Aim-Math: a ubiquitous mathematics learning tool for blind and visually impaired students

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Abstract: We present an assistive learning tool to drive the mathematical instruction for students with visual impairment; Aim-Math. Instructional-driven features and assistive features were designed to help the students understand a concept and ease the learning process. Aim-Math is an audio-based system that helps students with visual impairment learn exponents. In order to evaluate the overall understanding and satisfaction, participants were students with visual impairment in a secondary school level. We employed pre-test, intervention, and post-test design. The mean of students' post-test scores was significantly higher than those pre-test scores which indicates that Aim-Math could enhance the students' understanding of exponents. Moreover, the students were satisfied with the use of Aim-Math. In addition, practitioners, teachers, and other educators can simply apply the design of the instructional-driven system and assistive features for students with visual impairment in other desirable concepts.

Keywords: mathematics; assistive learning tool; visual disability; ubiquitous learning; teaching and learning; blind students; learning cycle; secondary school; audio-based learning; exponent concept.

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1 Introduction

Assistive technology is developed for people with disabilities to help them greater independently accomplish tasks that they were unable to perform or able to perform with great difficulty (Cercone, 2013), especially in mathematics. Screen magnification, screen reader, speech recognition and text-to-speech are powerful tools for people with visual impairment to retrieve and provide information via computers. People with visual impairment can fully access digital documents in a text form. There have been attempts to assist visually impaired people to access mathematical information as well (Raman and Gries, 1995; Stevens et al., 1997; Power and Jürgensen, 2010), including in Thai language (Wongkia et al., 2012). Moreover, ubiquitous access to mathematical information including mathematical expressions and graphical views also researched and developed (Awdé et al., 2008; Toyosaka et al., 2016).

Nevertheless, the assistive technologies themselves are inadequate to provide educational experiences for students with visual impairment, however; tools with teaching strategies and instructions can make full benefits in learning mathematics. To prepare effective learning experiences for students with visual impairment, we need teachers who have mathematical background, teaching pedagogies, and abilities to use the assistive technologies in teaching (Mishra and Koehler, 2006). Unfortunately, not many special-needed mathematics teachers are in the schools for blindness and visual impairment (Mani et al., 2005; Zhou et al., 2011; Bayram, 2014), especially in Thailand and other developing countries. Thus, various technologies, especially speech technology are utilised in teaching and learning of content knowledge to help the teachers inside a classroom, supplement a regular instruction outside the classroom, or fulfil a shortage of the special-needed mathematics teachers in the schools. Even though such speech technology could help people with visual impairment to overcome the first obstacle by generating speech output of mathematical information, understanding of a subject matter is another obstacle they have to encounter in learning mathematics.

The nature of mathematics presents great difficulties for students with visual impairment since it is full of symbols, tables, and pictures. The biggest challenge is how we can prioritise the content and depict it in the way that students with visual impairment are able to perceive. Nowadays, a huge number of mathematical instructions and resources have been available online all over the internet. Almost all is designed for students who can learn by three learning modalities including visualising, auditory and kinetics (Barbe and Milone, 1981). Unfortunately, students with visual impairment could not gain full benefits from those instructions because of their limitation of sight. They can gain knowledge only by touching and hearing experiences. An audio is widely used as a communication tool among students, between students and teachers and between students and computers.

To serve overwhelming desires of a mathematical learning tool for students with visual impairment that integrate assistive technology with the related pedagogical dimensions of seamless mobile learning, we developed an audio-based learning tool to drive the mathematical instruction for students with visual impairment, called *Aim-Math*, by concerning five features as follows:

- sequences of mathematical content,
- synchronization of texts, sounds, and pictures,
- communication between user-system and among users,
- questioning during the instruction and exercise,
- hints and feedback.

Moreover, the simplicity and consistency interface are designed to facilitate and support the students' learning. Therefore, we propose a new learning tool, called *Aim-Math*. *Aim-Math* was evaluated in two aspects: whether *Aim-Math* can enhance students' understanding of exponents and what students' satisfaction on using *Aim-Math* in learning exponents.

2 Literature review

Employing technology-based learning environments for teaching and learning has also become a popular educational issue (Hwang and Fu, 2020). With their personal devices, their engagement of a subject matter including mathematics can be drawn (Wong, 2014; Bano et al., 2018; Yang et al., 2019). Thus, they can learn at their own free-time and pace. Bano et al. (2018) revealed that a number of researches focused on mobile learning for mathematics school education. Whereas, a few developed systems or applications were integrated with knowledge building. Teaching mathematics to students with visual impairment is different from teaching mathematics to ordinary students since the limitation of sight. Students with visual impairment can develop their mathematical skills and understand mathematical concepts if they are provided with the suitable assisted tools and instructions.

Assistive technologies can be instruments, devices and software that ordinary people or people with disabilities use to accomplish tasks or do the tasks easily. For example, Braille are added into protractors, and rulers to facilitate the students with visual impairment in measuring lengths and angles. An abacus is used not only to calculate numbers but also reduce their mental load. Other devices, e.g. a talking calculator, can be more helpful for mathematical computations in the higher level. Besides, graphing and speech synthesis software have been presented to flexibly provide mathematical information in real time. These assistive tools can reduce their limitation of sight in learning. However, to fulfil the competence of an assistive learning system, adequate support (e.g. guidance, feedback, prompts, tools) should be considered (Hwang and Fu, 2020).

A well-known Zone of Proximal Development (ZPD) was termed and defined by Vygossky since 1987. He proposed that a student can learn by performing tasks individually (zone of actual development), but they can build up the stronger and higher knowledge when collaborating with others (e.g., peers, parents and teachers) in the ZPD. To help a student reach his/her ZPD, we can design challenging tasks and activities with suitable help (scaffolding). When the student stabilises, the assistance will be withdrawn for further success (Wong, 2014). Milrad et al. (2013) suggested that an even greater challenge lies into how to shift the epistemological beliefs of individual learners from absolutism and transmissionism to constructivism and social constructivism. One of the scaffolds to help students learn is a learning activity using students' devices. Sequences of content play an important role with helping students understand a subject matter. Effective teaching and learning approaches are needed to make mathematics be meaningful for the students. Such approaches could help students link their prior knowledge with the new concept. In theories of mathematics education, exploration is viewed as an important process of learning (Bruner and Kenney, 1965; Karplus, 1977; Lawson et al., 1989; Pirie and Kieren, 1994). Instead of being told the content, students are expected to explore (see, touch, hear and manipulate) provided examples, and discover the concepts through hands-on activities with minimum guidance. Then, they will notice the similarity and difference of the examples related to their existing experiences. Finally, new concepts or new terms with the help of language and symbols are introduced with meaningfulness and fruitfulness.

The challenges lie on adapting pedagogies, course materials and technological design to accommodate students with visual impairment. Stone et al. (2019) suggested that a combination of strategies and resources would be necessary to fully accommodate a student with visual impairment. An example was auditory learning aid that may be a useful option or supplement for learning mathematics material. Children with visual impairment can memorise temporal auditory information better than sighted children, and many of them spontaneously use audio representation for numbers (Leuder, 2016). The sound-based mediation with real-time information of objects' speech and location were investigated in what way the system can support science learning by blind people (Levy and Lahav, 2012). The results showed the achievement in terms of construction of a conceptual understanding and process of learning. Most assistive mathematics learning systems for blind students intended to overcome the limitation of sight. There is a shortage of incorporating in the pedagogical design.

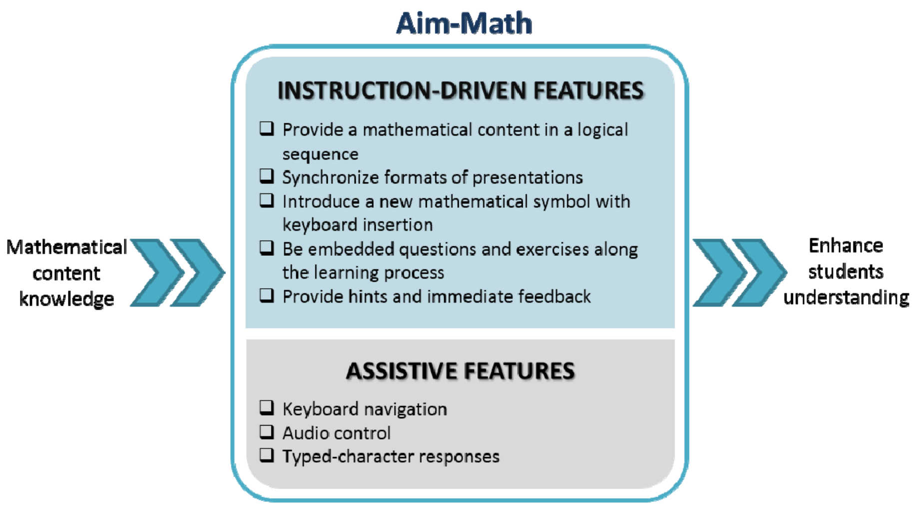
3 Aim-Math system design

Aim-Math system was designed in view of transforming learning practices with new technologies that enhance conceptual understanding, motivation, and attitude that lead to learning improvement. Therefore, *Aim-Math* includes necessary features for helping blind and visually impaired students in learning mathematics and all required utilities for interacting with the system conveniently.

All mathematical concepts are important for the students since they have hierarchical relationships. One concept might be a prerequisite for other concepts. To demonstrate the powerful potential of sounds for helping the students understand the concepts through an assistive learning tool, we prioritise concepts that can be illustrated by sound. In *Aim-Math*, the exponents concept is an example to present our idea. The exponent concept is the first introduction to a branch of algebra that symbols are used to represent arbitrary numbers. The exponent concept is the transitional stage from the world of numbers to the world of symbols. In the world of numbers, students can make sense of how many differences between numbers. For example, the students know $2 \times 3 = 6$. Even though the digits 2, 3 and 6 are symbols, students know their quantities or how many they are. So, they can operate (add, subtract, multiply and divide) numbers. However, in algebra (world of symbols) symbols, e.g. English letters, are used. We learn the rules to manipulate these symbols without knowing their quantities, e.g., $a^m \cdot a^n = a^{m+n}$.

Once the desirable concept is specified and its instruction plan is prepared, we focus on how to present the concept with the prepared instruction. Besides, interaction between *Aim-Math* and students with visual disabilities are emphasised to help them concentrate on the learning activities and enhance their understanding of the concept. Features of audio-based tools for students with visual disabilities are divided into two main parts: *instruction-driven features* and *assistive features* as shown in Figure 1.

Figure 1 A rational design of an audio interactive learning system



The instructional-driven features include how to increase students' motivation, maintain their interest in the instruction, and encourage them to think about and beyond what they are learning as followings:

- *Provide a mathematical content in a logical sequence*: Three-phase learning cycle approach (Karplus, 1977) is applied. Students are first encouraged to experience a concrete example (i.e. a multiplication table). Questions are used to guide and lead the students to connect this concrete representation with the abstract concept or expression for introducing a new concept. Finally, students apply the concept in different situations.

- *Synchronise formats of presentations (text, pictures and sound)*: Low-vision students could gain benefit from the displaying texts and pictures on the screen but totally blind students could not. Thus, speech sounds are synchronised to explain the instruction, convey mathematical expressions, ask questions and drop hints while the suitable non-speech sounds are used in the appropriate timing to represent parts of tables and pictures. *Aim-Math* utilises the speech generation of Thai and mathematical expressions from the *i-Math* system – an automatic math reader in Thai (Wongkia et al., 2012).

- *Introduce a new mathematical symbol with keyboard insertion*: Blind and VI students use a keyboard to interact with a computer. Using the keyboard to insert mathematical expressions remains a big barrier for students with visual disabilities since some symbols are not provided on a standard keyboard. For example, creating an exponent, 2^3 presents a difficulty for visually impaired students to insert the numbers ‘3’ in the superscript format using the keyboard. However, the students require this skill to present their mathematical ideas to their sighted friends or to their teachers. Therefore, the introduction of inserting mathematical expressions by the keyboard is necessary if the students face a new mathematical symbol.
- *Be embedded questions and exercises along the learning process*: Questions are not only used for evaluating students’ understanding but also for encouraging students to think about or beyond the concept. Likewise, exercises are provided for fluent performing in the concept and skills. Both questions and exercises are provided not only at the end of the instruction but also at the appropriate time along the learning process.
- *Provide hints and immediate feedback*: Appropriate hints are helpful to guide and direct students into the main points while feedback is able to increase the students’ motivation.

Assistive features are provided to facilitate visual disability students while using *Aim-Math*.

- *Keyboard navigation*: This feature can help students to fully control the learning tool instruction depending on their own pace and speed.
- *Audio control*: Pausing, repeating, and resuming audio are necessary to support the students’ requirements in the learning process.
- *Typed-character responses*: Each typed character has its immediate sound response to remind what the students are typing in.

To demonstrate the applicability of our design, the instructional-driven and assistive features are practically embedded in the implementation of *Aim-Math* to help the students understand the mathematical content and to facilitate them during the learning process.

4 *Aim-Math* implementation

Aim-Math is a system that does not require any assistive technology, e.g. screen reader systems, external text-to-speech systems, or special input/output devices. The only instruments required are a standard keyboard along with some form of audio device such as; speakers or headphones. All features embedded in *Aim-Math* are presented in this section.

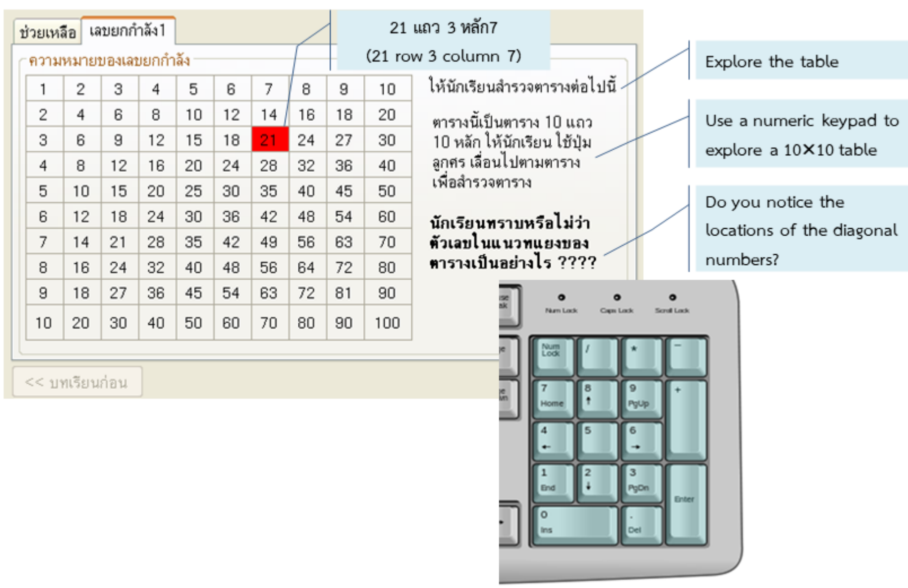
4.1 Instruction-driven implementation

4.1.1 Providing a mathematical content in a logical sequence (three-phase of learning cycle)

A three-phase learning cycle was provided for exponent concept formation:

Phase I exploration: *Aim-Math* provides the students with a multiplication table sized 10 × 10 and allows them to explore each number using a numeric keypad (Figure 2). Pressing buttons ‘8’, ‘2’, ‘4’ and ‘6’ on the keypad corresponds to the different directions: upwards, downwards, left and right, respectively. When a pointer stops moving for a few seconds, the sound is provided where each number is located. For example, when the pointer stops at the number, 21, (Figure 2) the Thai sound ‘*21 แถว*[1] *3 หลัก 7*’ is rendered to indicate its location.

Figure 2 A multiplication table sized 10 × 10 and the numeric keypad

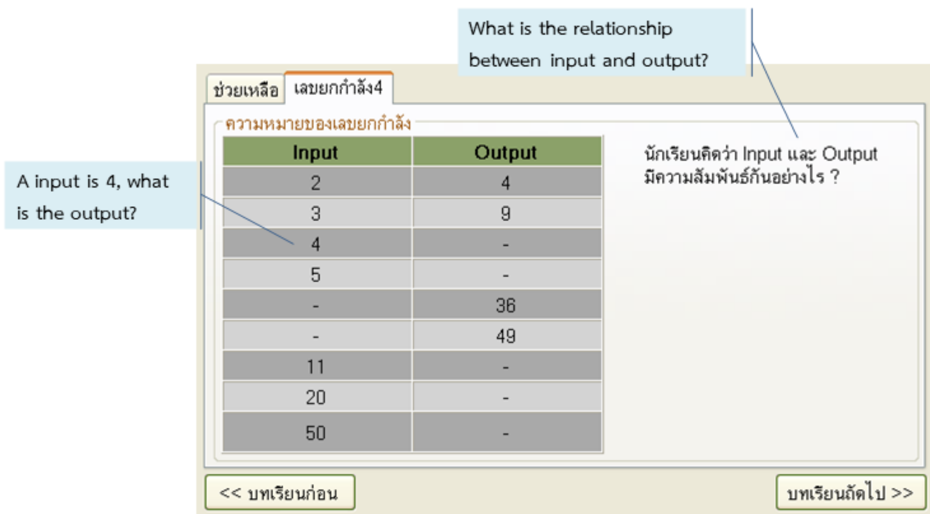


The students once explore the table along the diagonal line of the table where the square numbers are laid with pressing buttons ‘7’ and ‘3’ on the numeric keypad. Touching the numeric keypad not only allows students to control the pointer but also gives the students the mental idea of how a table looks like. These can lead the students to notice about square numbers and their locations laid along the diagonal line.

To lead the students into the concept, *Aim-Math* poses a series of questions. The first question is ‘*If a square table has 2 rows and 2 columns, how many cells do you need totally?*’. The answer should be 4. Two different methods could be applied to find an answer. Firstly, students can directly count the number of buttons while touching the numeric keypad, e.g. 4 buttons are needed to form a square with 2 rows and 2 columns. Another method is multiplication of the number of rows and the number of columns, e.g. 2 rows multiplied by 2 columns is 4. Similarly, these two methods can be applied for the 3-row and 3-column square, and the 4-row and 4-column square. Then, *Aim-Math* asks the students to predict the pattern of the 7-row and 7-column square. In this case, the number of buttons on the keyboard is not enough for counting, so the students need to calculate by the multiplication method to get 49 cells. If the students could find the solution of this question, they will apply the multiplication method in finding the solution for further numbers. The counting method is no longer needed.

For more practice, students have to complete an Input-Output table (Figure 3) while *Aim-Math* provides necessary information to help students realise a relation of input and output. For example, Thai sounds representing '*Input is 2, output is 4'* and *'Input is 3, output is 9*' are generated to give students examples of the relationship. Consequently, *Aim-Math* asks for the related outputs when inputs are provided or ask for the inputs when their output is given. In addition, the students are guided to predict the pattern of output and led to the relation of input and output.

Figure 3 An input-output table



Phase II concept introduction: *Aim-Math* introduces the concept of exponents by presenting that '*3 * 3 can be written in short as 3^2 and is called 3 ยกกำลัง* (/yók-gam-lang/, to the power of) *2*' in Thai. At this point, a new mathematical symbol is introduced by keyboard insertion. The hat symbol '^' is introduced to represent the exponent sign in the writing form of exponents. Moreover, *Aim-Math* provides the students to practice more on exponent writing forms with the central idea of the Input-Output table (Figure 4).

Phase III concept application: To extend the concept of square numbers, *Aim-Math* asks the students to write 2^3 in the form of multiplication (Figure 5). To help them to calculate the value of the exponent, 2^3, *Aim-Math* provides guided questions: '*If you arrange cubes in 2 of length and 2 of width, how many cubes do you need?'* and *'If you arrange cubes in 2 of length, 2 of width and 2 of height, how many cubes do you need?'*. Students are asked to take this step further by finding the number cubes for '*3 of length, 3 of width and 3 of height*' and '*4 of length, 4 of width and 4 of height*'. Once, *Aim-Math* uses the familiar Input-Output tables for challenging the students to the different experiences, e.g. Output = Input^3, Output = 10^Input.

Figure 4 An introduction of the exponent concept

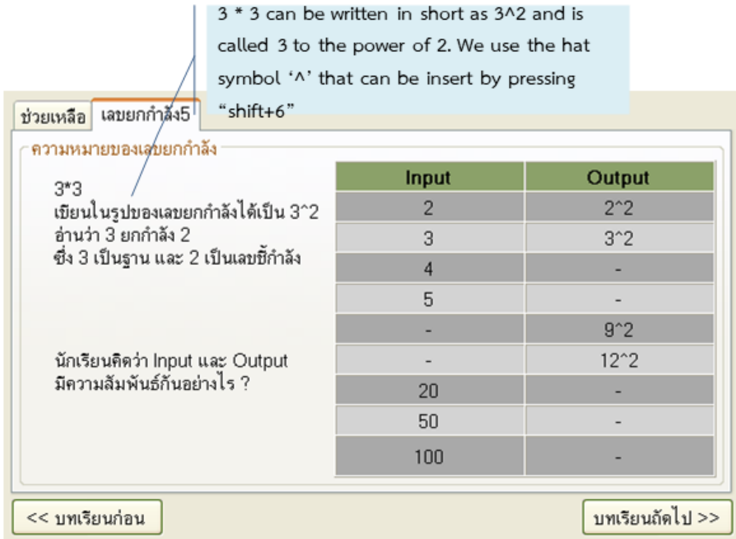
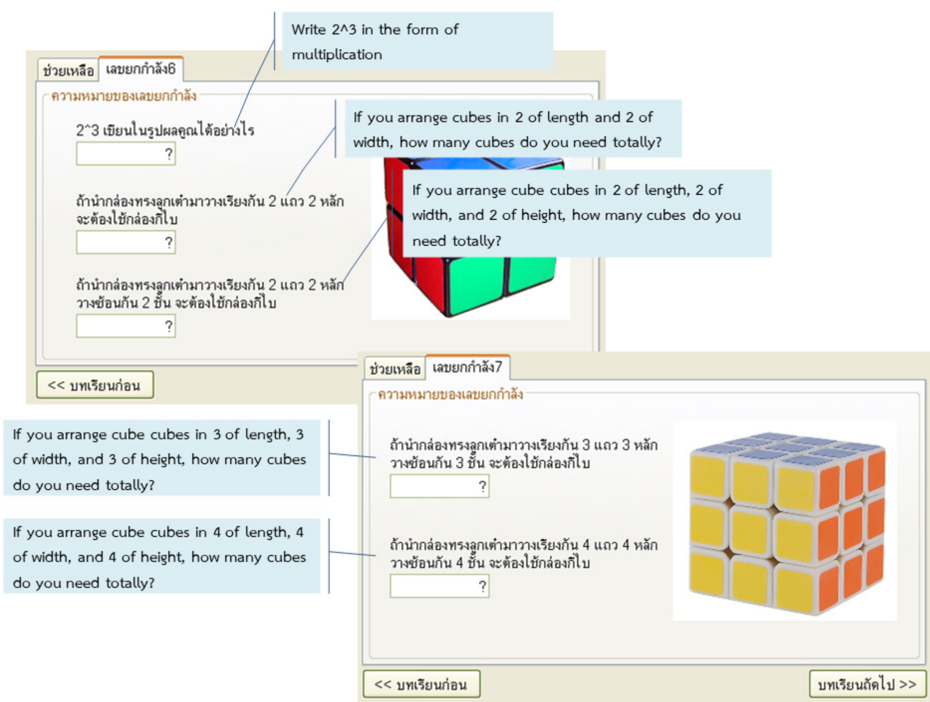


Figure 5 An extension of square numbers to a cube of numbers



4.1.2 Synchronising formats of presentations (texts, pictures and sounds)

To help the students focus on targeted objectives, the explanation sounds are rendered once at the time and allow the students to respond. For example, in Figure 2, *Aim-Math* firstly asks the students to explore the multiplication table with the sound *'Explore the table. (pause) Use a numeric keypad to explore the 10×10 table'*. Then, students are allowed to move the pointer around the table until they have finished exploring and pressing the Enter key. Every time the pointer moves, *Aim-Math* provides a non-speech sound 'Beep' to remind the students the pointer is moving. Higher pitch sounds, further right on a horizontal axis and shorter duration sounds, further down on a vertical axis. *Aim-Math* also provides pictures (Figure 5). Obviously, totally blind students cannot gain a benefit from the graphic displays on the screen, however, the students who are low-vision are able to enlarge the size and see the pictures. Moreover, teachers, parents or other assistants can use the graphic displays and texts during providing guidance.

4.1.3 Introducing a new mathematical symbol with keyboard insertion

To master the students' mathematical content and skills, the keyboard insertion of mathematical symbols is embedded (Figure 4). *Aim-Math* introduces two forms of expressions, i.e. a multiplication and an exponential expression. The star sign '*' is introduced instead of the multiplication sign '×' while the hat sign '^' refer to the to-the-power-of sign since these two signs can simply insert using a standard keyboard by pressing 'Shift+8' and 'Shift+6', respectively.

4.1.4 Being embedded questions and exercises along the learning process

As illustrated in Figures 2 to 5, *Aim-Math* asks several questions to engage students in thinking. For example, the question: '*Do you notice the locations of the diagonal numbers?*' (Figure 2) is asked for guiding the students to notice the diagonal numbers are located and encourage the students to begin exploring the diagonal numbers of the table. Besides, the question *'Could you predict the number of cells, if a square table has 7 rows and 7 columns?'* helps the students to think beyond what they can observe. To frame the students' idea of the relationship of input and output, *Aim-Math* asks the question '*What is the relationship between input and output?*' as shown in Figure 4. Besides, *Aim-Math* helps students practice at the appropriate time of the instruction by providing exercises both in forms of questions (Figure 5) and Input-Output tables (Figure 3). *Aim-Math* also challenges the students to do more complicated exercises.

4.1.5 Providing hints and immediate feedback

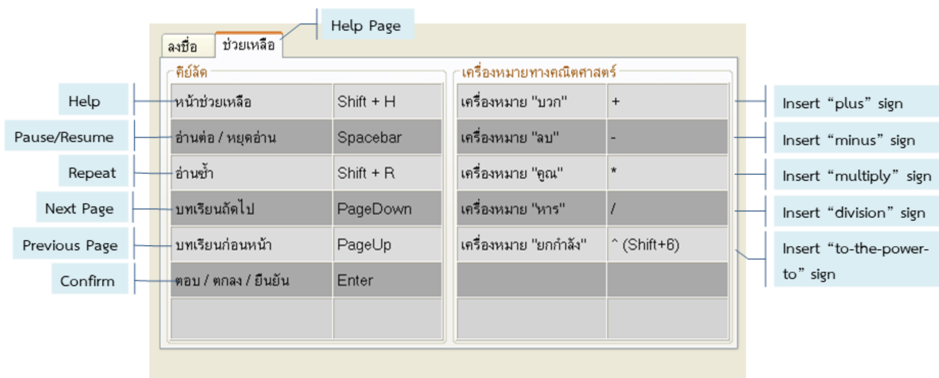
When the students submit an answer (pressing Enter), it will be checked to determine whether it is correct or not. If it corrects, the students will immediately receive the correct feedback and automatically go to the next question. Otherwise, the students will receive a hint. The users can then try to input their new answer. After checking, if the new answer is still incorrect, the students will be provided the correct answer and explanation. The feedback, hint, and explanation are provided in text format with synchronising sound.

4.2 *Assistive feature implementation*

4.2.1 *Keyboard navigation*

Aim-Math has both a visual interface for visually impaired students and completely auditory interface for blind students with keyboard navigation. Students who are totally blind are not familiar with using a mouse so we design to use a keyboard, arrow, and numerical keypad for moving a cursor. Besides, a help page is provided to describe keyboard controlling both in text and sound by pressing *H* on the keyboard (Figure 6).

Figure 6 A help interface



4.2.2 *Audio control*

During sound rendering, Spacebar is used to pause and resume sound. The sound can also repeat for the whole sentence, if the students press *R* on the keyboard.

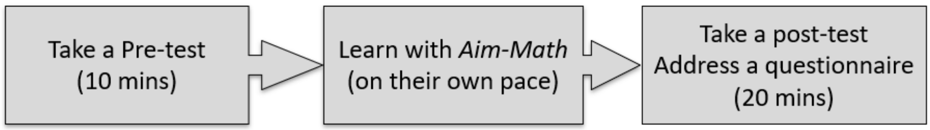
4.2.3 *Typed-character responses*

To help the students fully interact with *Aim-Math*, *Aim-Math* converts numbers, mathematical signs and notations into sounds. The sounds are immediately played aloud to help the students verify what they have typed in.

5 Research methodology

We conducted the experiment by voluntary visually impaired participants from schools for the blinds in Thailand. Pre-test, intervention and post-test design was employed. The purposes and benefits were described to all participants before the data collection begins. Their personalities were kept as private information. They took a 10-minute pre-test to assess their prior knowledge of exponents. The participants were asked to use *Aim-Math* outside their classroom. All students' interactions with *Aim-Math* were automatically recorded into electronic data (log files) for analysis and evaluation. Their learning spending continues at their own pace. The learning time started recording when a student logged in to *Aim-Math* and stopped recording when the student completed his/her post-test. They took a parallel post-test to evaluate their knowledge of exponents and addressed the questionnaire which took up to 20 minutes. All items of the questionnaire about the students' satisfaction were read aloud. The research design of this study shows in Figure 7.

Figure 7 Research design



5.1 Students' understanding of exponents

To illustrate the performance of *Aim-Math* in helping students understand the exponents, we designed a test to assess students' understanding of exponents. *Aim-Math* reads each item one by one. Each item reached one of four learning objectives:

1) Write an exponent representation into a multiplication form (Item 1st–2nd).
2) Convert a whole number to an exponent representation (Item 3rd–5th).
3) Convert an exponent representation into a whole number (Item 6th–8th).
4) Compare two exponents (Item 9th–12th).

The same set of questions was used again in post-test after students learned and practiced via *Aim-Math* with feedback and hints if the students cannot correctly answer at first time. All students' answers both in pre-test and post-test were automatically collected with one point marked for each correct answer, and the total scores of the test was 12. The average scores of all students in both the pre-test and post-test were calculated to compare whether the average pre-test score was different from the average post-test score with 95% confidence level. Then, we compare students' pre-test and post-test scores to see how many percentages that the students can gain more scores after learning with *Aim-Math*.

5.2 Students' satisfaction

We also investigated visually impaired students' satisfaction of using *Aim-Math*. A rating scale questionnaire was used to follow up students' opinions after using our system. We adapted Davis's questionnaire (1989) to measure how users accept and use a technology when the users were presented with a new technology, here is *Aim-Math*. Our designed questionnaire was approved by three experts who had experience in computer and technology in education. The Item-Objective Congruence (IOC) was 0.95 and Cronbach's alpha measurement was 0.70 which indicates that the designed questionnaire is valid and reliable. The students were asked to rate on a five-point rating scale (5-strongly agree, 4-agree, 3-neither, 2-disagree and 1-strongly disagree). After the questionnaire was completed, the items were analysed separately. All scores are presented by frequencies, and means. Moreover, the students were asked to give additional comments and suggestions.

6 Results

Two schools for the blinds in Thailand agreed to participate in this research. Twenty-one students who had mathematical knowledge in Grade 7–9 were recruited to participate in this study. They were 14 blinds (8 males and 6 females) and seven low vision students (four males and three females). They ranged in age from thirteen to nineteen (*mean* = 16.86, *sd* = 1.01). Fictitious names were used to protect the students' privacy.

6.1 Results of students' understanding of exponents

All participating students have learned the exponent concept in their regular classes. However, they have a variety of different understandings. A minimum pre-test score was zero while a maximum score was ten. The range was high because some students were unfamiliar with using *Aim-Math*, they had little understanding of the exponent concept and also synthesised sounds were unnatural.

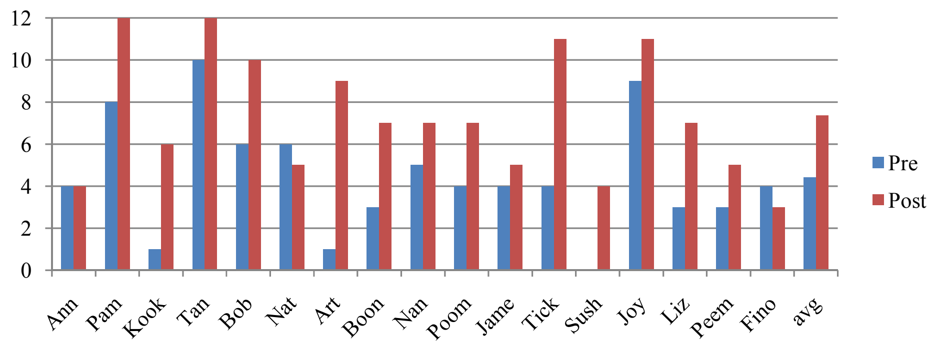
The students learned the exponent concept once again via *Aim-Math*, then they were asked to complete the post-test. Unfortunately, during the data collection four students could not complete their learning and post-test. Thus, their data were excluded from our students' understanding analysis part. However, four excluded students were willing to give responses on the questionnaire. Therefore, our data analysis in the part of understanding came from seventeen students, while the part of satisfaction was interpreted from the data of 21 students. Averages of pre-test and post-test scores were shown in Table 1. The test scores were numeric data. There were no outliers in the data, as assessed by inspection of a boxplot. The difference between pre-test and post-test scores are normal distribution (*Shapiro-Wilk's* $W = 0.951$, $p = 0.471$), the paired sample t test was calculated.

Table 1 Paired sample t test of pre-test and post-test scores for 17 students

	N	*Mean*	*sd*	*t*	*Df*	*Sig. (2-tailed)*
Pre-test	17	4.41	2.96	4.88	16	0.00
Post-test	17	7.35	2.74			

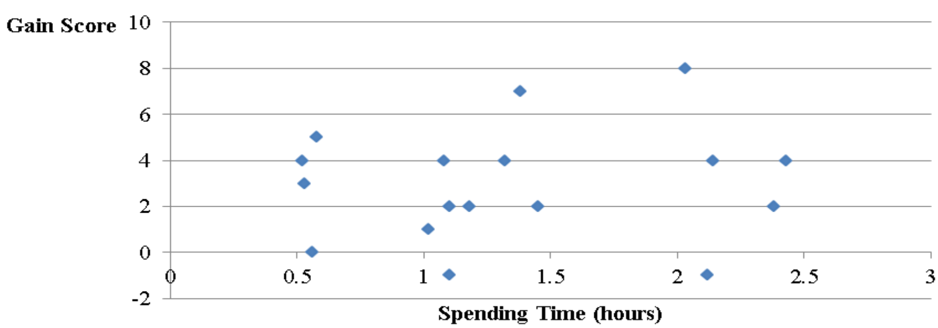
The post-test average score (7.35 out of 12, *sd* = 2.74) showed that they significantly gained better scores than the pre-test (4.41, *sd* = 2.96). Figure 8 illustrates that fourteen students gained the pro-test score higher than the pre-test scores. Nat and Fino have got one post-test score lower than pre-test score. Nat spent approximately 1 hour and 10 minutes working with *Aim-Math* (average = one and a half hours). During lessons and exercises, he went backward to correct some exercises. Although he was blind, he used the repeat function only nineteen times (average = 28 times for blind students) and the backspace function that also showed his good ability of using the computer. However, he might be tired or bored listening to a long continuous period. Thus, in the post-test he did not attend to complete it since he did not submit answers for his second chance even though he was provided that chance. Fino spent approximately 2 hours and 10 minutes which is very long compared with the average time (one and a half hours). He was low-vision whereas he pressed Backspace more than 75 times (average = 50 times for low-vision students). It indicated that he was not confident about his answers.

Figure 8 Comparison between pre-test and post-test scores



The students used *Aim-Math* based on their speed. They could work with *Aim-Math* anytime as long as they want. Figure 9 indicated that time consuming has no effect on students' gain scores (the difference between post and pre-scores). Students could be classified into three groups based on their time consuming: a half hour, 1–1.5 hours and 2–2.5 hours. However, three groups show a variety of different gain scores. For example, Art who gained eight more scores in post-test spent about two hours while Tick got seven gain scores with one and a half hour spending time. Therefore, we can conclude that *Aim-Math* enhanced the students' understanding of this concept and it also allowed students to learn the exponent concept at their own pace.

Figure 9 Relationship between spending times and gain scores



6.2 *Results of students' satisfaction*

After students had experienced using *Aim-Math*, the questionnaire on usefulness and ease of use of *Aim-Math* was read out loud to the students. After the questionnaire, the students provided some suggestions for further improvement. Table 2 shows frequencies calculated in questionnaire items responded by 21 students. It shows that the students had positive perception toward the use of *Aim-Math*.

Table 2 Frequencies of questionnaire items responded by 21 students

Questions	*5*	*4*	*3*	*2*	*1*	*Mean*
Aim-Math helped me understand the exponent concept.	9	9	3	0	0	4.29
Aim-Math helped me to pay more attention in studying.	10	8	2	1	0	4.29
Aim-Math reduced time consumed in practicing mathematics.	6	4	10	0	0	3.80
Aim-Math was useful in studying the exponent concept.	13	7	1	0	0	4.57
Aim-Math was easy to use.	14	5	2	0	0	4.57
I am willing to use the system like *Aim-Math*, if it has in studying other topics of mathematics.	17	4	0	0	0	4.81
I will recommend *Aim-Math* to my friends.	18	3	0	0	0	4.86

Table 2 displays the results from the questionnaire. The top three votes in the category of agreement were: I will recommend *Aim-Math* to my friends, I am willing to use the system like *Aim-Math*, if it has in studying other topics of mathematics, and *Aim-Math* was easy to use. The other results in the questionnaire show that students were still, at the very least, satisfied with their experience with *Aim-Math*. Students found *Aim-Math* as a usable tool that can help them pay more attention while studying as well as help them in understanding the exponent concept. In addition, the least voted item (Item 3) was that ten students reported that *Aim-Math* reduced time consumption in practicing mathematics. It might be because unnatural sounds generated by *Aim-Math* and students could not adjust the sound speed rate according to their preference.

Majority of students thought that *Aim-Math*'s speeches are understandable, however, a few stated speeches were too slow, needed to state more clearly and more natural human-like speech and they also recommended that users should be able to adjust the speed of sound. Some students said that they liked the keyboard control to navigate the system. For example, 'Repeat' function was helpful. Most students appreciate the sound of numbers, mathematical operations, and character when the buttons were pressed since they were told what was being typed. Moreover, some students recommended that they should be told what was being deleted as the backspace was pressed. As *Aim-Math* did not allow students to go forward and backward during pre-test and post-test, a few students thought that they should have a chance to correct the questions they have passed. Moreover, the students also suggested that it should have the learning tool like *Aim-Math* in other topics of mathematics and other subjects.

7 Discussion and conclusions

7.1 Discussion

The discussion addresses the instruction-driven concept and interactions with audio-synchronization. According to the limitation of the population who are students with visual impairment in secondary level, it is important to note that a limitation in the design of this study is the small sample size. Future research will enlarge the sample size.

The evaluation results indicated that *Aim-Math* could enhance students' understanding of exponents since *Aim-Math*'s features aligned with the study of Spinczyk et al. (2019). They proposed seven factors that influence the process of learning mathematics for students with visual impairment including behavioural, emotional, cognitive, motivational, social, distracting and modelling factors. *Aim-Math* satisfied five of seven aspects that affect the learning of mathematics. The first, behavioural aspect, *Aim-Math* allows students to learn at their own pace and gain independence of learning. Secondly, emotional aspects, students can control their own pace of learning depending on individual student's abilities. Thirdly, cognitive aspects, students can concentrate on important information relevant to the learning objectives. However, *Aim-Math* only allows the students to twice input their answers in each question before submitting their answer. It has no ability to fold back to any previous question. Future design to add an ability to repeat the task solving from any stage may provide. Next, distracting aspects, *Aim-Math* provide the simple way to acquire knowledge in mathematics. The plain designed and structural information can help students to focus on the content. Finally, motivation aspects, students receive hints and feedback for their progress as a form of motivation to continue learning mathematics.

In the aspect of interactions with audio-synchronisation, the learning activity started with a concrete exploration of the number keypad and its corresponding sound with increasing-decreasing pitch, short-long duration sounds and speech sound of number to let students notice square numbers (Edwards and Stevens, 1993). Cube numbers and other exponent numbers went beyond this exploration since those sound designs could represent two dimensions. Future research should address three-dimension and further by using touchable objects (Barbe and Milone, 1981; Stone et al., 2019) or other non-speech sounds with varieties of pitch, timbre, rhythm, and dynamics (Power and Jürgensen, 2010) as symbolic of the communication. We clearly see from the log files that students put their effort to interact with *Aim-Math*. They frequently used the keystroke 'Shift + R' to repeat the instruction or question sound (Sánchez, 2008; Levy and Lahav, 2012). However, we found a limit to the new introduction of a mathematical symbol to insert the 'to-the-power-to' sign. When the students wanted to insert the symbol with the keystrokes '* (Shift + 6)', they pressed wrong keystrokes around the '6', deleted the wrong one, and pressed the new one again and again. Instead of focusing on the learned concepts, the times were spent according to such a reason. The relationship between spending times and gain scores still showed that students could learn with their own speed to reach the expected outcomes and overcome the unfamiliar keystroke input. Additional training to help the students are familiar with the keystroke may be more beneficial to learning.

7.2 Conclusions

In developing a learning tool for students with visual disabilities, we have to carefully consider two aspects: students' understanding and satisfaction. Two main features (i.e. necessary instruction-driven and required assistive features) were emphasised to serve students' learning and satisfaction. The instruction was designed to help the students develop the concept according to the mode of learning. Both speech and non-speech sounds were used to both present the content and communicate between the students and the system.

All features were practically embedded in *Aim-Math* to provide the exponent concept sequentially, synchronise formats (i.e. pictures, texts and sounds) for presenting the content, introduce keyboard insertion for mathematical symbols, use questions and exercises along the instruction and provide appropriate hints and feedback. In addition, keyboard navigation, audio control and typed-character responses were provided to facilitate students to interact with *Aim-Math*. It also allowed students to learn the concept at their own pace anywhere and at any time. The analysed questionnaire indicated that the students had positive perceptions toward the use of *Aim-Math*. Meanwhile, *Aim-Math* demonstrated an integration of audio technologies and pedagogical approaches to promote mathematical understanding and motivation for students with visual disabilities.

The development and results of this study present the possibilities of enhancing quantity and quality of personal, portable, wirelessly-networked technologies in mathematics for students with visual disabilities. Practitioners, teachers and other educators can select the desirable mathematical contents, design their own learning activities and teaching strategies or adapt from other available sources, and importantly include the system design of instructional-driven and assistive features in developing *Aim-Math*-liked systems.

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References

Awdé, A., Hina, M.D., Tadj, C., Bellik, Y. and Cherif, A.R. (2008) 'Middleware for ubiquitous access to mathematical expressions for visually-impaired users', *Ubiquitous Computing and Communication Journal (UBICC)*, Vol. 3, No. 5, pp.27–41.

Bano, M., Zowghi, D., Kearney, M., Schuck, S. and Aubusson, P. (2018) 'Mobile learning for science and mathematics school education: a systematic review of empirical evidence', *Computers and Education*, Vol. 121, pp.30–58. Doi: 10.1016/j.compedu.2018.02.006.

Barbe, W.B. and Milone, M.N. (1981) 'What we know about modality strengths', *Educational Leadership*, pp.378–380.

Bayram, G.I. (2014) *Exploring the Academic and Social Challenges of Visually Impaired Students in Learning High School Mathematics*, Master thesis, Bilkent University, Turkey.

Bruner, J. and Kenney, H. J. (1965) 'Representation and mathematics learning', *Monographs of the Society for Research in Child Development*, Vol. 30, No. 1, pp.50–59.

Cercone, N. (2013) 'Introduction', in Cercone, N. and Naruedomkul, K. (Eds): *Computational Approaches to Assistive Technologies for People with Disabilities*, IOS Press, Amsterdam, pp.3–9. Doi: 10.3233/978-1-61499-258-5-3.

Davis, F.D. (1989) 'Perceived usefulness, perceived ease of use, and user acceptance of information technology', *MIS Quarterly*, Vol. 13, No. 3, pp.319–340.

Edwards, A.D.N. and Stevens, R.D. (1993) 'Mathematical representations: graphs, curves and formulas', Burger, D. and Sperandio, J.C. (Eds): *Proceedings of the INSERM Colloquium, Non-Visual Human Computer Interactions*, UK, pp.181–193.

Hwang, G.J. and Fu, Q.K. (2020) 'Advancement and research trends of smart learning environments in the mobile era', *International Journal of Mobile Learning and Organisation*, Vol. 14, No. 1, pp.114–129. Doi: 10.1504/ijmlo.2020.10024691.

Karplus, R. (1977) 'Science teaching and the development of reasoning', *Journal of Research on Science Teaching*, Vol. 14, No. 2, pp.169–175.

Lawson, A.E., Abraham, M.R. and Renner, J.W. (1989) *A theory of instruction: using the learning cycle to teach science concepts and thinking skills*, National Association for Research in Science Teaching (NARST) Monograph, Number One, Department of Science Education, College of Education, University of Cincinnati, Cincinnati, USA.

Leuders, J. (2016) 'Tactile and acoustic teaching material in inclusive mathematics classrooms', *British Journal of Visual Impairment*, Vol. 34, pp.42–53. Doi: 10.1177/0264619615610160.

Levy S.T. and Lahav, O. (2012) 'Enabling people who are blind to experience science inquiry learning through sound-based mediation', *Journal of Computer Assisted Learning*, Vol. 28, pp.499–513. Doi: 10.1111/j.1365-2729.2011.00457.x.

Mani, M.N.G., Plernchaivanich, A., Ramesh, G.R. and Campbell, L. (2005) *Mathematics Made Easy for Children with Visual Impairment*, Towers Press, Overbrook School for the Blind, Philadelphia, P.A.

Milrad, M., Wong, L.H., Sharples, M., Hwang, G.J., Looi, C.K. and Ogata, H. (2013) 'Seamless learning: an international perspective on next generation technology enhance learning', in Berge, Z.L. and Muilenburg, L.Y. (Eds): *Handbook of Mobile Learning*, Routledge, New York, pp.95–108.

Mishra, P. and Koehler, M.J. (2006) 'Technological pedagogical content knowledge: a framework for teacher knowledge', *Teacher College Record*, Vol. 108, No. 6, pp.1017–1054. Doi: 10.1111/j.1467-9620.2006.00684.x.

Pirie, S. and Kieren, T. (1994) 'Growth in mathematical understanding: how can we characterize it and how can we represent it?', *Educational Studies in Mathematics*, Vol. 26, pp.165–190. Doi: 10.1007/BF01273662.

Power, C. and Jürgensen, H. (2010) 'Accessible presentation of information for people with visual disabilities', *Universal Access in the Information Society*, Vol. 9, No. 2, pp.97–119.

Raman, T.V. and Gries, D. (1995) 'Audio formatting–making spoken text and math comprehensible', *International Journal of Speech Technology*, Vol. 1, pp.21–31. Doi: 10.1007/BF02277177.

Sánchez, J. (2008) 'User-centered technologies for blind children', *Human Technology: An Interdisciplinary Journal on Humans in ICT Environments*, Vol. 4, No. 2, pp.96–122. Doi: 10.17011/ht/urn.200810245832

Spinczyk, D., Maćkowski, M., Kempa, W. and Rojewska, K. (2019) 'Factors influencing the process of learning mathematics among visually impaired and blind people', *Computers in Biology and Medicine*, Vol. 104, pp.1–9. Doi: 10.1016/j.compbiomed.2018.10.025.

Stevens, R.D., Edwards, A.D.N. and Harling, P.A. (1997) 'Access to mathematics for visually disabled students through multimodal interaction', *Human-Computer Interaction*, Vol. 12, pp.47–92. Doi: 10.1207/s15327051hci1201&2_3.

Stone, B.W., Kay, D. and Reynolds, A. (2019) 'Teaching visually impaired college students in introductory statistics', *Journal of Statistics Education*, Vol. 27, No. 3, pp.225–237. Doi: 10.1080/10691898.2019.1677199.

Toyosaka, Y., Ogino, Y. and Fukuda, R. (2016) 'Evaluation of mathematical information created by a text-based communication tool for visually handicapped', *Universal Learning Design*, Vol. 45.

Wong, G.K.W. (2014) 'Engaging students using their own mobile devices for learning mathematics in classroom discourse: a case study in Hong Kong', *International Journal of Mobile Learning and Organisation*, Vol. 8, No. 2, pp.143–165. Doi: 10.1504/IJMLO.2014.062352.

Wongkia, W., Naruedomkul, K. and Cercone, N. (2012) 'I-Math: automatic math reader for thai blind and visually impaired students', *Computers and Mathematics with Applications*, Vol. 64, No. 6, pp.2128–2140. Doi: 10.1016/j.camwa.2012.04.009.

Yang, Q.F., Lin, C.J. and Hwang, G.J. (2019) 'Research focuses and findings of flipping mathematics classes: a review of journal publications based on the technology-enhanced learning model', *Interactive Learning Environments*, pp.1–34 Doi: 10.1080/10494820.2019.1637351.

Zhou, L., Parker, A.T. Smith, D.W. and Griffin-Shirley, N. (2011) 'Assistive technology for students with visual impairments: challenges and needs in teachers' preparation programs and practice', *Journal of Visual Impairment and Blindness*, Vol. 105, No. 4, pp.197–210. Doi: 10.1177/0145482X1110500402.

Note

1 The Thai words "แถว (/tăe/, row)" and "หลัก (/làk/, column)" are used to indicate location of numbers on the table.