Digital learning in mathematics for students with severe visual impairment: A systematic review

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Introduction

Digital-based learning and technology are important tools in mathematics education (Li & Ma, 2010). The role of educational technology in the teaching strategies has led to the increased use of technology and media-rich learning environments (NCSM & CoSN, 2015). In addition, people's expectations in the learning environment are changing with advances in digital technology. Many students today are offered computers equipped with increasingly sophisticated software, graphics calculators, hand-held devices with integrated graphics packages with dynamic geometry software, and web-based applications offering virtual learning (Kleanthous & Meletiou-Mavrotheris, 2018; Merchant, Goetz, Cifuentes, Keeney-Kennicutt, & Davis, 2014). The new educational landscape has a great potential to empower students to increase their learning.

Assistive technology has become a tool for mathematics exploration and learning in a range of curriculum topics (ref inn). Some programmes' may cover many areas of mathematics, while others are designed to allow for in-depth probing of only one area (Asebriy, Raghay, & Bencharef, 2018). 'Microworld program' create specific constructivist environments and are aimed at a limited set of mathematics ideas (Sinclair & Jackiw, 2005). The programs are 'filled with content' that can be configured to suite a wide range of learning modes, from guiding the student step-by-step and to more open-ended explorations. In our experience, 'guided tasks' are most often used by the youngest students to acquire specific mathematical skills and competence.

The emergence of technologies of broader mathematical expressivity managed to affect a range of curriculum topics (Sinclair & Jackiw, 2005). Digital tools that are 'empty of content', such as spreadsheets, graph software, and computer algebra systems (CAS), are technologies that are only loosely coupled to specific curricular contexts but are suitable for mathematical explorations. These tools are often used by students in lower and upper secondary school.

An increasing trend in mathematics education in lower and upper secondary school is that teachers make short instructional videos on given topics, which the student's study at home. This 'flipped classroom' is an instructional strategy that reverses the traditional learning environment by delivering instructional content outside the classroom. In a flipped classroom, students watch lectures online and collaborate in online discussions. In this way, learning is understood as including a social dynamic rather than being a solely individual learning process (Moore, 2016).

The development towards the increased use of digital learning opportunities is challenging for students with VI and their teachers (Asebriy et al., 2018; Ashraf, Hasan, Lewis, Hasan, & Ray, 2016). Therefore, it is relevant to gain more knowledge about how students with vision loss can follow the teaching in mathematics and succeed in learning their age-related curricula (Besnoy, Manning, & Karnes, 2005; Ferrell, 2011; Klingenberg, 2013).

In mathematics, physical textbooks are often replaced with digital textbooks, and the teaching materials are presented or read on a computer or similar device. Anderson-Inman and Horney (2007) define digital text (e-text) as textual materials presented electronically or digitally. Supported e-text is defined as digital text that is modified or enhanced in ways that are designed to increase comprehension and promote content area learning. Supported e-text allows digital text to be reproduced in a medium such as synthetic speech, human-voice audio recordings, video, large print books, and Braille.

Braille is a tactile writing system designed for use by people who are severe visually impaired (Augestad, Klingenberg, & Fosse, 2012). The different types of mathematical Braille codes create problems in the production of relevant software and hardware with regard to the universality of mathematics. Braille is traditionally written in the form of embossed paper, but written language can also be provided through an electronic Braille display. Screen readers (e.g. Job Access with Speech, JAWS) are software applications that converts materials displayed on screen into speech synthesizer or Braille (Asebriy et al., 2018; Stefano, Borsci, & Stamerra, 2010). The advantages of refreshable Braille displays over synthetic speech are that it provides direct access to information, allows the user to check the format, spacing, and spelling in the text, and is quiet (Jackson & Presley, 2012). In addition, Braille displays allow for notetaking and file storage. Furthermore, students with VI may connect a personal digital assistant (PDA) to a computer and use it as a Braille display or speech synthesizer (Ernst, Swan, Cheung, & Girouard, 2017).

Students with visual impairments can supplement their reading of Braille or printed text with aural outputs from screen readers or digital talking books (Argyropoulos, Paveli, & Nikolaraizi, 2019). For example, DAISY (digital accessible information system) books have been developed to assist people with VI in the learning process (Maćkowski, Brzoza, & Spinczyk, 2018). Supplementation with speech has been considered a necessary tool for increasing access to information because Braille and large print materials have not always been available when needed (Jackson & Presley, 2012). Nevertheless, Jackson and Presley (2012, p. 3) make the following claim: 'Today, however, advances in the production of digital media and in the design of technology tools have reached a point where they allow Braille or print readers to process tactile or visual information at the same time they are engaging with text in an auditory format. Newer technologies offer features that allow a user to more efficiently access and manipulate the Braille, print, and audio information conveyed.'

All students should have the opportunity to obtain an age-related level of competence in mathematics according to their abilities (Ministry of Education and Research, 2014; U.S. Department of Education, n.d.). However, students with VI face greater challenges in learning from digital libraries and the web (Ajuwon, Meeks, Griffin-Shirley, & Okungu, 2016; Asebriy et al., 2018). Moreover, their visual disability may mask their actual mathematical abilities, creative thinking, and academic achievement potential (Al-Dababneh, al-Masa'deh, & Oliemat, 2015). Therefore, teaching strategies and aids is an important component of the learning environment (Hassan & Salleh, 2017).

Gaps in digital skills may increase among students with VI compared with students without vision loss (Ramos & de Andrade, 2016), and one reason may be the fast development in digital-based learning. Another reason may be the lack of sufficient resources and adequate aids in the school system, even in developed countries (Borg, Lindström, & Larsson, 2009; UNESCO, 2015; UNICEF, 2013, 2017; WHO, 2018). Additionally, each country's economy and governmental priorities to finance support for special needs education and for developing teachers' competence and interests may play a role in the ability of students with VI to learn mathematics. Students with visual impairment need positive interactions with their teachers, and teachers' attitudes can shape their experiences (Dawn, 2015; Ravenscroft, 2015; Simui, Kasonde-Ngandu, Cheyeka, Simwinga, & Ndhlovu, 2018). Thus, teachers play a crucial role in creating meaningful experiences in mathematics for their students with VI. Peer comparisons and teachers' attitudes are among the main factors that contribute to either positive or negative experiences of mathematics for students with VI.

Many students with VI are fully integrated into state schools, but some countries still have schools exclusively for the blind (Duke et al., 2016; European Agency for Development in Special Needs Education, 2009). Simui et al. (2018) conclude that despite valuable steps towards inclusion taken by countries and their higher learning institutions, students with VI were still not fully included: 'Exclusive practice were manifested through inflexible time limits for assessment, lack of adaptive technologies, technical difficulties using e-learning and connecting to websites and Course Management systems, and poor use of e-learning by lectures' (Simui et al., 2018, p. 170).

The numbers of students with VI are highest in Asia and Africa, and relatively lower in Europe and North America (Mariotti, 2012). Many of the students with VI may not have access to the new technology and e-devices to learn mathematics in school (Simui et al., 2018). Hence, there is a need to be aware of the global situation when studying students with VI.

Following a preliminary search in the literature, we did not find any published systematic reviews of the use of digital learning in mathematics for students with VI. Therefore, we considered it relevant to conduct a systematic review, with the aim of summarizing current evidence-based scholarly knowledge about digital learning in mathematics among students with severe VI.

Methods

Design

Systematic reviews involve a detailed, comprehensive planned, search strategy designed a priori with the goal of reducing bias by identifying, appraising, and synthesizing relevant studies on the topic (Uman, 2011). We carried out a systematic review of pre-reviewed articles and described the study characteristics and major findings. In addition, we evaluated the quality of the studies and discussed possible interpretation of the results.

Search strategy

In order to identify relevant published articles, we searched the databases SCOPUS, PubMed, ERIC, and Web of Science using the following search terms: visual impairment, blind, low vision, mathematics, and education (Figure 1). It was an advantage during the literature search that one of the authors of this article is a librarian with special competence in literature searches.

Criteria for inclusion and exclusion

We included studies of children and young adults with visual impairment in the age range 5–25 years. The reason for the wide age range was to include studies of students of school age. However, some studies included subjects older than 25 years of age, but the mean age of the subjects in each of the included studies was lower than 25 years of age. Children with severe visual impairment may have major problems with accessing information, and when possible they may use additional years to graduate from secondary school (Yurtay, Yurtay, & Adak, 2015). We included articles written in English, published between 1 January 2000 and 31 October 2017 inclusive, and peer reviewed. We identified 278 abstracts.

After reading of the 278 abstracts, we excluded publications on children and young adults who had VI in combination with either comorbidity or multiple disabilities. In addition, we excluded articles that described analyses of teaching tools and materials in particular situations in countries, and articles that did not report separate data collections for individuals with VI. We were left with 108 publications. After discounting 55 duplications, the search yielded 53 articles.

Two of the authors read the 53 publications. Some studies did not have original data collections. Given the defined inclusion and exclusion criteria, we decided that 25 of the publications fitted the aim of the study. We evaluated the 25 publications and found it natural to divide them into two separate groups according to length. Our review of digital learning in mathematics for students with severe VI is based on 13 publications (Figure 1), while the other 12 publications will be presented in a separate article on learning algebra and geometry among students with severe vision loss.

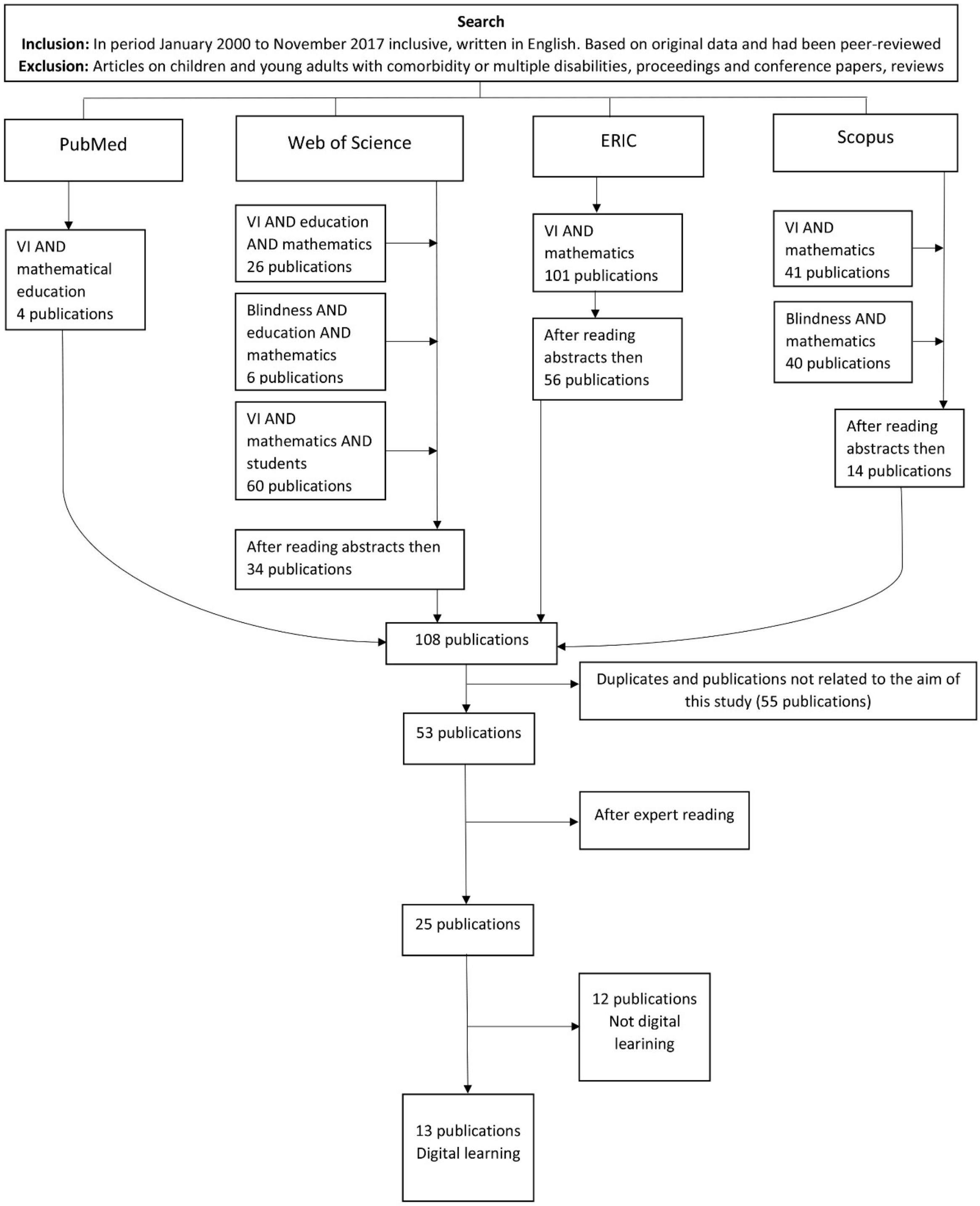

Figure 1: Flow chart of the systematic review search strategy.

Figure 1: Flow chart of the systematic review search strategy.

Data extraction

We used a standardized protocol and reporting form to abstract the following data from each publication: year of publication, first author's name, country in which the study was conducted, aim of the study, study design, age and number of persons in the study population, number of persons with visual impairment and number of sighted persons in each study, definition of visual impairment, and main results of each study. We used the first time the article was published online as the publication year, not the year of the print edition.

Evaluation of the studies

We used the Quality Assessment Tool for Studies with Diverse Designs (QATSDD) to evaluate the selected studies (Sirriyeh, Lawton, Gardner, & Armitage, 2012). The tool, which was developed to assess the quality of studies with one topic but using different approaches or designs, has been found to have good reliability (Cohen's kappa, $\kappa = 71.5$) and good face validity (Sirriyeh et al., 2012). Fenton, Lauckner, and Gilbert (2015, p. 1125) claim that 'the tool can spur useful dialogue among researchers and increase in-depth understanding of reviewed papers, including the strengths and limitations of the literature. To increase the clarity of the process, we suggest further definition of the language in each indicator and inclusion of explicit examples for each criterion.' For example, it is not defined or clearly explained how the indicators 'theoretical framework' or 'the statement of aims' should be scored, which may imply a change in construct validity. The QATSDD should therefore be used with caution.

We used the version of QATSDD with 14 items relating to quantitative studies. Each item was rated on a 4-point scale ranging from 'not at all' (0), 'very slightly' (1), 'moderate' (2), to 'completely' (3), with a maximum score of 42. The percentage score was calculated by dividing the actual score by the maximum score (i.e. 42). Studies scoring over 75% were considered 'high quality', 50–75% 'good quality', 25–50% 'moderate quality', and those scoring below 25% 'poor quality'. The quality ratings are presented in Table 1.

Two reviewers evaluated the 13 papers. The weighted kappa was 0.64 (indicating good agreement), and the Spearman correlation was 0.90 (indicating a strong association or relationship). Nine papers were given an identical rating, and four differed by one category between the two reviewers. Cohen's kappa coefficient is a statistic that measures inter-rater agreement for categorical items (Viera & Garrett, 2005). Kappa is one measure of inter-observer agreement and is the most commonly reported measure in medical literature.

Table 1: Characteristics of the thirteen studies of digital mathematics learning among students with VI[1]

Number Authors (Year) Country	Aim	Method			Main results (QATSSD[2])
		Study design	Sample	Definition of VI[1]	
1) Bateman et al. (2018) USA	To test the efficacy of an electrostatic touch screen for displaying graph-based information and to determine whether accuracy and efficiency changed across trails, to analyse the strategies by which participants explored the screen, and to determine whether the location of each dot on the screen significantly affected accuracy	A user-centred design approach Interviews with device experts and users with VI[1] A usability study consisting of trials Three cognitive tasks	12 VI[1] Age: 9–50 years Mean age: 18 years	WHO[3] definition of vision: Severe VI[1] Blindness Total blindness	Participants correctly located haptic points; the accuracy increased across trials; efficient patterns of user interaction involved either a systematic approach or a rapid exploration of the screen; haptic elements placed near the corners of the screen were more easily located. The device meets the desired accessibility needs as reported in previous studies. (High quality)
2) Leo, Cocchi, and Brayda (2017) Italy	To investigate whether VI students can understand and take advantage of tactile graphics presented using a programmable pin-array tactile display	Four sessions of training tests with raised-line drawings, with programmable tactile displays, a programmable spatial test (geometrical shapes recognition), and a	16 VI[1] Age: 6–22 years Mean age: 12 years	8 Legally blind 8 Low vision blindfolded Eye diagnoses Age at onset of VI[1]	Students who were blind or had low vision significantly improved their spatial skills during training when using programmable tactile displays. The observed learning effects were comparable with traditional raised-line control tests. There were no statistical differences in performances between young students who were blind or had

Number Authors (Year) Country	Aim	Method			Main results (QATSSD[2])
		Study design	Sample	Definition of VI[1]	
		programmable spatial-temporal test			low vision, only a trend towards a better performance in the latter. (High quality)
3) Bouck, Weng, and Satsangi (2016) USA	To understand the experiences and perceptions of five high school students with VI[1] who were accessed algebra via a digital textbook	Qualitative research methodology: training, online survey, observations	5 VI[1] Age: 16–22 years Mean age: 18 years Participated in Algebra 1 classes	Legally blind Light perception Eye diagnoses Age at onset of VI[1]	Students demonstrated a dependence on their traditional medium: Braille, large print, or standard-size print. The teacher encouraged the students' preferences for traditional textbooks over a digital textbook. Teachers' and student's preferences and willingness to use digital textbooks, is an important aspect of assistive technology consideration and decision-making. (Good quality)
4) Huang, Chiu, Hwang, and Wang (2015) Taiwan	To develop and evaluate a new e-learning approach to teaching mathematics to students with VI	Interviews with the teachers and students, then developed the DAISY[4] E-textbook Experimental design: four-day pedagogical mathematical programme	12 VI[1] Junior high school	9 severe VI[1] 3 moderate VI[1]	The value of the NASA-TLX[5] subjective scales was significant and the student accuracy rate increased. The authors concluded that the new method effectively improved students' proficiency in mathematics. (High quality)

Number Authors (Year) Country	Aim	Method			Main results (QATSSD[2])
		Study design	Sample	Definition of VI[1]	
		Assessment session			
5) Bouck and Weng (2014) USA	To understand the use of supported e-text to deliver algebra to students with VI[1] in mathematics classes To explore supported e-text in contrast to students' traditional means of accessing an algebra text	One individual training session Interview Online survey Observation Qualitative design	5 VI[1] Age 16–19 years Mean age 17 years High school 3 females 2 males Enrolled in Algebra1 or 2 2 teachers	Low vision Blind Light perception Enrolled in state school for the blind	Supported e-text has potential in terms of delivering mathematics content, but not without limitations and reflection on this approach as a sole means of presenting texts. There is a need for additional research and more reflection in the field in order to understand the use of supported e-text for mathematics among students with VI[1]. (Good quality)
6) Mukherjee, Garain, and Biswas (2014) India	To propose a novel method for converting digital to tactile Braille mapping of geometry diagrams on low-cost traditional Braille text printers	Over 4.5 months, one-month initial training until able to perceive Braille character chains as 10 geometric objects: e.g. point, line, square, and rectangle, followed by tests	16 VI[1] Age 13–55 years Mean age: 22 years 12 blind schoolboys 4 blind seniors 4 sighted teachers 7 test groups	14 completely blind 1 blind with deteriorating vision	Most of the students and seniors could recognize the Braille shapes with reasonable accuracy and could relate Braille diagrams to the problem statements within a short learning time. Using the integrated system, blind students were able to input a geometry word problem and perceive the underlying diagram on a Braille printout. The results of the usability tests and the pre- and post-test questionnaire surveys underline the need and impact of such an affordable teaching and

Number Authors (Year) Country	Aim	Method: Study design	Method: Sample	Method: Definition of VI[1]	Main results (QATSSD[2])
					learning aid for the blind community. (Good quality)
7) Oliveira, Quek, Cowan, and Fang (2012) USA	To make students who were blind aware of the deictic gestures performed by their teacher over the graphic xxx in conjunction with speech by employing a haptic glove interface to facilitate the embodiment awareness To evaluate whether haptic fingertip reading can replace visual material	Exploratory study Five educational groups: one VI[1] + three sighted Two status-quo educational groups with sighted students. Two or three lessons in maths with mini courses on trigonometry and planar geometry	4 VI[1] State University Undergraduate students: 2 females, 2 males Two sighted university students with teaching experience acted as guides	No usable vision 1 female blind at the age of 2 years and 1 blind at the age 16 years Two males, one blind from birth and one blind at the age of 13 years	The technology allowed instructors to: (1) adjust the pace of their lecture to ensure that all students were following them; (2) better understand the students' signs of confusion and act upon them to ensure their understanding; and (3) act more naturally, as they did not have to think of how to verbalize the information displayed on the graphs. All of the VI[1] students agreed (or strongly agreed) that the use of the system did not make them more tired than when not using it and none saw the system as an impediment to following the lecture. Three of them found it easier to understand maths concepts when the system was used. Despite the congruent and positive experience of instructors and students, it was not possible to reach a conclusion on learning. (Good quality)

Number Authors (Year) Country	Aim	Method			Main results (QATSSD[2])
		Study design	Sample	Definition of VI[1]	
8) Beal, Rosenblum, and Smith (2011) USA	To gather data using the AnimalWatch-VI-Beta system among students with VI[1] (a graphical web-based tutoring system) The computer program delivered 12 pre-algebra maths problems and hints through a self-voicing audio feature	Pilot test of the use of audio hints in problem solving	14 VI[1] Age 10–17 years Mean age: 13 years 7 males 7 females 9 students below grade level for maths	12 used Braille, 1 female used large print 1 female used print	Children with VI[1] need to have access to the same curricular materials as their sighted peers. Audio materials can be useful resources for students with VI[1] when learning maths. With further development and research, the concept of an AnimalWatch suite, based on AnimalWatch-VI-Beta, has the potential to increase the maths skills of youths with VI[1]. (Good quality)
9) Bouck, Flanagan, Joshi, Sheikh, and Schleppenbach (2011) USA	To explore the use of a computer-based VISO[6] calculator to assist students with VI[1] in the completion of computational maths problems	A single subject research design: assessment, training and/or intervention	3 VI[1] Age 18–19 years Mean age: 18 years 2 females 1 male Residential high school for the blind All students had similar math skills	WHO[3] eye diagnoses Visus stated 2 not proficient in Braille 1 had no training in Braille	The time to complete assessments and the average number of attempts per problem decreased as the students continued to use the VISO[6] calculator. Students reported positive perceptions of the calculator, compared with their typical means of calculation. Students with VI[1] needed and desired accessible graphing calculators with voice input. (Good quality)
10)	To examine the usability of an (AfL[7]) system that provides	ACED[8] was designed to assess	N = 4 Age 17–20 years	2 with low vision 2 blind Braille users	All four participants found both modes of ACED[8] a usable mathematics AfL[7] system in

Number Authors (Year) Country	Aim	Method			Main results (QATSSD[2])
		Study design	Sample	Definition of VI[1]	
Hansen, Shute, and Landau (2010) USA	audio-tactile graphics for algebra content (geometric sequences) for individuals with VI[1]	and support the learning of algebra Pre- and post-test treatment Interviews	Mean age: 18 years 2 females 2 men High school		general. The findings illustrated the value that some users with VI[1] find in such features of a test system as speech output (synthesized and pre-recorded) and interactive audio-tactile graphics. The diversity of accessibility features appeared to contribute to the overall positive response to the approach. (Good quality)
11) Isaacson, Srinivasan, and Lloyd (2010) USA	To develop an algorithm for improving the synthetic speech rendering of MathSpeak	Efficacy testing of the developed algorithm Parameters measured included reception accuracy, short-term memory retention, MathSpeak processing capacity, and the various ranking concerning the quality of synthetic speech renderings	5 VI[1] 21 sighted college students 1 VI[1] junior high school student	3 blind Braille users 3 with low vision who read enlarged texts	All parameters measured showed statistically significant improvements when the algorithm was used. This increased the capacity of individuals with print disabilities to perform mathematical activities and to fulfil science, technology, engineering, and mathematics and career objectives. (Good quality)

Number Authors (Year) Country	Aim	Method			Main results (QATSSD[2])
		Study design	Sample	Definition of VI[1]	
12) Sánchez and Flores (2005) Chile	To present the design, development, and usability of AudioMath, an audio-based interactive virtual environment designed to develop the use of short-term memory and to assist children with VI[1] in their learning of mathematics	Pre-testing Twice per week for four months interacting with AudioMath and solving cognitive tasks Post-testing	10 VI[1] Age 8–15 years 5 girls 5 boys	Legally blind Most of the students had additional deficiencies	As a result of interacting with AudioMath in association with cognitive tasks VI[1], students developed their mathematics skills and short-term memories. The results showed that an audio-based virtual environment could be powerful interface source to enhance memory and mathematics learning in blind children. (Good quality)
13) Landau, Russell, Gourgey, Erin, and Cowan (2003) USA	To explore the impact of the TTT[9] on the graphics displays for students with VI[1]	Items selected from MCAS[10] 8th grade mathematics test The items included either diagrams or graphic elements. Two groups of students	8 VI[1] Age: 14–42 years Mean age: 20	3 with no useful vision 1 with limited useful vision 4 with some useful vision 4 used Braille 4 used large print	The analyses suggest that using the TTT[9] had neither a negative effect nor a positive effect on the performance of students on Grade 8 mathematics items that involved graphic elements. The teachers and students generally embraced the TTT[9] and wanted to use it in the future as a test-taking and instructional tool. The results indicate that users of the TTT[9] perceived advantages in accessing graphics through the combination of tactile and auditory information. (Good quality)

Notes: [1]VI – visual impairment; [2]QATSDD – Quality Assessment Tool for Studies with Diverse Designs; [3]WHO – World Health Organization; [4]DAISY – Digital Accessible Information System; [5]NASA-TLX – NASA Task Load Index; [6]VISO – voice input, speech output; [7]AfL – assessment for learning; [8]ACED – Adaptive Content with Evidence-based Diagnosis; [9]TTT – Talking Tactile Tablet; [10]MCAS – Massachusetts Comprehensive Assessment System

Results

In total, 13 publications representing five countries met the inclusion criteria (Table 1). Twelve of the studies had an intervention or an experimental design, and one had a cross-sectional design. The number of students with VI reported in the 13 publications varies from 3 to 16. They ranged in age from 6 years to 55 years (mean age 19 years), and their mathematical training lasted from one session to 18 weeks of initial training. Four articles report ophthalmic diagnoses or WHO's definition of vision loss. The terminology used for describing VI, and the age of onset, comorbidity, and the use of cognitive testing or mathematics tests before the intervention varies between the articles, are not mention in most of the articles. Seven of the articles include both genders, but one mentions gender in the results. When assessed using QATSDD, three articles were classified as 'high quality', the other ten articles as 'good quality'.

The studies had somewhat different aims and foci, but issues related to audio-based applications were included in 9 of the 13 selected studies. The conclusions from the 9 studies are not unambiguous in terms of learning effects, nor are student attitudes to using auditory information in their learning. In five of the studies, a vital argument for developing computer programs and evaluating auditory learning modality was the desire to reduce costs in textbook production and to make the production less time-consuming. The focus in the five studies was on testing the preferences and willingness to use digital textbooks, developing and evaluating DAISY as an e-learning approach, developing an algorithm for improving the synthetic speech rendering, and converting a geometry word problem to Braille mapping of geometry diagrams on a low-cost Braille text printer. Common findings presented in the respective five articles, as well as in the other articles, are that students improved their skills during training.

One study tested a 'Microworld program' with an objective in pre-algebra, while guided tasks programs were used in three studies. In the three programs in the latter three studies, the audio feedback was given when the students manipulated a graphic display. The authors of one of the two articles that specifically focus on displays of graph-based information conclude that the electrostatic touchscreen is intuitive for users, although the devices still need to be more reliable.

Discussion

The results of our review show that there is lack of scientific evidence to establish research-based practice related to e-learning programs for students with VI. The research aims and methods reported in the 13 articles are diverse, which makes comparison complicated. The authors represent different academic fields, and the articles are published in different research areas, ranging from computer science and engineering to professional education. Their background and competence might have influenced the focus of their respective articles. Studies conducted to develop a prototype e-device for learning mathematics have revealed that expertise in computer science is crucial, and collaboration with other professionals such as skilled teachers in mathematics may lead to e-devices that are better suited to students with VI. Two of the articles in our review are published in open access journals. The results may therefore be more readily available for personnel working at institutions with large numbers of journal subscriptions.

Few studies included testing of the mathematical skills among the students prior to the start of the study. Teaching methods can be of importance to enable students to learn to think mathematically, although much depends on the degree of difficulty of the taught subject and the students' skills. It may be difficulty to evaluate the achievement of students with VI properly (de Verdier, Fernell, & Ek, 2018). The fact that a student may be able to use a device does not necessarily mean that they understand the mathematical concepts or will develop mathematical skills. The number of subjects in each study was small, and the inclusion criteria for subjects are unclear in most of the articles. Some of the reviewed studies included cases with a wide age range. Furthermore, the length of each experiment lasted from a few school hours to one week, while the study conducted by Mukherjee et al. (2014) lasted four and a half months. In some articles, it is not clear from the method section how long the intervention period lasted. The time frame of an intervention is important, regardless of whether the aim is to develop a device or to examine the usability of a program.

Students with visual impairment represent a heterogeneous group, not least due to a wide range of visual functions, and therefore it is important to account for visual diagnoses, visual conditions, and the history of visual disorders (Augestad et al., 2012; Rahi & Cable, 2003; Warren, 1984). When studying spatial performance, such as in geometry tasks, it is important to know the onset of visual disability because students who have had visual experience for only one year or less in childhood have considerable advantage in looking at and perceiving shapes (Millar, 2008). The age of onset of the visual condition is only adequately described in two articles (Leo et al., 2017; Oliveira et al., 2012), and only four studies reported eye diagnoses (Bateman et al., 2018; Bouck et al., 2011; Bouck et al., 2016; Leo et al., 2017). The diversity of eye pathologies implies that students differ in their preferences and possibilities concerning their choice of informatic tools (Carrière, 2012). In cases where information about sight functions was overlooked in the studies, the results may be less valid. In addition, students with certain types of eye diagnoses have coexisting neurodevelopmental disorders (de Verdier, Ek, Löfgren, & Fernell, 2018; Klingenberg, Fosse, & Augestad, 2012), and therefore, such information is important when considering the results of a study. Leo et al. (2017) have carefully outlined visual function, eye diagnosis, and age, and have considered these variables in their measurements. The effect results of programmable tactile displays on spatial learning skills are thus both credible and interesting. The main finding by Leo et al. (2017)was that both children and adolescents who were either blind or had low vision showed significant performance enhancement in spatial tasks using a pin-matrix display.

It is difficult to conduct educational research on students with visual impairments because it is problematic to identify an adequate group of study participants (Ferrell, 2011). This problem was evident from our review, as the age range of participants in the 13 studies was very wide: the youngest student was aged 6 years and the oldest ‘student’ was aged 55 years. In studies of tests of concrete devices, it is particularly important to have a suitable age range. Leo et al. (2017) established subject-specific difficulty levels in their tests and found that very different cognitive and tactile skills could be successfully trained by using both traditional and programmable display methods. Little research has been done on digital-based learning and younger students with VI. Only Beal et al. (2011) have tested microworlds software that is typical used in primary schools. Their pilot study of a self-voicing program for pre-algebra revealed that especially students who were working below grade level in mathematics benefitted from using integrated audio hints as they worked on solving problems.

Audio devices

Students with VI are sometimes characterized as individuals with print-reading disabilities (Bouck & Weng, 2014; Isaacson et al., 2010; Landau et al., 2003). Many individuals with print-reading disabilities use auditory input as a means of receiving information. The addition of an audio function to the device can be Audio added to the device can be a medium to provide information on visual mathematical phenomena, and to enhance learning and cognition. However, more knowledge is needed about how cognitive processes are activated in order to comprehend an auditory text, not least a mathematical text, and about effective navigational strategies using text-to-speech technologies (Argyropoulos et al., 2019)

The results of our review show that digital textbooks and aural feedback have become essential in learning technologies for students with visual impairments, as audio was applied in 9 of the 13 studies (Beal et al., 2011; Bouck et al., 2011; Bouck & Weng, 2014; Bouck et al., 2016; Hansen et al., 2010; Huang et al., 2015; Isaacson et al., 2010; Landau et al., 2003; Sánchez & Flores, 2005). The application areas varied from completely replacing Braille literacy to additional media and to tactile reading. In five articles (Bouck et al., 2011; Bouck & Weng, 2014; Bouck et al., 2016; Huang et al., 2015; Isaacson et al., 2010) audio is studied as an alternative to Braille. The use of audio added to the devices leads to new opportunities in educational contexts, but any suggestion that audio may be an alternative to Braille should be regarded with caution in the field of visual education. The rights of students with VI to learn and use a written language should be endorsed.

To access and interact with text in different modalities, both printed and paperless Braille are, in our opinion, the very best solution. The two-dimensional representations of mathematical content are not only about graphics and diagrams, but also about gaining an overview of the spatial structure of, for example, a stem-and-leaf plot or the written expression of the calculation of an equation. Whereas tactile graphics can display the relationships between components, text-to-speech screen reader technology can enhance the way a reader who is visually impaired interacts with text and will further augment the speed with which the reader can acquire information. Potentially, combining auditory and tactile information could provide students with a more complete concept, as shown in the article by (Bouck & Weng, 2014; Bouck et al., 2016).

Bouck et al. (2016) suggest that supported e-text has potential in terms of delivering mathematics but is not without limitations. From our teaching experiences, students with VI are more successful if they can read traditional texts and mathematical notations by themselves when learning algebra, whereas just listening to digital texts makes the learning process harder. These experiences confirm the findings reported by Bouck et al. (2016) that students felt less satisfied by the lack of physical text in front of them and wanted a textbook. In addition, teachers need training in order to implement the new technology effectively for their students.

Geometry and graphic devices

Our review shows that there are issues concerning reading and reading mediums that primarily characterize research on mathematics education and assistive technology in the field of visual impairment. Technologies as tools for mathematics learning and exploration are primarily linked to geometry and graphics. Seven studies focused on the development and usability of devices for graph-based information (Bateman et al., 2018; Hansen et al., 2010; Landau et al., 2003; Leo et al., 2017; Mukherjee et al., 2014; Oliveira et al., 2012). The results showed that touch-based assistive technologies are potential tools to provide graphical content to students who are blind and improved their learning possibilities and social inclusion. Students who read Braille and have access to refreshable Braille displays in mathematics can receive training in using spreadsheets or similar programs. The students learn to type text, numbers and formulae in the cells, but are dependent on assistance to interpret the results when they are presented as graphs and columns. In other words, there is a need for tools to display graphics representations for students with VI. However, one problem arises when devices remain prototypes and do not become available to larger groups of students.

Cost, usability, and school system

The cost of developing, producing, and marketing of the programs and devices in mathematics education may be high. In addition, the rapid changes in technology may influence the possibilities for children with VI to access aid and use the devices, programs, or apps. Of the 13 studies, 9 were conducted in the USA. To translate English for a population that does not have English as its primary language may be expensive and time-consuming. How many schools or parents are able to buy the aids and provide them for students who would benefit from them the most? Since the students with VI constitute a heterogeneous and relatively small group, the development of suitable aids may be influenced by the sustainability of profits. However, none of the 13 studies focused on how technology and flipped classrooms will suit students with VI. The use of digital technology in schools is increasing, and all students need to acquire technical skills that they will be able to use outside the classrooms.

Strength and limitations

We searched in multiple databases, which resulted in articles from different disciplines. One strength of our search for literature was that the second author is an experienced professional librarian. In addition, teaching mathematics to students with VI is the main working area for the first author, who has a PhD in mathematics education and 40 years of work experience with special education for students with VI.

The fact that we did not use keywords that included ‘e-learning’ during our search in the databases might have been a limitation (Figure 1). Therefore, we conducted an additional search in which ‘e-learning’ was an element in the keyword, but this did not result in any new articles that suited our inclusion criteria.

Confounding may have occurred in some of the reviewed studies. We strongly suspect there was bias in the studies that lacked randomization, especially those that included only a small convenience sample of children with VI and had a wide age range in the samples. The conclusions drawn from some of the reviewed studies might not have been accurate in cases when selection bias was not taken into account.

Conclusions

Interactive e-learning with audio and touch-based assistive technologies are potential tools to enhance good mathematical skills in students with VI. However, there is lack of evidence and a need for additional research and more reflection the use of digital technologies in mathematics among such students, especially the younger students.

Educational research on students with visual impairments is difficult to conduct, among other reasons because the study populations are geographically dispersed, which makes it difficult for researchers to identify an adequate group of study participants without involving considerable expense (de Verdier, Fernell, et al., 2018; Ferrell, 2011). In addition, students with VI are not a homogenous group. If the aim of an experiment is to develop a device, it is also important to know about the skills and knowledge of mathematics of the students participating in the experiment.

The teacher's competence and motivation, as well as the learning environment are important factors in order to succeed in the education of students with VI. In addition, lack of information on new technology and the possibility to add the new aids in the teaching setting may be complicated. The complexity of the picture does not bring hard evidence to contribute to the improvement of educational practices in mathematics, as well as to better treatment of students with visual impairments.

Newer technologies offer features that allow users to access and manipulate the information conveyed by Braille, print, and audio devices more efficiently. In general, further development and additional research in the field are necessary, and we need more knowledge to understand digital learning in mathematics for students with VI.

Declaration of conflicting interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

The authors thank Per Fosse, Head of Department for Visual Impairment at Statped midt, for support and excellent motivation during the work in connection with this article.

The publication charge for this article has been funded by a grant from the publication fund of NTNU (Norwegian University of Science and Technology). The authors thank Catriona Turner for valuable help checking the language of the manuscript.

Funding

The authors did not receive any financial support for the research, authorship, or publication of this article.

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