What Mathematical Images Are in a Typical Mathematics Textbook? Implications for Students with Visual Impairments

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Structured abstract: *Introduction:* Visually impaired students (that is, those who are blind or have low vision) have difficulty accessing curricular material in mathematical textbooks because many mathematics texts have visual images that contain important content information that are not transcribed or described in digital versions of the texts. However, little is known about the extent to which this issue exists within texts and what sort of information is contained in visual material in mathematics texts. This article describes a process undertaken to classify images in a selection of math textbooks that are currently being used in grades 5, 8, and 11. *Methods:* Representative textbooks were chosen that aligned with Common Core Standards. An exhaustive and mutually exclusive set of image categories was developed, researchers became reliable on coding procedures, and then all images in the representative texts were coded. *Results:* The most common images involved student interest, motivation, and organization, but contained little or no math content. The second most common area of image categories often contained large amounts of math content but were difficult to describe succinctly or might have been described without including important mathematical information. This grouping included tables, line graphs, and images specifically related to a single question. The final group of less frequently appearing images included ray or line diagrams, number lines, pie charts, bar graphs, and maps. *Discussion:* To improve access to visual math content, the focus should be on images that appear frequently and contain math content such as tables, scatter or line graphs, shapes, equations, and images specifically related to a single question. Less common image categories such as models, line diagrams, pictures of calculator keys, and number lines lend themselves easily to description. *Implications for practitioners:* Optimization of limited instructional time would be accomplished by having teachers focus on students' understanding of the most common types of images, such as tables and line graphs.

Data from the American Community Survey estimate that in 2013 there were 601,100 students aged 5 to 20 years with a visual disability in the United States (Erickson, Lee, & von Schrader, 2015). Many of these students have difficulty accessing the content of academic materials, and this difficulty is most profound in STEM (science, technology, engineering, mathematics) areas (Beck-Winchatz & Riccobono, 2007). Many current efforts on making STEM materials, mainly math, more accessible to visually impaired students (that is, those who are blind or have low vision) tend to use technology focusing on mathematical equations (for example, Bouck, Flanagan, Joshi, Sheikh, & Schleppenbach, 2011) or are relevant to a limited set of images such as line graphs (for example, Gardner & Bulatov, 2008; Summers, Langston, Allison, & Cowley, 2012). However, many math texts are full of mathematically oriented images that contain important information but which are not dealt with by any of the current technology.

Students with visual impairments have difficulty using the graphs, charts, diagrams, figures, icons, drawings, or other such images that are universally included in current STEM classrooms (Gardner, Stewart, Francioni & Smith, 2002; Gould, Ferrell, & O'Connell, 2009); and students tend to find these elements of mathematics to be the most difficult (Cahill, Linehan, McCarthy, Bormans & Engelen, 1996). For visually impaired students to access the information contained in the images found in textbooks, workbooks, reference materials, websites, or any other such teaching and learning materials, they must be provided with accessible formats of such content. Currently, access to images can be approximated through verbal description; a tactile graphic; use of a screen reader, or "sonification," in which an audio file is played in place of an image; and using changes in tone and volume to represent the image, which is of particular use for line and bar charts and equation graphs (Davison, 2012, 2013; Walker & Mauney, 2010). Although there is evidence that good descriptions of STEM content enhance students' grasp of the material (Ely, Wall Emerson, Maggiore, O'Connell, & Hudson, 2006), descriptions available to a student may not always be accurate or helpful, since readers in a student's classroom or the individuals responsible for creating the descriptions spoken by a software program might not be familiar with the content the image is meant to convey or the relationship the content has with the student's immediate task.

The purpose of the current study was to identify the types of images used in mathematics textbooks and the extent to which different types of images appeared. This knowledge may assist teachers and materials providers in allocating resources to optimize instruction for visually impaired students who use curricular material in digital, braille, or audio formats. Results on how these students are able to use different levels of description to access information contained in the different image types is reported in

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Methods

CHOICE OF TEXTBOOKS

In order to choose representative mathematics textbooks, the authors consulted experts in the field of teaching mathematics to visually impaired students and canvassed schools for these students and local education agencies (LEAs) to determine some of the most commonly used math textbooks. A great range of possible texts and publishers existed, but two popular publishers of math texts that were identified as being in common use were Pearson (Prentice Hall) and McGraw-Hill (Macmillan, Glencoe). As both of these publishers had recently come out with new texts aligned with the Common Core State Standards, representative math texts from grades 5, 8, and 11 from these publishing houses were chosen. The publishers and texts chosen were not meant to reflect the experience of all students, but rather to provide a snapshot of typical texts in common use. Grades 5, 8, and 11 were chosen because important milestones occur around those grades in many math curricula. After grade 5, many texts move from basic concepts toward more abstract presentation of materials. In the Common Core State Standards, grade 5 represents the year in which students have been introduced to all the basic operations and fractions, but have yet to delve into many of the more abstract concepts and operations (Common Core State Standards Initiative, 2016). Grade 8 represents the point in the math curriculum at which linear algebra, proportional relationships, rational numbers, and other increasingly abstract concepts have been introduced, but is just before the switch to high school math, where algebra and geometry are separated so that each can receive more in-depth treatment (Common Core State Standards Initiative, 2016). In grade 11, the separation of geometry and algebra intensifies the treatment of each subject and introduces more advanced concepts. Texts chosen are shown in Table 1.

Table 1
Math texts used in the study.

Grade	Title	Publisher
5	*Math Connects 5*	Macmillan
5	*Investigations*	Pearson
8	*Course 3 Mathematics Common Core*	Prentice Hall
8	*Pre-Algebra*	Glencoe
11	*Geometry*	Prentice Hall
11	*Algebra 1*	Prentice Hall
11	*Algebra 2*	Prentice Hall
11	*Geometry*	Glencoe
11	*Algebra 1*	Glencoe
11	*Algebra 2*	Glencoe

DETERMINATION OF IMAGE CATEGORIES

In order to develop a set of exhaustive image categories within the texts, both authors, along with two graduate students, went through the texts and created categories as they went through the pages. Categories were coded using a content analysis method (Krippendorff, 1980) by first open coding images, followed by an axial coding process. In the open-coding phase, any image that the team came across that did not fit into a category that was already created led to the creation of a new category. This process continued until all images could be placed into one of the categories on the list.

In the axial coding phase, the team discussed images and categories, refining the definition of each category and combining or separating categories to best reflect an exhaustive and mutually exclusive set. As part of the that phase, the team reviewed two randomly chosen pages from nine texts (one from the first half of each book and one from the second half) and categorized every image on each page. Due to an oversight, the grade-5 text *Math Connects 5* was not included in this round of reliability coding. In 18 pages from the nine other texts (Glencoe *Geometry*, Prentice Hall *Algebra 1*, Prentice Hall *Geometry*, Pearson *Investigations*, Prentice Hall *Course 3 Mathematics Common Core*, Prentice Hall *Algebra 2*, Glencoe *Pre-Algebra*, Glencoe *Algebra 1*, and Glencoe *Algebra 2*), the agreement rate was 56.2%. A large number of disagreements were clarified among headers, banners, icons, unrelated images, and extra feature notations, and placement of these within the same basic group of "side images" that raised the agreement rate to 71.3%. Clarification that the category of "equation" included only equations that involved a visually based image attached to the equation, such as a colored arrow pointing from one part of the equation to another, raised the agreement rate to 94.3%.

In a final portion of the axial coding phase, the two primary researchers chose two new pages from each text and coded each image on each of the pages according to the list of categories and definitions. In this round of coding, the raw agreement rate was 75% for 148 images. Sixteen of the disagreements were confusions of coding an image within the categories of side image and balloon or sidebar, or a question-specific image. There were images that seemed to straddle these categorical boundaries somewhat and that could lead to some confusion. Category descriptions were revised and rules for categorization were refined so that all visual symbols on a page were eligible for classification, which brought the agreement rate to 95.3%. The final list of categories and definitions is shown in Table 2. The category of equation was kept to be used for those instances in which an equation contained elements that might not be read by speech software. An example is a guided example in which an equation has differently colored numbers and letters to illustrate different parts of it.

CODING OF IMAGES AND RELIABILITY

With the list of categories and definitions established, coding checks of random pages were made to ensure that the two principal investigators and two graduate students were in agreement with one another above the 90% level. After the coding checks were completed, two separate coders fully coded all images in both grade 5 texts, both grade 8 texts, one grade 11 algebra text, and one grade 11 geometry text, for a total of six texts. This process involved coding every image in each of the textbooks. Once all images in a book were coded, the counts were compared, and image categories that had less than 95% agreement were discussed to determine what differences in coding decisions accounted for the discrepancies. Agreement levels lower than 95% were possible due to the large number of images being coded. Note that "agreement" in this case is a loose term, since the counting and coding of images in an entire mathematics text involved thousands of separate images. The total count of images between the two coders was

Table 2
Revised image categories with definitions.

Image category	Definition
Side image	An image not relevant to content such as background on a title page, colored borders, links to online content, a colored or bolded title, or images meant to make content approachable but not content related.
Balloon or sidebar	Information set apart from the main text, question, or flow of information, generally in a box set in the margin or information in a bubble that points to content or is being "spoken" by a character.
Screen shot	Screen shot of a computer screen or graphing calculator screen.
Question-specific image	An image that relates specifically to a particular practice or assessment question in the text. This is a broad category and includes images that do not fall into other categories.
Picture in a picture	A situation in which one category of image is totally subsumed within another image but in which the two images cannot be separated.
Procedural aid	Information presented visually to assist a reader in performing a task.
Organizational chart	An image in which how information is organized is central to what is being communicated. Often used to classify concepts.
Flow chart	Information in which an essential feature is the sequential ordering of steps. Often uses a series of arrows between text boxes or the text.
Equation	Elements that may not be communicated in braille or in which software designed to read math will not read accurately. This can be portions of the equation being different colors, check marks or x marks on parts of the equation, or the equation being presented in a typeface or font that makes it more of an image than text.
Shapes (2D or 3D)	An image whose essential information is a 2D or 3D shape.
Table	Information organized in a tabular format.
Scatterplot or line graph	Information presented as a series of x and y coordinates on a graph or a line of points on a graph.
Pattern or series	An image in which the essence of the information is the building of a pattern from one piece of the image to the next.
Bar graph	Information presented in histogram or bar form, either vertically or horizontally.
Directions or illustrations of a physical task	Information that shows the reader how to do a real-world task such as using a protractor or folding a piece of paper.
Pie chart	Presentation of information in a circular format, often with differently colored wedges representing categories of the information.
Number line	A straight line with graduated numbering along it, used to illustrate the sequential nature of information.
Ray or line diagram	An image that portrays angles. The simplest version is two rays extending out from a vertex. A more complex example is a demonstration of complementary angles using two parallel lines with a cross line.
Model used to indicate similarity	An image in which representations of items are used in place of the actual items, often for the purpose of generalizing an idea.
Calculator-related image	Directions for using a calculator, often with images of calculator keys.
Map	Information presented in the form of a map.

generally different within the text, so the counts in all the image categories could not be expected to reach 100%, especially for categories with hundreds of instances. For image categories with very few instances in a text, the agreement was often 100%, but when the tally was not exact, less than 95% agreement was accepted. This is because if one coder counted one instance of a given image category in a book and the other coder counted two, the agreement would only be 50%.

Agreement levels of less than 95% occurred for 60 image categories across the six textbooks. Initial agreements in these 60 categories ranged from 0 to 94.65 and averaged 73.5. The case in which the initial agreement was 0 was for situations in which there were very few instances of an image category in a text and so any disagreements were magnified in the agreement calculations. This occurred eight times. In Prentice Hall *Algebra 2*, the physical task was counted 10 times by one coder and picture in picture was counted 10 times by one coder; in *Course 3 Mathematics Common Core*, physical task was counted once by one coder; in Pearson *Investigations,* the physical task was counted once by one coder, picture in picture was counted 3 times by one coder, and pie chart was counted three times by one coder; and in *Math Connects 5*, picture in picture was counted once by one coder and flowchart was counted four times by one coder. In all instances in which discrepancies in the counts were large, differences in decision making were found that, when discussed and counts were corrected, brought the counts of the two coders to greater than 95% agreement for all but 28 image categories across the six texts. In these final 28 image categories, agreement levels ranged from 0 to 94.12 with an average of 72.68. If the specific instances of very low frequency discussed above are deleted from this group of 28 image categories, the remaining 21 categories across the six texts showed 85.48% agreement. The other 98 image categories across the six texts were all above 95% agreement.

Results

Once the counts were corrected for logical coding differences, the largest count for each image category was chosen to reflect that image category for that book. This method was followed in order to be as inclusive as possible in the count. The results of the count are shown in Table 3. For the two most common image categories (side images and balloons or sidebars) a count of pages was made instead of counting individual images. It was not uncommon for a given page to have a dozen or more of these images. This method was also followed for the shapes category in the higher-grade algebra texts.

In broad strokes, the categories of side images, balloons or sidebars, and shapes were most common, which was partly due to the increased focus on visual stimuli to attract the attention and increase the motivation of students, to organize content, to relate it to Common Core goals, and to link content to extended resources. The image categories, arranged in descending order from most to least common, are shown in Table 4.

All texts were highly visual, as demonstrated by the fact that the two most common image categories (side images and balloons or sidebars) were not related to math content at all but rather to visual interest, organization, or ancillary information. The high number of shapes was not due to geometry content, as might be expected, but rather to algebra content in the higher grades. After the three most common image categories, the most common content-related categories were tables, scatter or line graphs, and equations.

Table 3
Tallies of image categories by textbook.

Image category	Grade 5		Grade 8		Grade 11	
Text	*Math Connects 5* (787 pages)	*Pearson Investigations* (691 pages)	*Math Common Core 3* (402 pages)	*Pre-Algebra* (933 pages)	*Prentice Hall Geometry* (874 pages)	*Prentice Hall Algebra 2* (877 pages)
Side image	787 pages	689 pages	396 pages	896 pages	874 pages	812 pages
Balloon or sidebar	585 pages	366 pages	302 pages	616 pages	706 pages	690 pages
Screen shot	10	0	9	38	13	17
Question-specific image	500	139	159	513	443	172
Picture in picture	0	0	0	0	9	0
Procedural aid	121	17	10	30	81	7
Organizational aid	61	19	19	86	193	19
Flow chart	4	0	2	1	28	37
Equation	242	43	152	238	185	249
Shape	469	263	461	1,132*	566 pages	70
Table	482	154	222	646	25	256
Scatterplot or line graph	46	24	268	303	229	435
Pattern or series	11	5	2	37	16	30
Bar graph	22	10	2	48	0	5
Physical task	19	1	6	94	67	10
Pie chart	28	3	4	45	10	2
Number line	77	54	6	37	33	45
Ray or line diagram	52	6	67	47	549	1
Model	294	235	33	171	3	19
Calculator-related image	25	0	24	218	23	219
Map	8	3	8	4	22	5

* Images in the shape category were counted individually in texts in which they were less frequent and by page in texts such as grade 11 geometry, in which they were very frequent.

Table 4
Image category frequencies across grades.

Side image	4,454 pages
Balloon or sidebar	3,265 pages
Shape	2,961 pages and images
Question-specific image	1,926
Table	1,785
Scatterplot or line graph	1,305
Equation	1,109
Model	755
Ray or line diagram	722
Calculator-related	509
Organizational aid	397
Procedural aid	266
Number line	252
Physical task	197
Pattern or series	101
Pie chart	92
Screen shot	87
Bar graph	87
Flow chart	72
Map	50
Picture in picture	9

There were definite differences in the most common image categories by grade level of the mathematics text (see Table 5). Texts at all three grades showed many side images, balloons or side bars, shapes, question-specific images, and tables. Side images, balloons or sidebars, and shapes were the three most common categories in grades 5 and 8, but scatter or line graphs were more common than shapes in grade 11. However, this difference is complicated due to the shape category being counted by page for one text and by individual shape in all the other texts. Beyond these most common categories, tables were used much less in grade 11 than in the lower grades and scatter or line graphs were used very little in grade 5. Beyond the most common visually oriented categories, images in grade 5 tended to be models, equations, procedural aids, and number lines; images in grade 8 tended to be scatter or line graphs, equations, calculator related images, and models; and in grade 11 images tended to be scatter or line graphs, ray or line diagrams, and equations.

Discussion

A trend toward more visually based material in mathematics texts is making these texts, already somewhat inaccessible to students with visual impairments, more inaccessible (Gardner, Stewart, Francioni, & Smith, 2002; Gould, Ferrell, & O'Connell 2009). This inaccessibility is being partially addressed by technologies being developed to read mathematical equations (Cryer, 2013; Gardner, 2016; Jayant, 2006). These technologies are designed to read math equations; however, they only partially deal with the accessibility gap for students with visual impairments. Many times, a visually impaired student will receive a digital version of a math text and many of the visual elements, those devoted to organization and motivation as well as those containing important math content, will be represented only by the word "image" or an insufficient description (Jayant, 2006). Given that many visual elements in math texts are not currently accessible, and given the limited resources for creating accessible materials, knowing what kind of visually based elements occur most often in typical math texts would help professionals who are working on the accessibility of math texts to focus their efforts on areas that would offer the most return on investment.

In reviewing mathematical images from representative mathematics texts from grades 5, 8, and 11, there appeared to be

Table 5
Image category frequencies by grade.

Grade 5 (1,478 pages)		Grade 8 (1,335 pages)		Grade 11 (1,751 pages)	
Category	Count	Category	Count	Category	Count
Side image	1476 pp	Shape	1593	Side image	1686 pp
Balloon or side bar	951 pp	Side image	1292 pp	Balloon or side bar	1396 pp
Shape	732	Balloon or side bar	918 pp	Scatter or line graph	664
Question-specific image	639	Table	868	Shape	636 (pages and tally)
Table	636	Question-specific image	672	Question-specific image	615
Model	529	Scatterplot or line graph	571	Ray or line diagram	550
Equation	285	Equation	390	Equation	434
Procedural aid	138	Calculator- related image	242	Table	281
Number line	131	Model	204	Calculator-related image	242
Organizational aid	90	Ray or line diagram	114	Organizational aid	212
Scatterplot or line graph	70	Organizational aid	105	Procedural aid	88
Ray or line diagram	58	Physical task	100	Number line	78
Bar graph	32	Bar graph	50	Physical task	77
Pie chart	31	Pie chart	49	Flow chart	65
Calculator-related	25	Screen shot	47	Pattern or series	46
Physical task	20	Number line	43	Screen shot	30
Pattern or series	16	Procedural aid	40	Map	27
Map	11	Pattern or series	39	Model	22
Screen shot	10	Map	12	Pie chart	12
Flow chart	4	Flow chart	3	Picture in picture	9
Picture in picture	0	Picture in picture	0	Bar graph	5

three general tiers of image frequency. The most commonly seen images were the images devoted to interest, motivation, and organization, but that contain little or no math content. Within this most common tier, the most common images were in the categories of side images, balloons or sidebars, and shapes. The side images, balloons, and sidebars tended to be visual material geared toward attracting a reader's attention, organizing content, or linking to resources such as online material, which seems to reflect a move toward making mathematical materials much more visually oriented. Although most of these visual elements do not contain math content, not having access to them might lessen accessibility of visually impaired students to elements of the textbook designed to enhance their experience. For example, several of the texts had a recurring series of cartoon characters who introduced concepts or asked questions about the content. Knowing which character is associated with a given piece of text might affect a student's understanding of the difficulty level of the concepts in the text. Many of the texts in this study also had visual elements that noted links to related content in an online environment, links to Common Core objectives, or the presence of a linked audio file. In these texts, particular elements were all visual in nature and did not have text associated with them.

The second most common tier of images involved question-specific images, tables, scatter or line graphs, shapes, and equations with visual elements. These images often contained a large amount of math content. Since the most common content-related categories were tables, scatter or line graphs, equations, and shapes, efforts at accessibility should arguably target these types of images first. Although efforts are being made by several groups to increase accessibility to equations by creating technology that will speak equations and allow navigation through them (Gardner, 2016), the large number of equations that had some sort of visual image associated with them indicates that such efforts will not make all the educational aspects of even equations accessible to visually impaired students.

The final group of images appears less frequently and may or may not involve important mathematics content. This includes categories such as models, ray or line diagrams, number lines, pie charts, bar graphs, organizational or procedural aids, maps, and screen shots of items such as calculator displays. Many of these image types appear so infrequently that a drive to improve accessibility might arguably not require that much attention should be paid to them. For example, across all the pages of all the texts used in this study, only 50 instances of maps were identified.

Many of these least common image categories seem to lend themselves to description. Models, line diagrams, pictures of calculator keys, and number lines were generally not so complex that they could not be described in simple terms. The more common categories of tables and scatter or line graphs often did not lend themselves well to description, partly because of the large amount of information often contained in the images and partly due to the fact that these images can contain information central to conceptual understanding that is not necessarily included in descriptions of the image (particularly in the category of question-specific images). In this category, an image was portrayed that had to do with a specific question. The image was often very visually oriented and almost always contained mathematically oriented content. An example is a word problem asking about the angles of a triangle and an image showing an airplane approaching the ground with lines drawn between the airplane, a tree, and a control tower.

Conclusion

With the assumption that technological innovations will adequately provide access to mathematical equations, the large amount of visual material in mathematics texts that still cannot be accessed by students with visual impairments needs to be described or tactile versions of these items need to be created. Based on the three general frequency groupings of image categories seen in this study, improving access to math content contained in visual material should focus on content-heavy images that appear frequently such as tables, scatter or line graphs, shapes, equations, and question-specific images. Many of the less common image categories such as models, line diagrams, pictures of calculator keys, and number lines lend themselves easily to description.

LIMITATIONS AND FUTURE CONSIDERATIONS

This study used representative mathematics texts that were aligned with the Common Core State Standards, but there remains an extremely large number of other math texts in common use. With this study as a beginning, other math and science texts need to be analyzed in order to determine whether these results replicate across other math texts, texts from other publishers, and texts in other scientific disciplines. This study focused on what types of images occurred in math texts, but there needs to be research conducted that takes this sort of result and relates it to how visually impaired students react to information contained in the different types of images, including how that information is conveyed to them.

There were a limited number of coders working on this project, so it might be that other researchers, using similar image definitions, would code along different lines and have different results. As a corollary, image definitions for this study were developed by the researchers during the initial open-coding phase. As such, definitions grew out of the knowledge base of the researchers doing the coding. Other researchers replicating the study might develop different categories.

Even given these limitations, this study does offer an initial picture of the kinds of images used in a small selection of typical math texts. This information can be informative to creators of accessible materials, professionals working on technology for increasing math accessibility, and publishers of math texts. Technology being developed to make mathematical equations accessible or to make line graphs accessible through auditory means might be expanded to include some of the more common image types detailed in this study. Similarly, textbook publishers might develop ways to organize visual elements in future texts so that those containing mathematics content are tagged in such a way that these elements are linked to accessible formats of the content. Knowing the landscape affords those working on accessibility to better plan a path through that landscape.

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