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SIGHT, TOUCH, HEARING – THE CURRENT DIGITAL OPTIONS AND CHALLENGES IN ACCESS TO MATH CONTENT FOR LEARNERS WITH VISUAL IMPAIRMENTS

Abstract: Mathematics as a mandatory subject for *matura* exams needs to be taken by all high school students, including those with visual impairments. Naczelna Izba Kontroli (or Supreme Audit Office) reported in 2012 that 45% of Polish schools had inadequate learning material for learners with disabilities. It seemed prudent to investigate whether teachers and students have options to choose from. Furthermore the author implies that for any existing digital learning aids to be effective, the best format should be established. Available solutions usually have a combination of input and output methods ranging from visual, auditory to tactile or vibro-tactile systems. The author also discusses advantages and disadvantages of traditional versus digital learning aids and teachers' views of available accessible math instructional solutions.

Keywords: mathematics, visual impairments, STEM, digital, accessible.

Introduction

Mathematics has been listed again as a mandatory subject for final exams called *matura* at Polish high schools. As such it is also taken by students with visual impairments that is those who are blind or have low vision. Their success depends on a composition of several factors, including learning aids and technologies that support access to and understanding of mathematical concepts. Rubin, Faderewski and Mikułowski's report (2015) indicates that nearly 30% of the parents are unsatisfied with the quality of learning supports offered to their children with visual impairments. This finding is in line with what Naczelna Izba Kontroli (or Supreme Audit Office) foundout during their school inspection in 2012. As many as 45% of school have inadequate learning material adaptations and specialized educational equipment. Similar conclusions were drawn by NIK in 2017 during which astounding 75% of schools did not use available funding that could be spent to provide appropriate specialized services and teaching methods (2018). It appears that before school authorities, supervisors and eventually teachers are criticized for the described situation, it is worth investigating the availability of high end technology that can support learners with visual impairments in their math education. Furthermore, it is prudent to understand how to implement the existing, if any, learning technologies to achieve expected educational outcomes.

Students with visual impairments have a choice of visual, auditory, and tactile access or a combination of the above modalities. Each of them has its strengths and downsides contributing to difficulties students with visual impairments are still challenged with in mastering their mathematical skills. It appears crucial to define the most natural user interface that will meet individual needs for the least restricted access to math. Science, technology, engineering and math (STEM) areas have become essential for knowledge-based economies. We can assume that people with disabilities capable of mastering physics, chemistry or mathematics could participate in productive activities and further development of STEM areas. And yet the most recent research still indicates low percentages of learners with visual impairments interested in sciences and math.

Digital offerings

The digital technology has greatly contributed to the development of educational tools and systems that opened up hitherto inaccessible venues to text information for people with visual impairments. Recent years have also brought about digital solutions for math and sciences. Literature discusses numerous systems highlighting their strengths but also noticing potential issues that may have educational and social implications. A successful implementation of those solutions is dependent upon their technical merits but also the human factor represented by the teaching staff and their students.

NUI or natural user interface can be defined as one that allows users to interact with systems the same way they interact with real world (Widgor 2011). Learners with visual impairments will either use all senses, including residual vision, or compensate for the missing sight by strengthening their remaining senses. A clear understanding of how a particular student interacts with their surrounding will facilitate their access to and mastery of mathematical concepts. Digital and physical mathematical learning aids can be accessed in one of the three modalities – sight, audio, or touch. The most appropriate format will be determined by the student's particular learning styles, preferences, needs and abilities as well as by the type of activities students are supposed to complete (Koenig & Holbrook 1995; Wiazowski 2015; Wiazowski 2016). Several diagnostic instruments like Learning Media Assessment, WATI Assistive Technology Decision Making Guide, or other technology skills and needs assessments will ensure that observations and direct interviews with students lead to the most optimized selection of math learning tools (Wiazowski 2016).

A rapid development of text-to-speech technologies opened up broader avenues to accessing math. Special software reads even more complex mathematical expressions giving students who are blind less restricted access to math. Good examples of such software are ReadHear or MathPlayer (Alajarmeh & Pontelli 2012; Bouck, Joshi, Meyer & Schleppenbach 2013). Several other regional propositions like MiniMatecaVox can also be found (Henderson, S. (2014). Alajarmeh & Pontelli (2012) have noticed improved accuracy and decreased amount of time students with visual impairment may need to complete algebra activities when e-text is used vis-a-vis peers who work with magnification or Braille. Electronic text turned out to help learners with visual impairments comprehend math better (Bouk et al. 2013). Those digital readers are of particular importance because as of now screen readers commonly used to read digital text treat mathematical expressions as inaccessible images (Archambault, Caprotti, Ranta, & Saludes 2012; Cooper, Lowe, & Taylor 2008) unless math information is encoded in the MathML markup language or LaTex (Gardner 2014).

"a plus b over c" $a + \frac{b}{c}$ or $\frac{a+b}{c}$

Auditory access alone however may pose difficulties in interpreting a read expression like the one with complex fractions (Power & Jorgensen 2010). This is the reason audio information may have to be coupled with a tactile format as soft braille on a Braille device or Braille hard copy. Literature provides examples of expressions that pose potential issues with interpretation. It is an addition of an integer with a fraction. Some authors use specific numbers, while others exemplify this situation in a more algebraic format (Wongkiaa et al. 2012):

Other examples presented by Wararat Wongkiaa and others are fractions or powers where a learner may be confused by the syntax of the math expression (Wongkiaa et al. 2012). As seen above the digital presentation of mathematics may cause some level of ambiguity. Maćkowski, Brzoza and Spinczyk of Silesian University note a lack of standards for reading math formulae in Poland. Teachers customize the interpretation of the formulae according to the age and level of proficiency of their students (2018). In the long run it leads to numerous confusions and poor understanding of mathematical concepts.

To complement and enhance the voice output some solutions propose the addition of pitch changes and duration to differentiate between the base and super- or subscript. The prosody, however interesting may seem, is not a universal solution because of tonal languages spoken in Asia. It must be stressed here that changes in pitch are less cognitively demanding than extra wording suggested in AsTeR, MathPlayer, or Math Genie and follows the same concepts tested and implemented in some screen readers, known as earcons. Earcons as defined by

Blattner, Sumikawa, and Greenberg (1989) constitute "nonverbal audio messages that are used in the computer/user interface to provide information to the user about some computer object, operation or interaction" (p.13). Wiazowski (2009) notices the usefulness of earcons in math for interpreting mathematical and geometrical data. Non-verbal sonification adds extra cues to numerical expressions and recreates graphs acoustically. Apart from AudioTalking Calculator by ViewPlus, similar sonic concepts have been applied in Desmos, a free online graphing application, and PlatMat, a comprehensive math modular application (Brzostek et al, 2016).

Other math reading systems offer content output in both audio and Braille (TRIANGLE, REMathEx or LAMBDA). The multimodal access to math expressions was proposed to support individual preferences. As such it follows the concepts of universal design where tools are designed with many different users in mind. However, due to less complicated development and maintenance, researchers and developers focus more of their resources on single mode output solutions (Wongkiaa, Naruedomkulb & Cercone, 2012).

According to Regec (2016) teachers in Czech schools have a wide range of tools at their disposal. The Blind Moose editor developed at the Masaryk University in collaboration with the Teiresias Center is an MS Word set of macros for entering and editing math expressions in a linear format. It is accessible for all students regardless of their vision condition. The drawback of this solution is a lack of internal Tex and MathML converters. Despite certain shortcomings, The Blind Moose is praised by the author due to the native implementation of the Czech Braille code. LAMBDA is yet another conversion application teachers have at their disposal. This is a tool developed as part of an international project. The acronym stands for Linear Access to Mathematic for Braille Device and Audio-synthesis. The LAMBDA code can be presented in 8-dot Braille on the Braille display and visually translated into a standard print notation. Occasionally MathType and Math Equation Editor within MS Word are used to compose math worksheets.

EuroMath is a project aiming at a development of an international math system that supports teachers and their learners with or without visual impairments. It is an expansion of the PlatMat tool (platmat.org.pl). This tool is a multimodular mathematical application enhanced by a set of features and functions that allow for multimedial access to educational content. Learners receive instructional support that guides them to solve activities prepared by the teachers, exchange worksheets with their peers or submit homework to the teacher for correction. The two key features of EuroMath are a unified system used by teachers and their students, regardless of their visual condition, and multimodal input and output system for mathematical expressions, text based activities and mathematical graphics. Learners can read the content visually, auditorily, or tactilely according to their needs and preferences.

Accessing Graphics

Graphics related to mathematical activities usually involve diagrams, tables, or graphs. Tekli and others (2018) chose a different route assessing the efficiency of vibro-tactile solutions. They consider these a separate group from software or hardware-based options for accessing mathematical graphics. Vibro-tactile technology has forked into two different pathways. One is based on an audio--kinesthetic interface, known most commonly, from today's smartphones. The other one is known as a vibro-audio interface where a vibration under the user's finger is coupled with auditory labels (Poppinga et al., 2011; Giudice et al., 2012). Another example of a system that combines two access modalities are haptic boards like Tactile Talking Tablet or iVEO. A tactile overlay is placed over a touch sensitive board with digital text descriptions or acoustic signals programmed into it (Gardner, 2016). When a student comes across an interesting spot on the overlay, they apply a bit of pressure on the spot to either hear a digitized voice read the content or a digital sound that corresponds to the tactile image. Bateman, Zhao, Bajcsy, Jennings, Toth, Cohen, and Oliveira, criticize limitations of such systems and propose electrostatic haptics that is more refreshable making the changes in the image more dynamic (2018). Students are not confined to what had to be designed by their teachers prior to the instructional situation.

Apart from traditional tactile images even if paired up with vibro-tactile, touch sensitive or electrostatic platforms, learners with visual impairments can access graphs and charts with mainstream solutions that initially had not been developed with blind students in mind. Doush et al. mentions the Novint Falcon, a device for gaming that replaces a computer mouse but adds extra tactile and acoustic sensations (2010). Learners can either passively experience graphics or actively interact with a virtual 3D object.

Digital and/or traditional?

The digital textbook content opens up further access to educational content. New editions of textbooks and other educational material appear to be more friendly and accessible to learners with visual impairments. Nees and Berry (2013) notice that accessibility refers mostly to reading and writing text. Tools that allow for entering and reading math expressions and formula in digital formats are still greatly limited (Power & Jurgensen, 2010). Similar conclusions can be found in Wiazowski's article on inaccessible digital textbooks (2010).

A selection of two different access modalities by students with visual impairments is confirmed in a study by Bouk and others (2018). The students who initially had a very positive attitude towards electronic textbooks, eventually decided that traditional textbooks in Braille or print make studying more effective. There was one exception of a student who chose to continue working with an e-book, however as the researchers account, the students' teacher insisted that they revert to their print books. It can be derived that one solution does not fit all students or situations. Certainly, it is not the teachers who should have the last say about the most optimal format. It appears though that the learners are not always given sufficient privileges to select their preferred media.

Bouck and Weng (2014a) also observed that majority of students selected traditional, printed books because they struggled with answering questions when mathematical exercises were read out by a synthetic voice. On the other hand the literature highlights problematic situations related to availability of Braille books and the quality of Braille math notation in those books (Bouk et al, 2013). The same authors studied also how students with low vision handle large print books. Their findings indicate that there are some challenges. They claim that black-and-white images and untimely delivery of textbooks cause frustrations among school students (Bouk et al, 2014b).

We can observe two important factors. On the one hand, it is apparent that an auditory reading and writing format does not satisfy either learners who are blind or who have low vision. It may be because of what they are used to using as their literacy or numeracy tools, but also due to limitations of an audio format alone. On the other hand a total elimination of electronic (audio) textbooks would deprive students of an important option they may need. There will be also students who may want more than one access method to educational content. They may even have a strong preference for acoustic presentations due to their learning styles. Polish teachers also noticed a need for dual formats, for blind students in particular. They said that "learners and their teachers need to master Braille and math Braille notation without which math curriculum cannot be successfully followed, especially at the high school level. [tr. author, Rubin et al, 2015, p. 39]"

Modalities appropriately selected for individuals will facilitate the process of understanding the math content and help students work with mathematical activities. They will not guarantee a success in mastering math by learners who are blind or have low vision, though. The very mathematical language being abstract may cause various problems with conceptualizing math (Landau et al, 2003). And yet, the digitized content adds an extra level to accessibility.

STEM education and students with visual impairments

Audrey C. Rule and others (2011) posit that the presence of people with visual impairments in the STEM areas of economy is minimal. Jones and Broadwell (2008) claim that STEM should be friendlier for students with disabilities. Rubin and others (2015) inform in their post-research publication that learners in Polish schools receive either insufficient or low quality learning aids. Kumar, Ramasamy and Stefanich (2001) informed that only a small percentage of students with visual impairments attended STEM classes. The main reason was a poor preparation and training of teachers who had no skills to teach using nonvisual techniques and lack of teaching and learning aids. Such circumstances discourage learners with visual impairments from developing their interest in the STEM areas (Beck-Winchatz & Riccobono, 2007).

Teaching STEM has been found to be more successful when student-centered, activity-based methods with problem solving and experiments are used. Bennington (2004) reported that when science was instructed in a hands-on inquiry-based way, it was perceived by many students as a favourite subject. Other evidence shows that inquiry teaching raises overall student achievement (Rye et al., 2007). It can be concluded that since hands-on inquiry is important for all students to comprehend science concepts, students with visual impairments should be provided manipulatives and other tactile materials to provide sensory information that supports mental constructs (Jones & Broadwell, 2008). Mental images can be constructed from information delivered through different modality channels, including sound and touch (Cattaneo et al., 2008).

EuroMath mentioned earlier is important for two reasons. Firstly, it is a comprehensive math tool. It also affects how learners can function socially in their settings. Audrey C. Rule and others (2011) indicate that adaptations perceived as negative will be denied by learners with disabilities. They are more likely to use tools that all other learners have and use. Teachers in Sahin and Yorek's study (2009) determined that students with visual impairments generally learned more effectively in collaboration with sighted peers. This group work helped them form social connections to others and become more involved with class activities.

Study conducted as part of the EuroMath project also indicate a minimal involvement of high end educational technologies in math classes. Vojtech Regec of Czech Republic noticed the same when investigating barriers to digital information students with visual impairments encounter in their educational settings (2016). Although the situation has improved over the last few years, math and other STEM areas still require a lot of attention (Mendelova, Lecky, 2008).

Teachers and digital STEM education

Wiazowski (2017) presented a list of difficulties teachers of students with visual impairments face in the general education settings in mainstream schools. A low level of awareness of existing instructional material, a heavy load of additional responsibilities, or insufficient funding appear to be the main culprits that afflict math education. Regec (2014) indicated in his study that a mere 30% of trained teachers of the visually impaired in Czech Republic heard of more advanced technologies that support access to the math content. Even more concerning is the correlation between a lack of knowledge with unwillingness to reach out for digital tools and a lack of interest in increasing the knowledge base of new and modern educational solutions. One of the respondents to a study conducted by Regec openly stated that teachers are oftentimes unwilling to reach out for advanced technologies. They would rather simplify tasks for students with visual impairments than challenge them with higher level math. Simple math tasks means simple, uncomplicated format that can be easily created. This approach deprives students of opportunities to study more advanced math.

Teachers also complain that many available automatic math reader systems require a thorough knowledge of Latex or other markup languages to create math worksheets. They found these document preparation systems not easy to use, unlike Microsoft Word.

Wararat Wongkiaa, Kanlaya Naruedomkulb and Nick Cercone (2012) have more encouraging information. They found out that most teachers who participated in their study were willing to use i-Math in their classes and recommended it to others. The following are some statements the authors quoted in their publication (2012):

"I do not know Braille for mathematics well so i-Math is good for me because I can prepare the math lessons easily."

"I can type all math expressions on a regular editor and my students can use i-Math to read them. My students can practice exercises on their own. However, it is new to me. If I have more time to work on this tool I should be able to make it do whatever I want to do easier." (p. 2138)

Audrey and others (2011) reported that teachers' knowledge about contemporary adaptations of learning aids for learners with visual impairments had a direct impact on the learners' engagement in conceptualizing the math concepts. It also changed the teachers' attitude towards and perception of their learners' abilities to actively participate and succeed in developing their math skills and knowledge. The teachers who responded to their survey claimed that when well matched and adapted learning aids are provided, hiring additional support staff is not necessary. A thoughtfully constructed environment is conducive to an independent class participation where sighted peers or the class teacher can provide sufficient support when necessary. The teachers also indicated that it turned out that time needed to modify and adapt educational material for their students with visual impairment is not as significant as they had assumed and what is more those adaptations were also found useful and helpful for all other students.

Fraser and Maghuve (2008) criticize teachers for being unaware of important changes that need to be done to life science curriculum so that learners with visual impairments can benefit from the instruction. Among various accommodations they also mention the importance of assistive technology and specially adapted graphics.

Conclusions and discussion

Although the above examples of different digital technology solutions for math education do not exhaust all possible options, they indicate that students with visual impairment should not be limited in possible ways to access the math content. We can only speculate on the reasons research and inspections alarm about insufficient quality of math instruction and learning aids. Interestingly enough, the teachers themselves did not notice absence of high technology support in their classrooms (NIK, 2018). The factors that supposedly make inclusive education difficult include too little personnel and too many students per class. It may either mean that the assistive and educational technology they have covers all the bases, or that the teachers and instructors are uncomfortable in applying those contemporary solutions in math instruction.

Literature discussed here presents seemingly contradictory data. Some authors claim that traditional printed textbooks read visually or tactilely are superior over audio textbooks, while other authors attempt to provide convincing research findings showing how crucial digital propositions can be. This spread of available and continually improved and enhanced solutions will most likely increase a repertoire of math content provision options. Students with visual impairments and their teachers may have to figure out how to make the best out of different worlds. And individualization of math education will be taken to a new level. The way students with visual impairments study math will not only depend on their preferred media but also on specific types of math activities (Awde et al, 2008; Tsonos et al, 2009). The key challenge will be to find what works best for a particular student and how to train them to benefit for a greater variety of options and tools bearing in mind that the math content is at the focal point of the teaching and learning process.

Audrey C. Rule, Greg P. Stefanich, Robert M. Boody and Belinda Pfeiffer (2011) inform that enhanced auditory or tactile learning material in combination with assistive technology are crucial for students with visual impairments to learn visual science and math content. Without further digitization of math content input and output accessible for all, students with visual impairments will continue struggling with being involved more commonly in high level math and STEM education. Jones, Minogue, Oppewal, Cook, and Broadwell (2006) showed that when provided appropriate accommodations, students with visual impairments mastered higher-order science concepts as well as their sighted peers. Once all stakeholders understand that students with visual impairments is a heterogeneous group, they will realize that one simple solution will not suffice to facilitate their education. Schools and teachers are challenged by a continuous influx of new teaching and learning aids.

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DOTYKIEM, WZROKIEM LUB SŁUCHEM – WSPÓŁCZESNE CYFROWE ROZWIĄZANIA I WYZWANIA W DOSTĘPIE DO TREŚCI MATEMATYCZNYCH DLA UCZNIÓW Z NIEPEŁNOSPRAWNOŚCIĄ WZROKU

Streszczenie: Matematyka, która ponownie stała się obowiązkowym przedmiotem podczas egzaminu dojrzałości, jest zdawana między innymi przez uczniów z niepełnosprawnością wzroku. Naczelna Izba Kontroli w opracowaniu z 2012 roku stwierdziła, że 45 proc. polskich szkół nie posiada odpowiednich pomocy edukacyjnych dla uczniów z niepełnosprawnościami. Stąd należało się przyjrzeć, czy dostępne są jakiekolwiek opcje pomocy dydaktycznych, z których mogą skorzystać nauczyciele i uczniowie. Co więcej, aby istniejące informatyczne pomoce dydaktyczne były skuteczne muszą one odpowiadać najefektywniejszej technice pracy ucznia. Dostępne rozwiązania zwykle składają się z różnych metod dostępu – od wzrokowej, słuchowej, po dotykową i wibrująco-dotykową. Autor przedstawia też zalety i wady tradycyjnych oraz informatycznych pomocy dydaktycznych oraz opinie nauczycieli odnośnie dostępnych rozwiązań do nauki matematyki.

Słowa kluczowe: matematyka, niepełnosprawność wzroku, przedmioty ścisłe, zapis cyfrowy, dostępność.

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