Rainbow Math

A Case Study of Using Colors in Math for Students with Moderate to Severe Dyslexia

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Abstract. The goal of Rainbow Math is to investigate what font-related changes can be made to aid students with dyslexia and other learning disabilities. As part of the initial step, we developed software that allows students to customize coloring of text, modify the text’s spacing and style on a per-character basis. Additionally, students can use color to visually distinguish what is between parentheses, brackets, etc. Testing with 13 middle school students showed that most students liked larger fonts, extra spacing between operators, bold fonts, and highlighting of parenthesized expressions. Their self-chosen preferences resulted in decreased reading times and decreased errors.

Keywords: Math accessibility · Dyslexia · Fonts for dyslexia · Learning disabilities · Reading impairments · Visual processing

1 Background

Dyslexia is a developmental learning disability that interferes with the ability to read/recognize and spell words. Dyslexia affects an estimated 5%–10% of the U.S. population and varies significantly in its severity. Its symptoms also vary depending on age [11].

Many studies on dyslexia have been performed for readability and comprehension of text, both on paper and on a computer. Based on results of past studies, [10] focused on those things found most useful to change. Their study group was larger than previous studies and used eye tracking to help make sense of the results. They found that (in order of importance) font size (18–24pt), character spacing (0–14% increase), text and background color, and text grey scale were the most important factors related to reducing fixation time; the longer the eye is “stuck”, the more the reader is working to read the text. Their results with color did not completely match those of previous studies. In particular high contrast is often not recommended for people with dyslexia [1], but in their study, subjects preferred black on yellow, although eye tracking showed it had the highest fixation times. Factors not found to be important were line spacing, paragraph spacing, and column width. This group was composed of Spanish
readers, so results may not carry forward to English text readers, but do seem relevant for reading math because language differences are small in mathematics.

On computers, special fonts for dyslexic readers have been devised. However, several recent studies have cast doubt on their usefulness [9, 14]. Both of these studies show that italic fonts tend to increase reading time; italic fonts are typically used for variables in math. There do not appear to be any studies related to math, fonts, and dyslexia.

Many interventions to help with reading involve coloring. Colored lenses and overlays have long been used to aid reading because it is believed to reduce visual stress, although some studies have challenged their usefulness, at least for adults with dyslexia [17]. [8] showed that using a warm color such as peach for a background on a computer increased reading speeds among dyslexics and the general population by 50% over a cold color. [7] studied various coloring techniques such as coloring words different colors, coloring the start and end of words differently, and coloring each syllable differently. They found that “color wins against all of the known typesetting similarities such as underline, italic and bold fonts playing together” (p. 5).

The work above is about static text. On a computer, dynamic effects are possible. The most common technique is to read the text aloud. This can be done alone or with reinforcement by highlighting the words as they are spoken. Several meta-analyses have come to mixed conclusions on the effectiveness of read aloud as summarized in [15]. The authors performed their own meta-analysis. They concluded that read aloud may assist students with reading comprehension, but there are many variables that might moderate the effect. As they note, earlier computer voices were very mechanical and lacked prosody that makes human speech more interesting to listen to; many of the studies reviewed involved human readers. The ability to highlight words as are they are spoken is less well studied. [4] studied dyslexic children reading Japanese, so the results are not necessarily applicable to reading English. They found that sentence highlighting with blue background most strongly reduced eye fixation time. A second study they performed found that in side by side comparisons, students preferred blue sentence backgrounds along with blue or yellow word highlights, but no actually reading was done in the second study. [16] compared computer text to speech (TTS) with and without highlighting to silent reading, read aloud, and listen only. TTS (with and without highlighting) improves comprehension scores for students with dyslexia. Only children with reading & language impairments benefited from highlighting.

All of the above studies involved text, not computer reading of math. To the authors’ knowledge, Project SMART [5] and its follow-on MeTRC study [6] are the only studies that involved math with synchronized highlighting. The first study involved 48 middle school students with learning disabilities. This study modified textbooks to use MathML to encode the math. The study used TextHELP’s Read & Write Gold to read and highlight the text together with MathPlayer [12] to read and highlight the math. One textbook had systemic errors in the conversion and another had very few mathematical expressions; no benefit was seen in those texts. However, the textbook with the most math “exhibited the most consistent improvement in pre/post test scores for intervention students using the digital version in comparison to control students using the print version.” The MeTRC study expanded upon the
Project SMART to include workbooks, handouts, and quizzes in the materials that were made accessible. An initial assessment consisted of 17 students who had an Individualized Education Program that included an oral accommodation in math reading aloud both word problems and math symbols. The assessment found that these students had an average error rate of 6.7% in reading the plain text word problems, but their error rate for reading symbolic math content soared to 36%. At the end of the school year, students using MathML-encoded eText were compared to a control group that used standard read aloud accommodations. Those using enhanced math had gains of 16.7 points on a standardized test versus gains of 8 points for the control group. Remarkably, the gains for the math enhanced special ed group outpaced those of the average (non-special ed) 7th graders.

2 Study Software and Plan

This paper details a preliminary investigation into whether the pencil and paper coloring ideas currently in use in some classrooms for dyslexic children will work when transferred to a computer.

Because no one has developed software to color math, the goal of this initial study is to get qualitative feedback from students and teachers as to what features are subjectively useful, not useful, and what would be useful to add in the future. In particular, does the coloring used on paper by the teachers at the school to help students “see” the math also work on computer screens.

The end goal is to incorporate the useful features of Rainbow Math into Mathshare [13], an accessible math editor. Mathshare already supports synchronized highlighting of spoken math so this study focuses only on coloring math. To ease implementation and allow freer experimentation, the software designed for this study is text-based and allows only linear math (no superscripts, square roots, or 2D fractions). Most of the students who participated in the study are still learning basic arithmetic, so this restriction is not a major hindrance. The study software consists of two web pages: one to design a set of coloring and spacing rules (teacher and student working together) and another (simpler) page for students to try out the coloring rules to solve problems.

Based on classroom experience, students with dyslexia can confuse one character for another character – e.g., ‘3’ and ‘8’. They also have trouble reading thin/small characters such as “-” and “/”. Classroom experience has shown that some students are resistant to using coloring because it requires them to switch pens frequently. Poor handwriting and/or dysgraphia is often associated with people with dyslexia [2]. Using a computer, software can color the math automatically so less physical and mental effort is required to write math. By moving to a computer keyboard, issues surrounding handwriting are minimized. Color coding characters and being to make individual characters bold are two known requirements for the software. Being able to easily see bracketed expressions is another design goal.

The design page is shown in Fig. 1. Any character can be changed in the following ways:
The text color and background color can be changed
The character can be made italic, bold, or normal.
Extra space can be added around the character.

When a character is given some coloring, the system automatically calculates the opposite background color on the color wheel, and then picks a contrasting foreground color so the user can create easily distinguished characters pairs (useful for characters that are often confused with each other). The teacher and students never made use of this feature.

The software also supports highlighting the area between matching chars. These areas can be colored or have a line drawn above, below, or around the interior of the bracketed expression. The line can be colored and its thickness changed so that it is subtle or obvious. The bracketing characters can be included or excluded from the coloring. The first version of the software supported a more complicated scheme for individual coloring of matching areas based on the open/close characters. This was found to be confusing for the teacher. Support was tried for coloring each matching area differently, but that was non-intuitive in practice. The current version will color each nesting level differently up to the number of rules that are defined. In Fig. 1, two rules are defined; nesting in the “try it” example shows the two levels of coloring. This approach seems intuitive because it makes it clearer which part of the problem to solve first.

The coloring rules can be saved and distributed to students. A page for students to use to solve problems was created but never used in testing due to time constraints.

[Fig. 1. Design page]
The test page consists of lines where students can type/solve their math problems along with a palette of special symbols. There is also an area where students can control the amount of coloring used (e.g., they can lessen or remove foreground and/or background coloring). This was added because based on the teacher’s experience, as students progress, they tend to need less color support. Because of space limitations and because the page was not used, it is not shown here.

After an initial round of designing colorings with 7 students and one teacher, the software was revised and a second more thorough round of testing was performed with 13 students (5 boys, 8 girls), many of them the same as in the first round. Most of the students have many other diagnoses besides dyslexia. These include dyscalculia, dysgraphia, and ADHD. The students are from a small middle school focused on children with severe reading disorders; one student is in 12th grade and attended the school when she was in middle school. The second round of testing occurred during COVID-19 shutdowns and was done via Zoom. Because of this, we were not able to control the screens and viewing environments used during the tests.

The initial round of design/testing helped refine the features the software supports and also refined the user interface so that it was easier for the teacher to create the coloring and styling the students requested. The second round incorporated six test expressions that were presented to the students in a randomized sequence. Half the expressions were shown using 14pt Arial and half using 21pt Arial. The students were asked to read the expression (not solve it). The time taken and number of errors were recorded for each reading. A 14pt font was used because that is typical of what students read without accommodations, and a 21pt font was chosen because studies show many students prefer a larger font. Testing proceeded as follows:

1. Students were asked to read the first expression at 14pt, then asked to read the second at 21pt. Errors and timings were recorded for both readings and all subsequent readings.
2. The size was reduced to 14pt and the students were asked the open-ended question: “what would make this easier to read?” If they didn’t suggest something, they were asked “would spacing changes to specific symbols make this easier to read?” Based on the earlier study, this was a common part of a student’s eventual preference. If they said yes, they were asked which characters should have more space and were given a range of choices for the amount of space.
3. They then read the third expression and were again asked if they wanted to change anything. If they hadn’t already mentioned it, they were asked “would bolding or highlighting changes to specific symbols make this easier to read?” Any requested changes were made, sometimes repeatedly until the student was satisfied with the bolding/coloring.
4. They then read the fourth expression and were again asked if they wanted to change anything. After asking if they wanted more changes, they were asked “would coloring the insides of parentheses and brackets make this easier to read?” Any

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1 Two students struggled to see 14pt well and 16pt was used instead; one of those students also used 26t instead of 21pt to read one question.
requested changes were made, with demonstrations of options of including/excluding the parentheses in the coloring/box.

5. They then read the fifth expressions. They were asked if they wanted to change anything.

6. The sixth and final expression was read\(^2\).

Two examples of chosen coloring of expressions are shown in Fig. 2.

\[
2(\begin{array}{c} [4+3+5] \\ \div \end{array} (4-1)+9) = 17 \\
7(\begin{array}{c} -12 \cdot 4 \end{array} \div \begin{array}{c} [8 \cdot 9] \div 3 \end{array}) = 9.6
\]

Fig. 2. Two example equations with student preferences

Based on the research cited above and an initial round of testing, we hypothesized that font size, font spacing, and font colors would be features the students requested and that the error rates and time it takes to read the questions would decrease as they narrowed in on their preferred renderings.

3 Results

The primary goal of this study was to get qualitative feedback on whether students with dyslexia and other learning challenges find font-related changes helpful. Based on the students’ choices/verbal feedback:

- 12 out of 13 said increasing the font size made the problem easier to read
- 11 out of 13 said that spacing things out made it easier to read
- 9 out of the 13 said highlighting the parentheses/brackets and their contents made the math problems easier to read and know what to do first.
- 9 out of the 13 said bolding the operators and symbols made it easier to read
- 6 out of the 13 said having the operators and symbols in a different color made it easier to see the symbols

There did not appear to be any strong similarities among the students with regard to color preference – sometimes a “+” had yellow background, sometimes purple, and sometimes it was not colored at all. During the tests, students would often say something like “purple is my favorite color, so highlight it in purple”. Often, the student would modify the color to increase the contrast between foreground and background.

Students with more severe visual impairments found a greater number of changes helpful. This is shown in Table 1.

\(^2\) One student stopped after reading five questions.
The expressions were of similar length, but we did not account for the different length of time it takes to read different characters/numbers in the test design. For example, “1” takes less time to read than “7”. To compensate, the authors read the expressions, averaged their times, and scaled the data to reflect the relative differences in reading times. The adjusted times are reported in Table 2. The slope of a linear regression (Slope\(_{e+}\)) gives the trend; a negative value indicates decreasing times as testing progressed and modifications were made. Because some of the errors students made were omissions of characters, the omissions lower the time taken and skew the regression. The cells with a yellow highlight in Table 2 indicate times that include those omission errors. The regression line slope with those cells omitted is “Slope\(_{e-}\).”

| Table 1. Number of changes by amount of impairment |
|-----------------------------------------------|
| Degree of impairment          | # of changes |
|--------------------------------|--------------|
| Mild (B1, C1, C2, E1, E2, V1) | 1 0 2 2 1 0  |
| Moderate (T1, II, J1)         | 0 0 0 1 2 0  |
| Severe (L1, S1, A1, G1)      | 0 0 0 0 1 3  |

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| Table 2. Adjusted Reading Times (secs) for questions (in reading order) |
|---------------------------------------------------------------|
| B1 | C1 | C2 | E1 | T1 | L1 | S1 | A1 | H | E2 | J1 | G1 | V1    |
|-----|----|----|----|----|----|----|----|---|----|----|----|------|
| 1   | 14 | 14 | 20 | 18 | 23 | 12 | 16 | 11| 33 | 16 | 23 | 19 | 19  |
| 2   | 18 | 13 | 17 | 19 | 21 | 26 | 18 | 11| 18 | 11 | 18 | 24 | 20  |
| 3   | 19 | 12 | 29 | 17 | 36 | 29 | 16 | 15| 24 | 11 | 22 | 19 | 19  |
| 4   | 18 | 14 | 14 | 14 | 24 | 31 | 17 | 17| 12 | 14 | 27 | 16 | 18  |
| 5   | 16 | 16 | 18 | 18 | 31 | 12 | 12 | 21| 12 | 17 | 21 | 18 |     |
| 6   | 15 | 16 | 12 | 27 | 14 | 19 | 19 | 15| 14 | 20 | 19 | 19 |     |
|     |    |    |    |    |    |    |    |    |    |    |    |    |     |
| Slope\(_{e+}\) | 0.0 | 0.7 | –1.5 | –0.6 | –0.3 | 0.7 | –0.2 | 1.2 | –2.7 | –0.1 | –0.3 | –0.3 | –0.2 |
| Slope\(_{e-}\) | –0.9 | 1.4 | –0.6 | –0.9 | –3.4 | 1.2 | 0.7 | –0.5 | 0.1 | –0.2 |

Based on these times, the Slope\(_{e+}\) and Slope\(_{e-}\) values show that reading times for most students decreased as the students added their preferred modifications.

| Table 3. Errors in reading questions |
|-------------------------------------|
| B1 | C1 | C2 | E1 | T1 | L1 | S1 | A1 | H | E2 | J1 | G1 | V1 |
|----|----|----|----|----|----|----|----|---|----|----|----|----|
| 4  | 6  | 3  | 0  | 2  | 8  | 1  | 0  | 5 | 6  | 2  | 0  | 3  |
| 0  | 4  | 2  | 1  | 0  | 4  | 0  | 4  | 4 | 1  | 2  | 0  |    |
| 0  | 6  | 0  | 0  | 1  | 0  | 6  | 0  | 3 | 3  | 0  | 3  | 1  |
| 0  | 6  | 3  | 0  | 0  | 12 | 3  | 0  | 4 | 2  | 4  | 2  | 0  |
| 0  | 0  | 3  | 0  | 0  | 15 | 3  | 0  | 3 | 0  | 2  | 0  |    |
| 0  | 0  | 2  | 0  | 0  | 1  | 0  | 0  | 2 | 1  | 0  |    |    |
Table 3 shows the errors the students made in reading the expressions. Although there appears to be a trend towards fewer errors at the end of testing, the low number of errors by most students prevents drawing any conclusions about errors decreasing significantly. The yellow highlight coloring indicates the students with the most severe visual impairments. Except for A1, they made the most errors. L1’s and J1’s errors initially jumped when bracketed quantities were colored; they started reading those parts first, as if they were going to solve the problems.

4 Conclusions and Future Work

With the exception of the one student who did not make changes, the students felt that the coloring and font changes would help them read, understand, and do math problems with fewer errors. This study provides evidence that they do read more quickly and that the error rate may drop with the individual modifications they made. The next step is add this functionality to Mathshare as mentioned earlier and then see if these results hold for 2D mathematical notations.

In our study, many of the students with dyslexia were also diagnosed with Attention Deficit Hyperactivity Disorder (ADHD). One estimate is that 30% of those with dyslexia also have ADHD [3]. The original coloring ideas were based on issues related to dyslexia, but research on ADHD has also indicated that coloring of background, numbers, and operators can help because it acts as visual stimulation to keep students on task [18]. As with dyslexia, [18] reports that students with ADHD and other LDs have greater deficits in math than in reading as compared to students with just ADHD. Because maintaining attention is critical in this group, additional work looking at randomizing colors or using other means to present novel stimulus on each problem is an option that should be pursued.

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