Math-to-Speech Effectiveness and Appreciation for People with Developmental Learning Disorders

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ABSTRACT

Accessing written math content can be difficult for students with Developmental Learning Disorders. Through a user study with 19 representative participants, we investigate how text-to-speech access compares to reading for these students in terms of math syntax memorability, as well as the perceived accessibility, ease of access, and usefulness.

Results show that text-to-speech is regarded as significantly easier and more useful for accessing math content, compared to reading access. The perceived accessibility of math content is also higher for text-to-speech access, but actual improvement could not be verified as much of the content was correctly memorized in both conditions. However, some of the considered content was consistently better memorized through text-to-speech, indicating promising future applications of this technology.

CCS CONCEPTS

• **Human-centered computing** → *Accessibility systems and tools*; *Touch screens*; • **Applied computing** → *Arts and humanities*; • **Social and professional topics** → **People with disabilities**.

KEYWORDS

Developmental Learning Disorders, Text-to-speech, Mathematics

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1 INTRODUCTION

Developmental Learning Disorders (DLD) [27] can affect various aspects pertaining to math access, memorability and reasoning [12]. For example, Dyscalculia impacts the ability to access, memorize and manipulate numbers and mathematical concepts [25]. Math fluency can also be influenced by other, seemingly unrelated DLD, such as Reading Disorders (RD) [18, 20, 29]. The co-occurrence of RD and Dyscalculia is a common condition as well [14], and other DLD conditions such as Nonverbal Learning Disorders may also have a similar impact on math proficiency [16].

There are many compensatory tools used to facilitate writing, reading or math accessibility, promoting autonomous and independent learning for students with DLD. For people with RD, verbal access to text information, as recorded voice or through text-to-speech (TTS), is an effective accessibility accommodation [9]. Similarly, verbal access to scientific content is reported as a possible compensatory tool for people with DLD [11, 15, 22, 29]. However, to the best of our knowledge, the effect of TTS access to mathematical content for people with DLD has not been previously assessed.

In this work, we conduct a user study with 19 participants with DLD, examining how TTS access impacts math syntax memorization, as well as its perceived usefulness, ease of use and accessibility, compared to reading. To enable TTS access to math content, we use three key components:

(1) ***Axessibility*** [4], a LaTeX package that allows to embed, within the generated PDF documents, an alternative text for math content, namely, the corresponding LaTeX code;
(2) ***ePico!*** [3], a software suite designed as a compensatory tool for people with DLD, which also provides an environment for TTS access to digital documents;
(3) ***Axessibility* dictionaries for *ePico!*** [5] that enables natural language reading of math content inside *ePico!* for documents generated with *Axessibility*.

Subjective feedback from participants indicates that TTS access to math content is deemed significantly easier, more accessible, and more useful than reading access. While the memorization of math syntax did not seem to be significantly impacted by the use of TTS, further analysis revealed that memorization of specific math formulae improved with TTS.

Table 1: Participants' demographic data

PID	Course	Course Year	Dyslexia	Dyscalculia	TTS expertise	Math syntax expertise
P1	Intercultural Studies	5	Severe	Severe	None	Low
P2	Education Sciences	1	Light	Severe	None	High
P3	Comunication Sciences	3	Moderate	Moderate	None	Low
P4	Education Sciences	3	Moderate	Moderate	Moderate	Low
P5	Philosophy	2	Severe	Severe	None	Low
P6	Business Comunication	3	Light	Moderate	None	High
P7	Herbal Sciences	1	Light	Severe	None	Low
P8	Modern Literature	1	None	Light	None	Low
P9	Law	3	Moderate	Severe	Low	Low
P10	Education Administration	4	Moderate	Moderate	Moderate	Low
P11	Comunication Sciences	1	None	Light	None	High
P12	Social Services	1	Moderate	Moderate	Moderate	Low
P13	Education Sciences	1	Moderate	Moderate	Moderate	Low
P14	Philosophy	3	Moderate	Severe	High	Low
P15	Law	4	Moderate	Light	None	High
P16	Nursing	3	Moderate	Severe	None	High
P17	Business Administration	1	Light	Light	Low	Low
P18	Comunication Sciences	2	Severe	None	None	High
P19	Natural Sciences	1	Moderate	Moderate	Low	Low

2 RELATED WORK

Students with DLD have difficulties in accessing, memorizing and elaborating math content [12, 14, 16, 18, 20, 25, 29]. Verbal access to text, commonly used as a compensatory approach for people with DLD [9], has been previously proposed to improve scientific document accessibility for people with DLD [22] in fields such as math, physics [19], or chemistry [23]. In particular, it has been also suggested as a possible way to improve the accessibility of math content, such as equations or other formulae [29].

However, scientific documents [7], and in particular math content [26] are largely inaccessible to TTS software. This issue not only impacts people with DLD but also people with visual impairments who rely on screen readers to access documents [7, 19]. Prior works focused on ways to make math content accessible using TTS on web pages [8] and in PDF documents made from LaTeX [1, 17]. However, to the best of our knowledge, the effect of TTS access to math content for people with DLD has not been previously studied.

3 RESEARCH PROBLEM

Our prior research addressed the problem of math content accessibility for people with visual impairments, through *Axessibility* [4], a LaTeX package that embeds within the generated PDF documents, as alternative text for math content, the corresponding LaTeX code. This way, the math content in the produced documents is accessible to people with visual impairments through screen readers. To improve the clarity of the math content added using *Axessibility*, we also proposed screen reader dictionaries that convert math formulae from LaTeX code to spoken language [1].

A natural extension of our prior work, which we explore in this paper, is to apply our approach also to people with DLD. We therefore integrated *Axessibility* with the document reading environment provided within *ePico!*, a software suite designed as a compensatory instrument for people with DLD. We implemented Italian and English dictionaries for *ePico!* to translate LaTeX math content provided by *Axessibility* [5] into spoken language. For example, "$f(x) \geq 0$", in LaTeX code: "`f(x) \geq 0`", would be read as: "f of x greater than or equal to zero".

4 USER STUDY

We investigate whether TTS access to math content, provided through our solution, improves math accessibility for people with DLD. Specifically, we explore two research questions:

(1) What is the effect of TTS access on memorability of math syntax by people with DLD, compared to reading?
(2) How do they perceive ease of access, usefulness and accessibility of TTS access to math content, compared to reading?

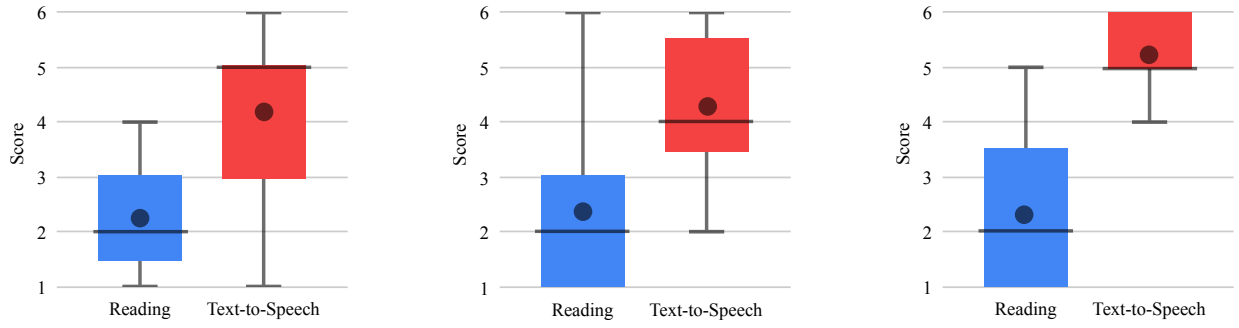
4.1 Participants

To answer these questions, we conducted a study with 19 participants with DLD. All were Italian university students, from various courses and years of study. They participated to the study voluntarily, with no compensation.

All participants were between 20 and 30 years of age. They self-reported different severity levels of Dyslexia and Dyscalculia, as shown in Table 1. Specifically, 3 students reported to have a severe Dyslexia, 10 moderate, 4 light and 2 None. Regarding Dyscalculia, 7 reported to have a severe form, 7 moderate, 4 light and 1 none. We purposefully excluded students from Mathematics and other related courses as their continuous exposition to math syntax could be a confounding factor for this experiment. Thus, most participants (13) had a low expertise with math syntax and for the remaining 6 it was reported as high.

Most students had no prior expertise with TTS software (11). Among the others, 3 had a low level of self-reported TTS expertise, 4 moderate and 1 high. For those who had prior TTS experience, the main use case was the reading of long texts (P4, P9, P10, P12, P17, P19), in particular for literature (P9,P17,P19). Those who had low self-reported TTS expertise explained that they rarely or never use TTS because they prefer reading (P9), they loose concentration with TTS (P17) or because they prefer not using the computer (P19).

Most often, TTS was used for studying (P4, P9, P10, P15, P17), and some also used it for leisure reading (P4, P10). P13 uses TTS for all documents, and was the only participant that used *ePico!*. Others (P10, P19) used Carlo Mobile [2] from the same developer, Alfa Reader [10] (P14, P17), Voice Over (P4, P10) or others (P9, P12).



(a) Ease of Use (b) Accessibility (c) Usefulness

Figure 1: Intelligibility and Distraction results.

4.2 Apparatus and Stimuli

The experimental apparatus consisted of a PC with *ePico!* reader environment installed. For participants who did not have a PC compatible with *ePico!*, we provided a lab PC. For those who could not reach the lab due to distance or COVID19 mobility restrictions, we ran the test remotely using a teleconferencing software.

We created 4 PDF documents as stimuli, based on diagnostic tests for DLD, but adapted to university level complexity. They contained high school level math, which therefore should be comprehensible to the participants, who were all university students. Specifically, the documents were drawn from Mathematical Analysis 1 [21], an Italian textbook for 1st year university math course, compiled from LaTeX using *Axessibility*. Each document was one page long, and contained one theorem in Italian with 2 to 3 math formulae[1].

4.3 Study Protocol

Before the study, participants were provided with a short guide to acquaint them with the experimental apparatus and help them to set up *ePico!*, adjust preferences (such as reading voice speed) and install *Axessibility* dictionaries. The study started with a brief written introduction of the experiment, which was accessed using *ePico!*, to verify that the apparatus was functional and usable by the participants. After signing the study consent form, we collected participants' demographic data and started the experiment.

During the experiment, each participant accessed 2 of the 4 stimuli, one in each condition (reading and TTS), counterbalanced to avoid effects of order. After accessing each document, participants were given a short questionnaire. Two of the formulae contained in the considered document were presented, displayed as images (without TTS) and the participants were asked to select the correct reading for the formula, among 4 provided options.

We also asked the participants to evaluate the perceived accessibility and ease of access for the examined condition, on a 1-6 Likert scale. At the end of the experiment a final questionnaire asked the participants to assess the usefulness of the two conditions (1-6 Likert scale), select their preferred condition, and provide further open comments and suggestions. In total, the study lasted about one hour.

[1]Supplementary material contains the four PDFs

5 RESULTS

We compare the two conditions considering the resulting math syntax memorability and subjective feedback. We also report participants' comments and suggestions.

5.1 Memorability of Math Syntax

We set the condition (reading/TTS) as the independent variable, and the result of the follow-up questionnaire (correct/wrong) as the dependent variable. McNemar's Chi-Square Test was used to assess whether the two conditions had significantly different effects on the outcome. Despite the fact that 32 out of 38 formulae (84%) were read correctly with TTS and only 26 (68%) without, the difference was not found to be statistically significant. Participants with low math syntax expertise seemed to benefit the most from TTS usage, with 23 out of 26 formulae memorized correctly (88%) with TTS and 16 (61%) without. TTS expertise did not seem to influence the memorability outcome.

We further investigated the outcomes and discovered that, for most of the formulae, participants were able to recall the correct reading equally well in both conditions. This indicates that the selected formulae were perhaps too simple. However, for 2 of the 8 formulae, results without TTS were consistently worse than with TTS. Specifically, the formulae were "$I(l) \cap I(m) = \emptyset$" and "$x > r_1 \implies |f(x) - m| < \epsilon$". For the first formula, 3 out of 4 participants who accessed it without TTS confused intersection ($\cap$) with union ($\cup$), and only 1 out of 5 with TTS. Also, in both conditions empty set ($\emptyset$) was confused with zero once. For the second formula 2 out of 5 participants who accessed it without TTS confused implication ($\implies$) with "if and only if" ($\iff$) and one confused greater ($>$) with lesser ($<$). Instead, none of the participants who accessed the formula with TTS gave wrong answers. We note that many error were "mirrored letters", typical in DLD [24].

5.2 Subjective Feedback

For subjective feefback analysis, the condition was again set as the independent variable. The ease of use, accessibility and usefulness scores were considered as the dependent variables. We used Mann-Whitney U Test to assess the differences between the conditions for each dependent variable. The results of the analysis revealed that there is a stark preference by the participants for the TTS condition.

Specifically, as shown in Figure 1(a), TTS access was perceived as easier to use with respect to reading ($U = 47$, $p < .001$). Similarly (see Figure 1(b)), the perceived accessibility was higher for TTS than for the reading condition ($U = 62.5$, $p < .001$). Finally, as seen in Figure 1(c), usefulness score was also significantly higher for TTS than for reading ($U = 10.5$, $p < .001$). Considering the preferred access modality, all but P13 selected TTS. Instead P13 preferred reading to TTS access in general, using TTS only for longer literature texts.

5.3 Comments

Participants' comments were largely in favor of TTS access. Most participants highlighted that complete reading of all symbols helped them to better access the content (P5, P7, P8, P9, P11, P12, P15, P16, P17) and that it was clearer for them (P1, P2, P3, P6, P11, P14, P16). For example, P16 highlighted that with TTS access:

> "...the reading is clearer and more fluent. You don't need to check what various symbols mean."

Participants also mentioned that TTS access caused less fatigue and was less cognitively demanding than reading (P4, P18). P4 supported this by saying:

> "It is helpful when you are tired and it causes fatigue to read while trying to comprehend at the same time."

Finally, participants also noted that concurrent audio-visual access to math content was helpful for memorizing the content (P5,P19). Indeed, P5 stated that TTS is easier for accessing math:

> "...because it provides a correct way to read formulae. Furthermore, reading while listening helps to remember the content."

Participants also had suggestions and ideas for improving the TTS access. Mostly, the suggestions focused on making the spelling of the TTS clearer (P2,P8,P9,P10,P17). For example, P10 explained:

> "The pronunciation of the phonemes and diphthongs should be clearer."

Others stressed the importance of pauses, in particular in presence of punctuation and symbols (P6,P14,P15,P16). On this, P15 added:

> "There should be a pause after a parentheses and before its content."

P4 and P18 also highlighted that speed perception is subjective and may vary depending on the content. Indeed, despite the fact that speed was customized by each participant at the beginning, P18 highlighted that for formulae:

> "It should be slower."

Instead, P11 argued that explicit reading of the parentheses could confuse the reader:

> "On long formulae you can get lost due to the continuous repetition of open parenthesis/close parenthesis."

Among other suggestions, P5 commented that color highlighting of the read symbols could be useful. P16 suggested the integration of a zoom functionality, and P7 imagined that a functionality to access the definitions and explanations of various symbols could be useful. P11 argued that the system should be provided from grade school onward, while P9 proposed to make the software available, for study and exams, for all university students with DLD.

6 DISCUSSION AND LIMITATIONS

6.1 Key findings

Subjective feedback was consistently favorable to TTS compared to reading, for all of the considered metrics. It was deemed easier to use, and caused less fatigue. It was considered more accessible, providing correct reading for all symbols and terms. It was also perceived to be more useful, to the point that some of the participant requested to be allowed to use it for studying and exams. While the effect on the memorability of the formulae could not be assessed, preliminary positive results for some of the formulae indicate that a more thorough investigation, based on the characteristics of the formulae and the participants, could reveal positive effects.

6.2 Stimuli Selection and Memorability

As stimuli we selected math content that was compatible with the education level of the participants. However, most formulae were correctly accessed and memorized both with and without TTS. We believe that a greater variety of formulae and diverse levels of complexity are needed to assess the actual benefit of the TTS access. Furthermore, there could be an effect related to specific symbols that are frequently confused, which should be investigated.

6.3 Participants' Characteristics and Expertise

Our participants were university students without math or related courses as their core university topic. This allowed us to examine the effect of TTS access to those who had the least experience with math syntax and perhaps could benefit the most from it. Indeed, those with lowest math syntax expertise seemed to benefit the most from TTS. We wonder whether similar results would be obtained for students with DDL who frequently access math content.

6.4 Dictionary Limitations

Natural language translation of LaTeX formulae is limited in *ePico!* dictionaries. It currently only allows one-to-one mapping of terms and translations, and does not support more complex conversions. For example, it is not possible to correctly translate expressions with multiple parts (*e.g.*, fractions, as they are composed of a numerator and a denominator). We avoided unsupported expressions in the study, but to access to all formulae, either the dictionary support in *ePico!* should be modified or a different TTS should be used.

7 CONCLUSIONS AND FUTURE WORK

In this paper we propose text-to-speech access to math formulae for students with Developmental Learning Disorders. We evaluate this approach, comparing it to reading access, and we show that TTS is perceived to be significantly easier to use, more accessible and more useful than reading access. While effective improvement on the memorability of the formulae could not be assessed, evidence of validity for specific formulae looks promising.

As future work we will extend the study to students of math courses, and we will include diverse symbols and levels of content complexity. Additional metrics will also be considered, such as the time needed to access formulae. Finally, we will improve the translations to support more complex formulae, and to provide additional verbal [6] and non verbal [28] cues.

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