynamic geography software, and web applications for virtual learning, contributing to an overall better learning experience in mathematics [2]. However, for students with visual impairment, the process is further hindered by the inability to process complex mathematical formulas or visual cues.

This disadvantage leads to a significant knowledge gap between students with visual impairment and students without disabilities. According to the U.S. Department of Education, as mentioned in [3], 15% of all visually impaired students are five or more grade levels behind their sighted peers. This knowledge gap leads to a staggering unemployment rate among disabled individuals. According to the employment data collected by American Foundation for the Blind (AFB) between May 2016 and April 2017, people with vision loss ages 16-64 had only a 37% labor force participation rate and a 12% unemployment rate [4]. According to [5], this gap does not emerge from a lack of interest in STEM-related fields because many college students showed equal interest in a STEM career as their non-disabled peers [6].

This paper carried out a literature review of technologies developed for VI students in the last decade. The study also investigated the use of auditory methods in developing the web application mentioned in [7]. This review is based on the following research questions:

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

This paper is structured as follows: Section 2 consists of a literature study methodology, which discusses search strategy and inclusion/exclusion criteria; Section 3 provides detailed information on the included studies. Section 4 concludes the project along with discussions on results.

II. Literature Study Methodology

This paper examines existing assistive technologies developed for teaching mathematics and differentiates non-visual learning and interaction techniques. One reason for the focus on this discipline is that although ICT has improved the productivity of people with a physical disability, there are limited resources for VI students in the academic field [8].

With the increased interest in digital learning over the past decade, several authors have carried out systematic literature reviews documenting assistive technologies implemented for VI people. These existing systematic reviews cover the effects of computer technology on school students in mathematics learning [9], ICT applications for VI people [8], or digital learning technology for VI students [10], [11].

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A. Search Strategy

Accurately searching for all relevant publications from all possible sources is the most crucial step in a literature review. Table I shows the list of databases and search engines.

TABLE I: LIST OF DATABASES AND SEARCH ENGINES

Database and Search Engine	Link
ERIC	https://eric.ed.gov
EBSCO Information Services	https://www.ebscohost.com
ProQuest	http://www.proquest.com
Wiley Online Library	http://onlinelibrary.wiley.com
JSTOR	http://www.jstor.org
ACM Digital Library	http://dl.acm.org
Science Direct	http://www.sciencedirect.com
Google Scholar	https://scholar.google.com/

B. Inclusion and Exclusion Criteria

Based on our research questions, we had the following search terms: assistive technology, digital learning, high school mathematics, and visually impaired students. These search terms with different combinations were searched against the aforementioned databases and search engines. Once we obtained all the results, we applied inclusion criteria to filter out irrelevant publications. Table II shows inclusion and exclusion criteria for this study.

TABLE II: INCLUSION AND EXCLUSION CRITERIA

Inclusion Criteria	Exclusion Criteria
Published in English	Publication is a review/thesis/summary
Developed for VI students	For students with multiple disabilities
Published between 2010 and 2020	Research is in early stages
Investigates approaches for digital math education	

The search operations on databases and search engines resulted in 153 publications. After scanning through the title and abstract, 134 papers were able to pass through all inclusion criteria. After further scrutiny, we removed duplicate publications and were left with 126 publications. We applied inclusion criteria on the methodology of the remaining papers; it yielded 57 papers. We evaluated 57 publications and discarded publications that did not include digital or math learning. After expert reading, we decided to have ten publications that motivated self-learning for VI students.

Figure 1 shows the search and selection summary.

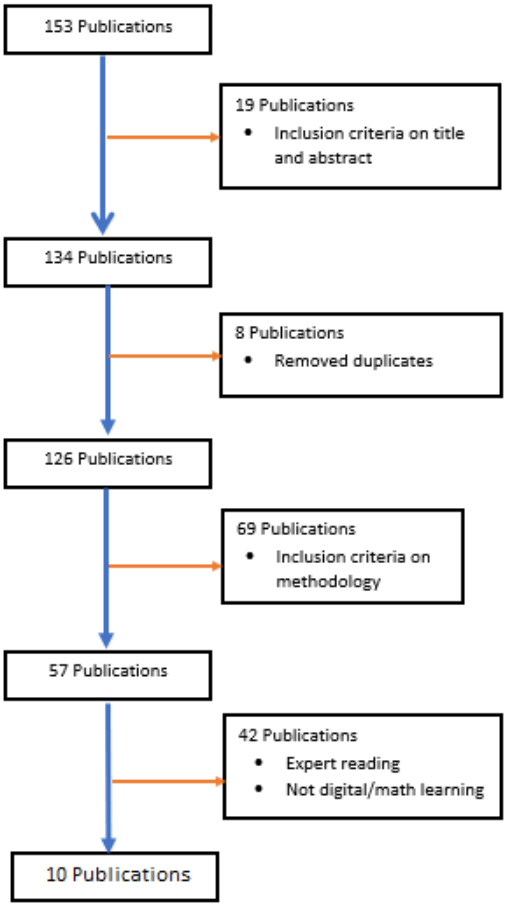

Fig. 1: Search and selection summary.

III. RESULTS

This literature review presents 10 publications. In this section, we explain the study results and analysis.

The main focus of all the studies was to investigate the different accessibility and interaction approaches. It is interesting to note that most of the studies are somewhat related to technology rather than pedagogical aspects of learning.

The included studies evaluated the use of three types of technologies: either mobile/tablet application or an independent system or a library/package improving the accessibility to the existing system. Different accessibility and interactive approaches investigated by these publications are shown in Table III.

In total, we presented ten publications investigating ways to make mathematics content digital and accessible. Seven of these studies had participants evaluating the usefulness of the proposed approaches. The number of participants in these studies varied from 3 to 20. Five studies used audio rendering of mathematical formulae, which are also compatible with screen-readers and Braille bars. In these studies, even though the delivery method of mathematical formulae differed from the traditional method, participants appreciated audio representation.

Authors in one study introduced a novel approach to represent mathematical graphs through auditory methods. Innovations in digital learning technologies have led authors to launch an iPad application to teach students basic math and prealgebra. The application introduced in [12] uses a simplified on-screen keyboard for students with VI and has been downloaded over 14000 times.

The diverse and accessible techniques mentioned in these publications make the comparison between them complicated. Participants in these studies range from teachers, experts, and

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TABLE III: LIST OF APPLICATIONS IN INCLUDED STUDY

#	Title	Study Sub-domain	Study Objectives	Interaction Approach	Study Results
LR1	A Pilot Study of a Self-voicing Computer Program for Prealgebra Math Problems	Prealgebra	To field-test the accessibility of a self-voicing computer program, AnimalWatch-VI-Beta, with 14 VI students working with prealgebra math problems.	– The program provided the participants with audio hints for word problems. – Participants interacted with the program with keyboard keys.	– Although the study was not designed to evaluate the participants' algebra skills, the participants used audio hints to efficiently solve easy and medium difficulty problems. – The results showed that the audio materials could be useful resources for students with VI in learning math.
LR2	Accessing Algebra via MathSpeak: Understanding the Potential and Pitfalls for Students with Visual Impairments	Digital access to math formulae	Three VI high school students participated in this study to evaluate the impact of eText player ReadHear to access and understand algebraic expressions.	– The eText player provided algebraic expressions in speech format.	– Finding suggests that even though the method was different from the traditional approach, students successfully used the technology to access algebraic expressions.
LR3	Math Melodies: Supporting Visually Impaired Primary School Students in Learning Math	Basic math operations	An iPad application to teach basic mathematics to primary school students. Two sighted and three blind primary school students participated in the study.	– The application is accessible for blind students through a screen-reader and a simplified on-screen keyboard to answer questions.	– Participants were able to interact with the system and found the application accessible and entertaining. – The application enables exploring audio-visual elements on a touchscreen and provides feedback to keep VI students engaged and entertained. The iPad application has been downloaded over 14000 times.
LR4	AudioFunctions.Web: Multimodal Exploration of Mathematical Function Graphs	Exploring math functions graph	Thirteen VI participants engaged in this research study to investigate the use of sonification, earcons, and speech synthesis to explore mathematical functions graphs.	– AudioFunctions.web provides verbal or musical earcons on graph exploration. Additional graph information is provided through verbal messages when requested. – Users may interact with the application using a keyboard, mouse, touchscreen, or touchpad. The application is available on all browsers, mobile devices, and PCs.	– The participants managed to proficiently use the system and explore the presented graphs. – Six students preferred a touchscreen and five students appreciated the touchpad/mouse and touchscreen interaction equally.
LR5	An interactive math braille learning application to assist blind students in Bangladesh	Braille	A mobile application to teach VI students math Braille and help solve mathematical calculations. 20 VI participants provided feedback in improving the functionality of the mobile application.	– Participants can interact with the application through a touch screen and the application provides audio and vibrational feedback to help the user make a decision.	– The application evaluation by the teachers, experts, and students suggests that voice and vibrational feedback can assist students to learn Nemeth code.

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TABLE III: (Cont.) LIST OF APPLICATIONS IN INCLUDED STUDY

#	Title	Study Sub-domain	Study Objectives	Interaction Approach	Study Results
LR6	Adaptable Accessibility Features for Mathematics on the Web	Digital access to math formulae	This study enabled the rendering of math formulae on the web. The work is implemented in the MathJax library with new personalizing features. This package also offers accessibility features for speech and tactile outputs.	– MathJax accessibility features are mainly aimed at supporting users with reading disorders. MathJax provides speech and tactile output to support screen-reader users and provides visual aids to maximize accessibility on the web.	– MathJax provides aural rendering for mathematical expression, which can be generated on the fly when running in the web browser or pre-computed by the author. – MathJax offers various techniques such as highlighting, contrast, formula coloring, magnification to increase the accessibility of math formulae on the web.
LR7	Axessibility: A LaTeX Package for Mathematical Formulae Accessibility in PDF Documents	Digital access to math formulae	A LaTeX package to provide math formulae accessibility in PDF documents. Four VI students participated in the evaluation of this study using Acrobat DC PDF reader.	– The package enables the creation of accessible PDF documents by inserting hidden replacement text for maths formulae using *ActualText* PDF attribute, making it visible to screen readers and braille bars.	– The participants correctly read formulae inside PDF documents produced using Axessibility.
LR8	Web-ALAP: A Web-Based LaTeX Editor for Blind Individuals	LaTex editor	Web-ALAP is a web-based LaTeX editor that provides speech-based prompts and automatic narration of the error messages. It also offers a "Math Mode" that offers a natural language description of the mathematical content within the document.	– Web-ALAP offers a comprehensive set of keyboard shortcut keys to maximize accessibility and easier navigation for math equations. – A web-based LaTeX editor is equipped with accessible debugging features for real-time auditory feedback.	– The user testing with ten VI students showed that the users appreciated the Math Mode of the web application. All participants recognized the importance of being informed through audio feedback.
LR9	MathSpeak: a non-ambiguous language for audio rendering of MathML	Digital access to math formulae	To introduce a new method to provide audio-rendering of complex mathematical formulae provided in MathML.	– Non-ambiguous speech representation of math formulae.	– While presenting mathematical terms in non-visual format, it may lead to multiple interpretations. – With MathSpeak technology, authors enabled the rapid translation of STEM material into MathML format and eventually into a non-ambiguous speech format.
LR10	Improving accessibility to mathematical formulas: the Wikipedia Math Accessor	Digital access to math formulae	To improve the accessibility of mathematical formulae by providing natural language processing descriptions of more than 420,000 formulae from Wikipedia's repository.	– Graphical representation of mathematical formulae.	– This study introduced the MathAcc, an assistive technology designed to help VI students gain access to the graphical representations of complex mathematical formulae published on Wikipedia.

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students. In summary, the following findings hold for our research questions:

- What are the reported accessibility approaches and outcomes in existing mathematics learning apps?
  - The research study mentioned in the literature review employed a variety of accessible methods. The main objectives of the studies include 'the alternate delivery method' and 'the effectiveness of the technology.' Nine publications stated that students appreciated the audio representation of mathematical formulae.
- What are the domains, interactive mechanisms, and accessibility features of these apps?
  - Three studies investigated the effectiveness of a digital platform to teach mathematics to students with VI. One study introduced the use of sonification, earcons, and speech synthesis to explore mathematical function graphs. Auditory methods were the most frequently applied technology in the included studies.
- What are the contextual settings in which these applications are scrutinized?
  - The VI participants evaluated most of the included studies using different interaction methods varying from the keyboard keys, mouse, trackpad, and touchpad. All research studies achieved their desired results.

IV. Conclusion

This paper presented 10 assistive technologies developed between 2010 and 2020 that focused on improving mathematics accessibility and offered a new way to teach mathematics to students with VI. After a systematic review of the focus of studies, the subdomain, and the context in which the studies took place, we can conclude that digital learning with auditory and tactile methods can improve mathematics education for VI students.

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APPENDIX A. LIST OF STUDIES

Study ID	Citations
LR1	C. R. Beal, L. P. Rosenblum, and D. W. Smith, "A pilot study of a self-voicing computer program for prealgebra math problems, "Journal of Visual Impairment and Blindness, vol. 105, no. 3, pp. 157–169, 2011.
LR2	E. C. Bouck, N. K. Meyer, G. S. Joshi, and D. Schleppenbach, "Accessing algebra via mathspeak™: Understanding the potential and pitfalls for students with visual impairments, "Journal of Special Education Technology, vol. 28, no. 1, pp. 49–63, 2013.
LR3	D. Ahmetovic, V. Alampi, C. Bernareggi, A. Gerino, and S. Mascetti, "Math melodies: Supporting visually impaired primary school students in learning math," in Proceedings of the 14th Web for All Conference on The Future of Accessible Work, 2017, pp. 1–2
LR4	D. Ahmetovic, C. Bernareggi, J. Guerreiro, S. Mascetti, and A. Capietto, "Audiofunctions.web: Multimodal exploration of mathematical function graphs," in Proceedings of the 16th Web For All 2019 Personalization - Personalizing the Web, 2019, pp. 1–10.
LR5	L. Nahar, R. Sulaiman, and A. Jaafar, "An interactive math braille learning application to assist blind students in Bangladesh, "Assistive Technology, pp. 1–13, 2020.
LR6	D. Cervone and V. Sorge, "Adaptable accessibility features for mathematics on the web," in Proceedings of the 16th Web For All 2019 Personalization - Personalizing the Web, 2019, pp. 1–4.
LR7	D. Ahmetovic, T. Armano, C. Bernareggi, M. Berra, A. Capietto, S. Coriasco, N. Murru, A. Ruighi, and E. Taranto, "Axessibility: A latexpackage for mathematical formulae accessibility in pdf documents," in Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility, 2018, pp. 352–354.
LR8	S. Arooj, S. Zulfiqar, M. Qasim Hunain, S. Shahid, and A. Karim, "Web-alap: A web-based latex editor for blind individuals," in The 22nd International ACM SIGACCESS Conference on Computers and Accessibility, 2020, pp. 1–6.
LR9	W. Sheikh, D. Schleppenbach, and D. Leas, "Mathspeak: a non-ambiguous language for audio rendering of mathml, "International Journal of Learning Technology, vol. 13, no. 1, pp. 3–25, 2018.
LR10	J. Fuentes Sepulveda and L. Ferres, "Improving accessibility to mathematical formulas: the wikipedia math accessor,"New Review of Hyper-media and Multimedia, vol. 18, no. 3, pp. 183–204, 2012.

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