An Online Math Problem Solving System for Middle School Students who are Blind

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Abstract

There has been growing interest in designing online learning systems that are accessible to learners with special needs. In this project, an existing online math word problem solving system was modified for use by blind students. Text-to-speech technology was used to present math word problems in audio format, and to provide audio feedback to students about their answers. The adapted system was evaluated with blind middle school students (N = 11). Results indicated that blind students' problem solving was comparable to that of sighted students who had worked with the original system.

Keywords: Visual impairment, Special education, Mathematics education, Online learning, Middle school students

Introduction

The dramatic growth of online learning has made educational opportunities more widely accessible to students, who can now access instructional content without the traditional constraints of time and location. The expansion of online education has been accompanied by growing awareness of the need to ensure that all students can benefit from online instruction, reflected in the new interest in Universal Design for Learning (UDL) principles (Center for Applied Special Technology, 2009). These principles hold that instructional programs must provide students with multiple ways to access information and demonstrate their understanding. In the case of online learning, application of UDL can help to ensure that web-based materials are accessible, engaging, and effective for learners with diverse backgrounds and capabilities.

In some cases, students' special needs with regard to accessing online instruction require custom accommodations that go beyond the application of UDL principles. For example, students who are totally blind face significant and unique challenges in working with web-based systems. Screen reader software can be used to navigate links and buttons and to listen to text on a web page, yet such software does not typically address the interactive potential of online instruction. Effective online systems do more than display information on a static web page; rather, the student is engaged in an active process of viewing and requesting instructional content, entering information in response, and receiving immediate and customized feedback. Many questions arise in relation to how to make such interactive systems accessible to students with visual impairments (VI), particularly students who cannot see the screen at all.

One exciting possibility is suggested by text-to-speech software, which can now quickly generate custom audio files of acceptable quality without the time and expense required to produce human voice recordings. Text-to-speech offers the potential to make online instruction accessible to students who are blind through audio narration. In fact, the growth of audio books and other audio-based products has been identified as a potential threat to Braille literacy, although it is not entirely clear that rates of Braille acquisition have actually changed in recent years (Engelen, 2008). In the case of web-based instruction, the option to listen to the materials could be potentially valuable for students who are blind. Ferrell, Buettel, Sebald and Pearson (2006) identified narration as a potential "promising practice" for instruction for blind students, but did not find any research on the use of instructional audio over the Web for students who are blind.

One reason for the gap in research on audio as an alternative form of access to instruction for blind students is that the number of users who might ultimately benefit is quite small, in absolute terms. Total blindness is a very low incidence disability to begin with, and is much more common among adults than in school-aged children (Steinkuller, Du, Gilbert, Foster, Collins & Coats, 1999). In addition, children who are blind frequently have other disabilities that would be likely to limit their achievement in school, again reducing the number of target users for audio-based educational interventions. Although there is no central national registry to provide authoritative data, best estimates from the American Printing House for the Blind (APH) are that there are fewer than 10,000 academic blind students in the United States, meaning students who are totally blind and working at or near grade level in school (APH, 2009).

Although their numbers are small, there is growing recognition and expectation that students who are blind can be academically successful. In addition, educators and members of the VI community have argued that new approaches to instruction, including online learning, should be investigated to help students who are blind to meet higher academic goals (Corn & Koenig, 1996). The need for effective instruction for blind students is particularly clear in the area of mathematics learning. Although there have been relatively few studies of math learning by students who are blind, there is general recognition that these students face significant challenges in learning mathematics (Ferrell et al., 2006; McDonnall, Geisen, & Cavenaugh, 2009). In addition, few general education mathematics teachers receive any training in how to help students who are blind (DeSimone, & Parmar, 2006; Smith, 2008). An online system that made math instruction available via audio could therefore be of great potential benefit to blind students, especially those who are not acquiring Braille skills.

The goal of the present study was to adapt components of an existing online mathematics tutoring system for use by students who are blind. The existing tutoring system focused on word problem solving at the pre-algebra level, suitable for middle school students. The ability to solve word problems has been identified as a central component of mathematics proficiency (Kintsch & Greeno, 1985; Koedinger & Nathan, 2004; National Council of Teachers of Mathematics, 2000). Word problems also presented an ideal test case for the use of text-to-speech to generate audio files that could then be integrated into an online system for use by blind students. The process of adapting the existing system to support audio access by blind students is described in the next section.

System Modifications for Use by Blind Students

In the existing tutoring system, sighted students are presented with sequences of word problems about environmental science content (e.g., calculating the loss of habitat for the Giant Panda due to human population growth in China). Each word problem is presented on the screen in the form of a text box with an accompanying graphic illustration (e.g., a picture of a panda eating bamboo). The student can read the problem, enter an answer in the answer box, and receive immediate feedback (correct, incorrect). The original system for sighted students also includes extensive multimedia help resources, such as video lessons and interactive animations (e.g., how to carry digits in a multiplication problem). However, in the present project, the goal was simply to adapt the system so that the blind student could access the word problems via audio narration, enter answers, and receive audio-based feedback.

The adaptation process involved several tasks: selecting word problems that would be appropriate for the VI version, creating the new audio content, and ensuring that it could be deployed within the browser and that students' actions, such as playing the audio files, would be recorded.

Word problems from the original system were screened to locate problems that would be loaded into the VI version. There were several constraints on selecting appropriate word problems. First, only problems that could be solved with the information in the problem text were included. Problems that relied on information in an associated table, graphic, map or figure were not considered, because it was not immediately clear how to make the graphic information readily available via audio.

The second constraint in selecting the word problems for the VI system was that at least 20 sighted students had previously solved the problem in the original system. Researchers in the VI community have argued that the context of learning for blind students is so distinctive that it is not appropriate to compare their performance directly with that of sighted students (Ferrell et al., 2006; Warren, 1994). However, it still seemed important to have some prior performance data from sighted students to provide context for the evaluation of the adapted VI system. For example, if blind students could not solve a particular word problem at all, it would be useful to know that sighted students had also found it to be difficult, that is, perhaps that particular problem was just very difficult rather than difficult to understand in audio format.

The third constraint was that the problem fit one of eight targeted math topics, including arithmetic topics (four addition, four subtraction, four multiplication, four division) and fractions topics (four problems that required specifying the numerator or denominator, four multiplication of fractions, four subtraction of fractions with like denominators, four addition of fractions with unlike denominators). These topics were selected to facilitate comparisons of problem solving for material that was predicted to be relatively easy (arithmetic) and material that would be expected to be more challenging (fractions). Easy problems were included to check that blind students could successfully use the system to listen to the word problems and solve them correctly. More difficult problems were included to establish that the students could receive audio feedback (e.g., that their first answer was wrong) and continue to work on the problem, that is, that the adapted VI system could support a modest amount of audio-based interactivity.

The fourth constraint was based on the number of words in the problem. Accessing information via audio might be expected to place considerable demands on working memory. Because cognitive resources are limited, the demands of listening to longer problems might be expected to impede problem solving operations (Royer, Tronsky, Chan, Jackson, & Merchant, 1999; Sweller, 1998; Walczyk & Griffith-Ross, 2006). To investigate this possibility, word problems were selected so that both relatively brief and more expansive items were included for each math topic. The average number of words for the 32 problems that were ultimately included in the VI system was 57 per problem, with a range of 37 to 85 words.

After the word problems had been selected, audio files were generated for each problem using the Cepstral text-to-speech (TTS) software application. Simple spelling changes were sometimes necessary to ensure proper pronunciation. The final TTS rendering generated three files per problem, one for the problem text and two for the problem answer, depending on whether it was answered correctly or incorrectly. Two sets of generic feedback for the incorrect attempts were also rendered, for example, “Check your calculations and try again” and “This is a challenging problem. Try once more.” Finally, all Cepstral wav files were converted to mp3 files using NCH Software’s Switch sound file conversion software.

Additional adaptations were made to support audio presentation of the word problems within the online system. Playing audio over the Web is typically handled by a Web browser’s helper applications. Although many blind students listen to audio over the Web and thus know how to navigate external applications, some students do this more easily than others. It was important to minimize the need for blind students to navigate away from the VI system page to an external page to play the problem audio and then to return back to the original page to enter an answer. The resulting VI implementation is a fairly simple HTML-based wrapper that uses only Java Servlet and JavaScript technology, with two exceptions: An embedded Flash-based object is used to play the audio file within the system web page and Ajax, or XML HTTP Request, is used to record the number of times a student requested to hear the problem.

After these modifications, the new VI system was reviewed to ensure that it could be successfully navigated with JAWS, the screen reader software used by blind students in the partner school district. Careful use of the name, value, and alternate tags are generally necessary to support Web accessibility and are essential for the JAWS application, specifically. All page links and form tags in the system were tested and missing links and forms were filled in.

The VI system was then beta-tested with the assistance of a district VI technical specialist, two teachers of students with visual impairments (TVIs), and a blind high school student (not part of the study sample) from the partner school district. Finally, the adapted system was evaluated with blind students to establish its feasibility of use in authentic classroom settings. The study and results are described in the following sections.

Evaluation Study

Participants

Blind students. The study participants included 11 academic blind students attending middle schools in Los Angeles, California. The students were enrolled in general education courses and also spent part of their school time working with their TVIs in the school's VI program resource room. Although this sample size may appear small, it is substantial for research with participants who have a low-incidence disability. Most research with blind students involves single case studies or samples of 2-5 students (Ferrell et al., 2008; Horner et al., 2005).

Sighted students. The analyses (described below) also included data from sighted participants who had previously used the original online tutoring system in a separate project. Data were available for each of the 32 word problems from an average of 32 sighted students, with a range of 20 to 70 students per problem.

Procedure

The researcher met individually with each blind student during the student's VI resource room time at school. To access the adapted system, students used a computer in the VI resource room, which was equipped with JAWS screen reader software. In the session, the student opened the VI system URL and logged in, using an assigned name and password provided by the researcher. The student then solved word problems presented in the system in sequence. On each problem, the student used the "play problem" link to listen to the audio file as often as he or she wished. Answers were entered via the keyboard. Students could enter up to three incorrect answers before hearing the correct answer. They were permitted to use a Brailler or abacus to help them solve problems, in lieu of the pencil and paper used by the sighted students who had worked with the original system. However, devices with calculators, such as the BrailleNote mPower, were not allowed. Most students required two sessions to complete all 32 word problems.

The system automatically recorded the number of times each problem was played by the student, along with the incorrect and correct answers entered. These data were subsequently extracted for the analyses. The sighted students' data were also extracted from the original tutoring system database, and included the number of incorrect answer attempts made on each problem, and whether the problem was solved correctly. However, because sighted students could read the problems on the screen, they did not generate any data that were directly comparable to the audio file replay data for the blind students.

Study Results

Each blind student solved 32 math problems presented in the adapted system. For each problem, the student received a score of one if the problem was solved correctly (out of three attempts), as well as a count for the number of incorrect answers entered (out of three possible). The number of times the "Play problem" link was activated was also recorded. Mean scores were then calculated for each math topic (four arithmetic topics and four fractions topics). These scores are shown in Table 1.

As expected, blind students performed better on the arithmetic problems (82% correct) than on the fractions problems (59% correct). They were also less likely to make incorrect answer attempts on the arithmetic problems (mean of 0.67 incorrect answers per problem, vs. a mean of 1.4 errors for the fraction items). Interestingly, there was no difference in the number of times that blind students listened to arithmetic and fractions problems (roughly, twice per problem), suggesting that the lower performance with fractions was due to the more challenging mathematics, rather than some issue with the audio quality for the fractions problems. This was reassuring because off-the-shelf text-to-speech software does not always function particularly well with relatively infrequent or technical terms such as "one-twelfth" or "three-thirty-seconds". However, the present results suggest that the blind users could understand the audio of the fractions items reasonably well.

Table 1. Mean problem solving scores for blind and sighted students on word problems involving arithmetic and fractions topics. Standard deviations are shown in parentheses.

Math topic	Student Sample	Mean Proportion Correct Per Problem	Mean Number Incorrect Attempts Per Problem	Mean Number of Audio Plays Per Problem
Addition	Blind	.95 (.15)	.47 (.81)	2.25 (1.43)
	Sighted	.86 (.34)	.52 (.48)	--
Subtraction	Blind	.92 (.22)	.36 (.88)	1.63 (.74)
	Sighted	.72 (.45)	.98 (1.4)	--
Multiplication	Blind	.70 (.49)	.91 (1.15)	2.18 (1.23)
	Sighted	.84 (.35)	.59 (1.02)	--
Division	Blind	.73 (.40)	.93 (1.14)	2.25 (1.36)
	Sighted	.83 (.37)	.61 (1.07)	--
Arithmetic Overall	Blind	.82 (.31)	.67 (.99)	2.07 (1.19)
	Sighted	.81 (.37)	.68 (.99)	--
Identify Numerator & Denominator	Blind	.61 (.49)	.97 (1.31)	2.11 (.84)
	Sighted	.87 (.36)	.63 (.97)	--
Multiply Fractions	Blind	.61 (.47)	1.50 (1.63)	2.04 (.91)
	Sighted	.87 (.42)	.63 (1.36)	--
Subtract Like Denominators	Blind	.69 (.47)	.97 (1.23)	1.63 (.91)
	Sighted	.57 (.44)	1.34 (1.47)	--
Subtract Unlike Denominators	Blind	.48 (.47)	2.13 (1.23)	2.16 (1.75)
	Sighted	.44 (.46)	1.57 (2.23)	--
Fractions Overall	Blind	.59 (.47)	1.39 (1.35)	2.01 (1.10)
	Sighted	.68 (.42)	1.04 (1.50)	--

Data from sighted students who had solved problems in the original online system are also included in Table 1 for context. As may be seen in Table 1, the overall pattern of performance appeared to be quite similar for both student groups. More specifically, both groups of students found the arithmetic items easier than the fractions items. Also, within the fractions items, both groups performed better on the relatively easy problems (identifying the numerator or denominator) than on the most difficult problems (subtracting fractions with unlike denominators).

The word problems included in the VI system had been selected so that there would be variation in the number of words included in each of the four problems per math topic. For example, the four addition problems were 46, 56, 63 and 85 words, respectively. The mean proportion correct scores for the blind students are shown in Table 2, from shortest to longest problem.

As may be viewed in Table 2, word count alone did not seem to influence students' success on the problems: Performance on the longer problems was quite similar to that observed on the shorter problems. Problem word count also did not appear to influence the probability that the student would replay the problem or make incorrect answer attempts.

Table 2. Mean proportion correct for word problems by problem word count. Data are from blind students.

	Word Count				
Math Topic	1 (shortest)	2	3	4 (Longest)	Topic Mean
Addition	1.00	.90	1.00	.90	.95
Subtraction	.90	.90	1.00	.90	.92
Multiplication	.72	.72	0.72	.63	.70
Division	.82	.91	0.36	.81	.73
Numerator/Denominator	.45	.54	.72	.72	.61
Fraction Multiplication	.90	.81	.45	.27	.61
Subtract Like Denominators	.64	.56	.78	.78	.69
Subtract Unlike Denominators	.50	.40	.52	.48	.48
Mean Across Topics	.74	.71	.69	.68	.71

Discussion

The project goal was to adapt an existing online math problem solving system so that it could be used by students who were totally blind. Word problems were prepared in audio format using text-to-speech software, and embedded into the online system so that blind students could listen to the problems as often as needed, enter answers, and receive feedback on the correctness of their answers.

An evaluation was conducted with blind middle school students who solved arithmetic and fractions problems in the adapted system. The results indicated that blind students could successfully solve math word problems presented in audio format, using text-to-speech technology. The blind students' performance was roughly comparable to that of sighted students who had used the original system.

The study conclusions are somewhat limited by the difficulty of comparing the performance of blind students with that of sighted students. The blind participants in this study were a relatively select group, that is, they were academically successful even though they faced considerable challenges in the school environment. In contrast, the sighted students whose data were used as a comparative source included many students who were struggling academically; in their school district, fewer than 40% of the students scored at the "basic" level of proficiency or better on the end-of-year state math achievement test. Thus, the study results might have looked different if data from sighted students attending relatively high-performing schools had been available. Even so, the success of the blind students with audio presentation of the materials was impressive.

Although the blind students' reactions to the program were not formally assessed, all student comments were positive. For example, one girl remarked, "Miss, I *love* this program!" and asked when she could use it again.

Surprisingly, the blind students' problem solving did not appear to be strongly influenced by the number of words in the problems. The word problems had been selected to vary in word count, from a low of 37 words to a maximum of 87 words, to learn if working memory constraints might impede blind students' ability to solve the problems. However, there was no indication that the students did better on shorter problems. Rather, the strongest influence on performance was the difficulty of the math operation required to find the solution. For example, students did very well on simple addition but less well on problems in which they had to find a common denominator for two unlike fractions, regardless of the problem length.

The adaptations investigated in this study were limited to the goal of presenting the word problems via audio and supporting a limited amount of interaction with the student, including modest prepared feedback regarding the correctness of his or her answers. There are several next steps in the project: First, the bank of word problems in the VI system will be expanded, using text-to-speech to generate the audio files. The original system used by sighted students includes over 900 word problems; preparing human voice recordings of this much content would be prohibitive in terms of time. Second, brief audio descriptions of the problem illustrations will be added so that the blind student can hear information about what is shown in the image. Third, additional hints to help the student when he or she has difficulty solving a problem can be added. For example, the teacher could type a short explanation for a problem, and text-to-speech can be used to generate a customized audio file that can be played by the student on demand or when an incorrect answer is entered.

A remaining challenge to be addressed in future work involves the need to provide the blind student with access to information conveyed in graphics such as maps, figures, charts, geometric shapes, plots, and graphs. This type of graphic does not lend itself particularly well to audio description due to the spatial nature of the information (Yesilada, Stevens, Goble & Hussein, 2004). To date, researchers have focused on providing spatial information to the blind user in the form of tactile graphics, using embossed paper to represent lines, shapes and other forms. Although tactile graphics are extremely valuable for the blind user, it can be difficult to include enough information on the page due to physical space constraints (Braille Authority of North America, 2008). A hybrid approach in which the student listens to audio files linked to the problem while exploring the embossed graphic manually may provide a solution to this challenge (Landau, Russell, Gourgey, Erin & Cowan, 2003; Miele & Van Schaack, 2009; Walker, Lindsay & Godfrey, 2004).

Conclusions

As innovations in online learning are developed, it is important to consider the ways in which online instruction can be made accessible to learners who have unique challenges, such as total blindness. Text-to-speech software now affords the opportunity to create customized audio instructional materials for blind students quickly and at relatively low cost. The present study investigated the use of this approach in the context of an online math problem solving system, and the results from an evaluation with bind middle school students were encouraging.

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References

American Printing House for the Blind. (2009). *Annual research report*. Louisville KY: Author.

Braille Authority of North America (BANA) and Canadian Braille Authority. (2008). *Guidelines and standards for tactile graphics*.

Center for Applied Special Technology. (2009). *Universal Design for Learning*. Wakefield, MA: Center for Applied Special Technology.

Champion, R. (1976-77). The Talking Calculator used with blind users. *Education of the Visually Handicapped*, *8*, 102-106.

Corn, A. L., & Koenig, A. J. (1996). *Foundations of low vision: Clinical and functional perspectives*. Louisville KY: American Printing House for the Blind.

DeSimone, J. R., & Parmar, R. S. (2006). Issues and challenges for mathematics teachers in inclusion classrooms. *School Science and Mathematics*, 106, 338-348.

Engelen, J. (2008). Modern digital libraries: The case of the audio book boom. In *Lecture Notes in Computer Science: Computers Helping Students with Special Needs*, (pp. 284-290). Berlin: Springer.

Ferrell, K. A. (2005). The effects of NCLB. *Journal of Visual Impairment and Blindness,* 99, 681-683.

Ferrell, K. A., Buettel, M., Sebald, A. M., & Pearson, R. (2006). *Mathematics research analysis.* Louisville KY: American Printing House for the Blind.

Horner et al. (2005). The use of single subject research to identify evidence-based practice in special education. *Exceptional Children*, 71, 165-179.

Kintsch, W., & Greeno, J. G. (1985). Understanding and solving word arithmetic problems. *Psychological Review*, 92, 109-129.

Koedinger, K. R., & Nathan, M. J. (2004). The real story behind story problems: Effects of representations on quantitative reasoning. *Journal of the Learning Sciences,* 13, 129-164.

Landau, S., Russell, M., Gourgey, K., Erin, J. N., & Cowan, J. (2003). Use of the Talking Tactile Tablet in mathematics testing. *Journal of Visual Impairment and Blindnes*s, 97, 85-97.

McDonnall, M., Geisen, J. M., & Cavenaugh, B. (2009, June). *School climate, support and mathematics achievement for students with visual impairments.* Poster presented at the annual Institute of Education Sciences Research Conference, Washington DC.

Miele, J. A., & Van Schaack, A. (2009, June). *Audiotactile graphics using Smartpen technology.* Paper presented at the National Science Foundation Joint Annual Meeting (JAM), Washington DC.

National Council of Teachers of Mathematics. (2000). *Principles and standards for school mathematics.* Reston VA: National Council of Teachers of Mathematics.

Royer, J. M., Tronsky, L. N., Chan, Y., Jackson, S. J., & Merchant, H. (1999). Math fact retrieval as the cognitive mechanism underlying gender differences in math test performance. *Contemporary Educational Psychology*, 24, 181-266.

Smith, D. (2008, May). *Assistive technology competencies for teachers of students with visual impairments: A Delphi study*. Unpublished doctoral dissertation, Texas Tech University, Lubbock TX.

Steinkuller, P. G., Du, L., Gilbert, C., Foster, A., Collins, M. L., & Coats, D. K. (1999). Childhood blindness. *Journal of the American Association of Pediatric Opthamology and Strabismus*, 3, 260-32.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, 12, 257-286.

Walczyk, J. J., & Griffith-Ross, D. A. (2006). Time restriction and the linkage between subcomponent efficiency and algebraic inequality success. *Journal of Educational Psychology*, 98, 617-627.

Walker, B. N., Lindsay, J., & Godfrey, J. (2004, Oct.). The Audio Abacus: Representing numerical values with nonspeech sound for the visually impaired. *Proceedings of the 6th International ACM SIGACCESS Conference on Computers and Accessibility*, (pp. 9-15).

Warren, D. H. (1994). *Blindness and children: An individual differences approach*. Cambridge: Cambridge University Press.

Yesilada, Y., Stevens, R., Goble, C., & Hussein, S. (2004, Oct.). Rendering tables in audio: The interaction of structure and reading styles. *Proceedings of the 6th International ACM SIGACCESS Conference on Computers and Accessibility*, (pp. 16-23).

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