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Research Report
ETS RR–16-23

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August 2016

ETS Research Report Series

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ETS Research Report Series ISSN 2330-8516

RESEARCH REPORT

Development and Initial Evaluation of the ClearSpeak Style for Automated Speaking of Algebra

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The work described in this report is the first phase of a project to provide easy-to-use tools for authoring and rendering secondary-school algebra-level math expressions in synthesized speech that is useful for students with blindness or low vision. This report describes the initial development, software implementation, and evaluation of the ClearSpeak speech style — implemented for initial testing purposes using prerecorded synthetic speech, and implemented later in the project as a collection of predefined rules and in some cases variations (called *preferences* in ClearSpeak) — for automatically generated synthetic speech. In addition to wording, speech styles can specify pausing (or other prosodic cues) within the speech. The ClearSpeak style focuses on speech for secondary school algebra. The evaluation compares a prototype of the ClearSpeak style to two pre-existing speech styles: MathSpeak and SimpleSpeak. The primary parameters evaluated are students' success in drawing conclusions about the content and structure of math expressions and their perceptions regarding the familiarity, helpfulness, and understandability of the expressions as spoken. Please see Appendix E for information on obtaining a version of this report that is fully accessible using the tools described.

Keywords math; accessibility; blindness; visual impairment; text-to-speech; MathML; algebra; STEM; ClearSpeak; assistive technology; screen reader

doi:10.1002/ets2.12103

There is a great need to improve mathematics achievement in students with visual impairments (SVIs), for whom there is a large achievement gap compared to students without disabilities (Blackorby, Chorost, Garza, & Guzman, 2003). This gap is consistent with the very low number who works in science, technology, engineering, and math (STEM) careers and is recognized by leading organizations serving individuals with blindness or low vision. It is one reason math is a focus of their research and product development efforts (American Printing House for the Blind, 2007). Removing access barriers to math instruction and testing is a necessary step in narrowing this gap.

Our project seeks to remove access barriers by improving SVIs' access to math expressions in computer-based materials, including assessments, instruction, and other informational materials — materials that are already fully accessible to their sighted peers. All too often, such materials are not fully accessible (or are completely inaccessible) to SVIs. Thus there is a clear access gap, which can reasonably be expected to be a contributor to the documented achievement gap. This report describes the development and initial evaluation of ClearSpeak, a speech style intended to improve audio access to math expressions by allowing MathML-encoded expressions contained in Microsoft Word or HTML documents to be rendered in understandable, mathematically accurate, and easily navigable synthetic speech.

SVIs typically benefit from a variety of learning modalities, depending on individual needs. For example, students might use modalities that are visual (large print, mechanical or electronic enlargement, font or color modifications), tactile (refreshable or hardcopy braille, tactile graphics), and/or auditory (live human reader, prerecorded human speech, or live or prerecorded synthetic speech). Textbooks and other materials prepared in advance can be produced in the required formats, but doing so in a timely fashion is often problematic for math materials, with difficulties increasing with the level of math. Materials generated on the spot (e.g., worksheets or assignments developed to meet immediate needs) by teachers or others are even more problematic, because they cannot always be readily prepared in the some of the formats needed. Even though a live reader can, in theory, work with material on the spot, such a reader generally needs detailed guidelines or a carefully prepared script in order to reliably relate the math understandably and consistently. That there is a perceived need for such guidelines is evidenced by the development and use over the past few decades of a variety of guidelines and rules (see discussion under Progress).

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Assistive technology (AT) such as screen readers, which provide synthetic speech for electronic text, allow compatible material to be represented in multiple simultaneous modes of access. Screen readers enable the content provider to present the same textual material simultaneously in audio, on screen, or via refreshable braille to provide a multimodal presentation that can make the material more accessible to some learners, as argued by Stevens, Edwards, and Harling (1997) when they concluded that “the difficulty of the problem of making mathematics accessible suggests that a multimodal approach is not only attractive but necessary” (p. 89). However, although some schools are able to obtain electronic versions of some books and tests from publishers for use with their students’ AT, and although teachers can easily develop electronic text-only documents for classroom or homework use, mathematical material had not heretofore been able to be made accessible in this way because the mathematical expressions had usually been opaque to the AT: It did not “know” how to speak them, especially in a way that provides access to the expressions’ structure, which may be two-dimensional (e.g., superscripts, numerators, and denominators). Past efforts to address these limitations are discussed in the section, Computerized Speech Rules.

Our project aims to help close the access gap by making math expressions[1] in more electronic materials accessible to SVIs via audio AT using synthetic speech. The synthetic speech can serve either as the sole modality or as one of multiple modalities (e.g., speech with large print, embossed braille, or refreshable braille).

Because the mastery of secondary school-level mathematics (particularly Algebra 1) has been shown to be an important gateway to college completion as well as to the study of and careers in math and other STEM domains (Fennell et al., 2008), and because Algebra 1 introduces types of mathematical structures that can benefit from the tools our project is developing, we selected Algebra 1 and some of Algebra 2 as the content focus for the project.

Math Expressions in Audio

Math expressions have been notoriously difficult to access in audio, due in part to their structure, which is often nonlinear, layered, and/or two-dimensional; they can consist of multiple substructures, such as fractions, exponents, and roots, and can involve multiple operations or multiple levels of nesting. Consider the quadratic formula:

$$\frac{\left(-b \pm \sqrt{b^2 - 4ac}\right)}{2a}.$$

It is a fraction with multiple substructures. The numerator is a sum, and the denominator is a product. Inside the sum in the numerator is a square root, which has substructures of its own—and so on. To be useful, an audio rendition must allow the listener to note the structure and nested substructures and to distinguish the boundaries of each structure—in the current case, the boundaries of the square root, the exponent, the numerator, and the denominator. The visual/spatial layout allows a sighted person to distinguish those boundaries at a glance.

In addition, an audio rendition should not needlessly contribute to verbal or memory load. That consideration is important because it is generally held that short-term memory can hold 7 ± 2 chunks of information at a time (Miller, 1956) and only for about 15–30 seconds (Atkinson & Shiffrin, 1971). An audio rendition that is unambiguous, that reveals essential structures and substructures, and that avoids excessive verbal memory load is a much greater challenge to produce than is the visual layout usable by sighted people. To produce such a rendition algorithmically is an even greater challenge. These difficulties are compounded by the fact that solving math problems typically requires working through multiple steps, each involving mathematical expressions of varying degrees of complexity. Even the best possible speech for some expressions will be unavoidably long, and so, providing the ability to navigate an expression interactively is also essential. While beyond the scope of the current paper, we developed interactive navigation in another phase of our project (see Frankel, Brownstein, & Soiffer, in press).

Progress

This section describes relevant work that preceded this study, starting with work in audio math accessibility in general, and work that directly influenced the development of the new speech style that is the subject of this evaluation.

Several methods for speaking math expressions have been developed over the past few decades based on a variety of goals and guiding principles. This section reviews the most significant of these, starting with speech styles that were initially designed for human readers (as opposed to computerized text-to-speech, which requires more formalized rules) and continuing with a discussion of development efforts for computerized math speech.

Math Speech Rules for Human Readers

Several styles of math speech rules for human readers have been developed. The best known sets of such rules are those developed by a blind mathematician, the late Abraham Nemeth, best known as the developer of the Nemeth Braille Code for Mathematics and Science Notation (1972), which is the standard for braille mathematics in North America (Do-It, 2015), and those developed by a blind scientist, the late Lawrence Chang. Both Nemeth and Chang initially developed their rules for the use of readers or aides who read math expressions to them, and later they published those rules. Their rules and strategies are significantly different from one another, as will be described in the next sections.

MathSpeak

Nemeth developed his rules in the 1950s, with the goal that readers would speak math expressions in a way that maps one-to-one with symbols used in Nemeth Code, so that he could conveniently write the information in Nemeth Code as it was read to him. He named his system MathSpeak and noted that "the speech generated by this protocol is not exactly what a professor in class would use, but it is absolutely unambiguous and results in a perfect Nemeth Code transcription" (Nemeth, 2013, p. 4). That is, this set of rules is optimized for real-time Nemeth Code transcription and requires the user to be proficient in both the Nemeth Code and its vocabulary.

> *Example:* $x^n + 1$ is spoken as "x superscript n baseline plus 1." The words *superscript* and *baseline* correspond to indicators in Nemeth Code. This expression is distinguished from x^{n+1}, which is spoken as "x superscript n plus 1." For the latter expression, because the end of the exponent is the end of the expression, the *baseline* indicator is not used in the Nemeth Code or MathSpeak representations of the latter expression.

Larry's Speakeasy

Chang's (1983) *Handbook of Spoken Mathematics: Larry's Speakeasy* (usefully expanded by Research and Development Institute, 2006) took a different approach with his rules. Chang's approach was based on his experience of learning mathematics not from braille but from listening to live readers who spoke mathematics using the more natural language of mathematics instruction. He argued that a symbol-by-symbol interpretation "can be very tedious and hard to understand" (Chang, 1983, p. 1). Chang's rules, some of which include optional variations, as seen in the example below, which provides two options, use common phrases (e.g., "to the n power" for the associated mathematical notations) rather than mapping to Nemeth Code ("superscript" and "baseline").

> *Example:* $x^n + 1$ is spoken as "x to the n power plus 1" or as "the sum of x to the n and 1." (Chang, 1983, p. 20)

Learning Ally

When adopting guidelines for audio math, organizations including Recording for the Blind and Dyslexic (RFB&D, now Learning Ally) have used Chang's work, along with National Braille Association's (1996) *Tape Recording Manual*, as references for speaking math in their recorded audio productions. This approach is consistent with the goal of providing access to a wider audience than just those accustomed to Nemeth Code and its vocabulary. The MathSpeak style can be difficult to understand even for Nemeth Code users, because as we found (see the Qualitative Findings section), not every Nemeth Code user correctly associates the words (e.g., baseline) with the corresponding notation.

Assessment Guidelines

Providing spoken math that is both unambiguous and usable by a wide variety of listeners is an important consideration in assessments. An important common thread among Chang's (1983) and Learning Ally's (National Braille Association, 1996) sets of guidelines is their emphasis on common and correct mathematical terminology as it is used in the context of the material being read, as opposed to MathSpeak's mapping of terms to individual braille or print symbols. When the Educational Testing Service (ETS) planned strategies to make its assessment and assessment-related audio materials useful for a variety of listeners, regardless of their experience with Nemeth Code and its terminology, it based its speech rules for its recorded audio and scripts for live readers on those adopted by Learning Ally—essentially adopting the Chang strategy.

This strategy is consistent with the recommendation of the National Braille Association (1996) to "insofar as possible, call things by the same names that will be used in the classroom" (p. 14). The ETS implementation of these guidelines includes strategic pauses to emphasize and support grouping within expressions.

Much more recently the two primary consortia for Common Core tests, PARCC (PARCC, 2014) and Smarter Balanced (Measured Progress/ETS, 2012), published guidelines that reference a variety of read-aloud guidelines, including Chang, ETS, and MathSpeak, though the actual guidelines are more in line with the Chang/Learning Ally/ETS strategy than the MathSpeak strategy—that is, they favor classroom-like speech over Nemeth Code–like speech. In introducing its guidelines, Smarter Balanced states:

> These guidelines are based on 1) research studies involving the read aloud accommodation 2) preexisting state read aloud guidelines for standardized assessment and 3) discussion and feedback from state officials, experts on accessibility, and content experts. The guidelines were made to inform decisions on scripting and tagging of mathematics items for computer-based delivery of the read aloud accommodation. One of the overarching goals of this project is to help facilitate standardization of mathematics read aloud and in doing so minimizing the inconsistencies and complications that exist in the current human and text to speech read aloud delivery systems. The guidelines contained in this document are not intended to be rigid rules, but rather a guide to creating read aloud scripts and tags that best help students access the content without violating the construct being measured. (Measured Progress/ETS, 2012, p. 4)

Similar guidelines, intended to be used for creating scripts and tags for computer-based delivery of read-aloud accommodations for Common Core State Standards, were also developed for the Guidelines for Accessible Assessments Project (GAAP; Measured Progress Innovation Lab & MD State Department of Education, 2014). Although scripts developed according to the PARCC, Smarter Balanced, and GAAP guidelines could be used for live or recorded human speech or scripted text-to-speech, the scripts themselves are not computer-generated but developed by people who have an understanding of the guidelines, the testing construct, and the content of the material.

Computerized Speech Rules

AT has for some time been capable of making textual material accessible to people with visual impairments, thus providing far greater independence than reliance on human readers. For math to be similarly accessible, to move from a style for human speech or script writing to one usable by computers and other electronic devices, it is necessary to codify speech guidelines into speech rules that the computer can implement with little or no human interaction.

ASTER

One of the earliest software developments in computerized spoken math was by T. V. Raman (1994) who developed the ASTER system, which reads LaTeX documents. Prosodic cues (i.e., pauses plus changes to pitch, rate, volume, and voice) are central features and help make the speech more concise than is possible through words alone. ASTER uses a higher pitch for superscripts and a lower pitch for subscripts. The pitch remains raised or lowered for the duration of the superscript or subscript, thus making the scope unambiguous and avoiding the need for begin/end language. Grouping (e.g., parentheses) is similarly indicated by variations in the voice used, with pauses providing additional emphasis for grouping. ASTER includes additional features, the discussion of which is beyond the scope of this report.

> *Example of the use of prosodic cues in ASTER*: In x^{n+1}, $n+1$ is spoken in a higher pitch to distinguish the expression from x^n+1 where only the n is spoken in a higher pitch; both expressions would be spoken with the same words.

Other Projects

In addition to ASTER, various other software projects have developed systems for spoken math. Some of those projects are MathTalk, developed by Stevens et al. (1997), MathGenie (Karshmer, Bledsoe, & Stanley, 2005), the Lambda Project (Edwards, McCartney, & Fogarolo, 2006), WinTriangle (Gardner, 2005), AudioMath (Ferreira & Freitas, 2004), and ReMathEx (Gaura, 2002). The latter two projects used math expressions encoded in MathML as the basis for speech, but neither project is under active development as of this writing.

Summary Regarding Computerized Speech Rules

All of the projects mentioned so far were self-contained software environments, as opposed to being able to work within standard applications or with common types of AT, thus making them not very suitable for making mainstream electronic material accessible to SVIs.

Requirements for the New Speech Style

In this section, we discuss the requirements we established for the speech style and the reasons underlying those requirements. The requirements are listed briefly below, followed by an explication of each:

1. Ease of decoding expressions
2. Similarity to classroom speech
3. Standardization
4. Customization
5. Externalization

Ease of Decoding Expressions

As the purpose of speaking math expressions, like that of speaking text, is to allow the listener to receive and make use of the information, the primary measure of success for any speech style is how easily users can determine what the math expression is (or, to borrow a term from discussions of literacy, “decode” the expression). Only once a student has successfully decoded the expression—grasped both its structure and its content—can the student go on to work with it to solve problems and further their knowledge of mathematics.

Similarity to Classroom Speech

Students are used to hearing math spoken in the classroom, and so it is reasonable to assume that math decoding is facilitated by a speech style that is as similar as possible to typical classroom speech. Anecdotal comments by teachers, as well as comments students offered in our first feedback study, support this assumption. Classroom-like speech has the advantage of minimizing any additional learning curves for students.

Standardization

The existence of a variety of guides for spoken math—whether spoken by people or by computers—shows that it is often less than obvious how a given math expression should be spoken and that there are expectations of variation based on mathematical or educational context from any proposed standards. But it is desirable that math speech rules used in instruction should be as consistent as possible and that speech used in assessments should be consistent with speech used in instruction. Just as there are standards for printed notation (e.g., superscripts indicate exponents), so should somewhat standardized speech be given (e.g., use of the word *power* in exponents). Otherwise, it can be necessary for a listener to perform a mental translation when changing environments (e.g., moving among different textbooks or between an instructional context and a test-taking one). In each case, the math should ideally be spoken using the same basic language.

Customization

Yet alongside the need for standardization is a need for flexibility: Just as standardized print symbols allow for some degree of variation and contextualization (e.g., (1, 2) can represent the coordinates of a point or an open interval), different contexts, situations, or audiences can call for variations in the way mathematics is spoken. For example, (1, 2) (meaning point coordinates) should be spoken differently than the same notation indicating an open interval.[2] Verbosity needs may also vary with the listener’s level of experience and with the complexity of the material. Less complex expressions used by beginning students may be verbose but relatively short because of the brevity of the expression. More complex expressions will impose increased memory load if spoken verbosely, but the more advanced students likely to work with the more complex expressions may prefer a less verbose presentation.

Context, as already suggested, is highly relevant to the way an expression should be spoken. In addition to the fact that the mathematical meaning of the same notation can vary contextually, even within a given meaning, context can affect the optimal speech for an expression. For example, while it may appear obvious that 1/2 should be spoken "one half," when it becomes part of a larger expression such as

$$\frac{1}{2} + \frac{3}{5} + \frac{23}{423} + \frac{x}{y}$$

it may be preferable to match its speech to that of the surrounding fractions—"The fraction one over two [pause] plus [pause] the fraction three over five [pause] plus [pause] the fraction twenty-three over four hundred twenty-three [pause] plus [pause] the fraction x over y"—so that all of the fractions within the larger expression are spoken according to the same basic scheme. Concerns such as those described in this section lead to the conclusion that in order to make math accessible via synthetic speech, it is important to define a speech style that is robust and flexible and that allows content creators and users to make choices among speech styles and among speech preferences within the overall style. It is also useful to allow content providers to enter the exact speech (including pauses and other prosodic elements if desired) for parts of an expression, for cases in which the available rules and preferences are not sufficiently robust to provide the desired speech or for special situations. The ability to specify exact speech is also useful for prototyping and testing proposed rules and preferences before they are programmed into a speech style.

Externalization

As discussed earlier in this paper (see the section, Summary Regarding Computerized Speech Rules), previous projects implemented spoken math in self-contained environments, meaning that users would have to obtain, learn, and use a system that might not work with their customary AT and that any changes or updates to the speech rules would be closely tied to the environment in which the system was developed. We instead sought an environment that allowed the speech rules to be stored externally and thus capable of being revised or adopted independently of the delivery software, and which could be used with a wide range of commonly used software (Web browsers, Microsoft Word) and AT (most notably, screen readers and refreshable braille displays).

Purpose

This report describes the development and evaluation of the ClearSpeak style, which is intended to address the requirements detailed above. The project, Expanding Audio Access to Mathematics Expressions by Students With Visual Impairments via MathML, was funded by a US Department of Education, Institute of Education Sciences Special Education Development Grant (R324A110355), which supported the iterative development of the speech style, authoring tools, interactive navigation, and integration with Microsoft Word. Four feedback studies—the one described in this report, focusing on speech styles; one on the use of certain prosodic elements in the speech style; one on the interactive navigation capability; and one on authoring by teachers and service providers—guided development, culminating in a final pilot in the spring of 2015.

Method

The MathML Audio Project and Its Overall Strategy

When this project was conceived, the MathPlayer software (Design Science, 2008; Soiffer, 2007) was selected for a number of reasons. First, it was an existing, free plug-in that already implemented some aspects of spoken math, including two pre-existing speech styles. Second, it satisfies the externalization requirement described above: Its architecture, which stores speech rules externally to the program, allows for multiple sets of integrated speech rules with optional variations (preferences), and it is easily extensible, allowing for the implementation of ClearSpeak without requiring any changes to or elimination of its pre-existing styles. Moreover, MathPlayer is not self-contained but instead works within widely used software (e.g., Microsoft Word and some browsers) and with AT to supply speech data (and braille data for refreshable braille displays) to text-to-speech synthesizers that are already on the user's computer.

Steps in the Development of the ClearSpeak Style

This section describes the major steps in developing ClearSpeak to the point that enabled us to perform the preliminary evaluation described in this paper.

When our project began, the speech styles available in MathPlayer were SimpleSpeak and an implementation of MathSpeak, which as noted previously (see the section, MathSpeak), is a speech style based on Nemeth Code and optimized for real-time Nemeth Code transcription by one-to-one mapping of speech to Nemeth Code symbols. MathSpeak was also implemented and documented by gh (2004–2006).

SimpleSpeak's guiding principle is to speak simple expressions simply and to disambiguate complicated expressions with begin/end bracketing. It focuses on rendering the meaning of the mathematical expression as simply and briefly as possible and does not map to Nemeth Code or to any other braille system, nor does it attempt to replicate classroom speech.

We believed that there was a need for ClearSpeak because of industry and ETS practice (see the Learning Ally and the Assessment Guidelines sections) and reports from blind individuals suggesting that MathSpeak's focus on mapping to Nemeth Code symbols was not optimal for most non-braille readers or even for most braille readers, and that something more like the ETS speech style (which, like SimpleSpeak, does not map to braille symbols, but which, unlike SimpleSpeak, attempts to replicate classroom speech and correctly reflect the mathematical meaning of the expression) should be available. Because neither MathSpeak nor SimpleSpeak meet the requirement for classroom-like speech, a major goal of our project was the creation of a new automated synthetic speech style (ClearSpeak) that would meet that and the other four requirements presented previously.

The rules of the ClearSpeak style were developed by carefully considering the current ETS speech style for human readers (live or recorded), which is based on classroom-like speech, and deciding how it should be adapted for computer-generated speech—codified into programmable algorithms. We began by creating a comprehensive list of mathematical structures and types of expressions used in secondary school algebra (master expression list) and how they ought to be spoken in various circumstances. Then we revised and augmented it as needed. This list served as a reference for the resulting ClearSpeak rules and preferences (Brownstein, Soiffer, & Frankel, 2015a). An excerpt from the master expression list is in Appendix D; the full list includes hundreds of expressions and covers a wide variety of math structures, symbols, and other conventions found in secondary school math. See Brownstein, Soiffer, and Frankel (2015a, 2015b).

We next followed an iterative process of developing the rules and variations (preferences) and testing them against the master expression list. We presented early drafts of the rules and preferences for the structures most fundamental to secondary school algebra (fractions, exponents, parentheses, and roots) to our advisory committee, which consisted of experts in the field of mathematics education for blind students, including Dr. Abraham Nemeth, Susan Osterhaus, and Maylene Bird, for comment. The resulting rules were used (prototyped using the exact speech capability that was developed early in the project) for the spoken math used in the first feedback study, the purpose of which was to perform the initial evaluation of the ClearSpeak style.

ClearSpeak and the Speech Style Requirements

A central component of this project is the construction of the new automated speech style, ClearSpeak. The MathPlayer platform with its pre-existing styles MathSpeak and SimpleSpeak already had standardized external rules, and so satisfied Requirements 3 and 5 described previously (standardization and externalization). These styles did not, however, support preferences, nor was the resultant speech similar to classroom speech, and so they did not satisfy Requirements 2 and 4. ClearSpeak is designed to satisfy all five requirements—most importantly, the primary requirement of ease of decoding.

Ease of decoding is, we argue, substantially based on the similarity of the synthetic speech to the speech students are familiar with from their classrooms, as we have stated in Requirement 2. That said, any synthetic speech style will at best be classroom-*like*; it cannot be identical to classroom speech, but it can and must differ in certain respects. In classroom speech, a teacher can consider relevant characteristics of the students the teacher is addressing (e.g., their math background and the speech they are used to). If a teacher is speaking an expression in a way a student finds difficult to understand, the student can ask the teacher for clarification whenever needed. As a result, for human speech, guidelines, as opposed to an exhaustive rule set, are often adequate. Synthetic speech cannot be asked for clarification if it is not immediately understood, so the development of rules is a far more involved and meticulous process than is the development of guidelines for human readers.

Another important difference between human and synthetic speech is the ability to adapt to context, particularly to the larger contexts (e.g., those of a problem, proof, or assessment question) in which math expressions typically occur. For example, in a lesson on functions $f(c)$ is "f **of** c," while in a multiplication lesson it is "f **times** c." A teacher will naturally speak the expressions according to the appropriate context. Since much of that context is outside the expression itself, systems for generating synthetic speech for expressions cannot automatically adjust for that external context. But well-considered rules and authoring tools that allow the selection of relevant variations can help bridge this gap. ClearSpeak provides such tools, so that content authors can make adjustments to how an expression is spoken (see Requirement 4). Adjustments are made primarily through the use of speech preferences, which are alternative common ways of speaking math expressions. ClearSpeak also provides the ability to enter exact speech for an expression, when neither the rules nor any available preference give the desired speech. See Frankel, Soiffer, and Brownstein (2013) for details.

One class of potential difficulties in understanding spoken expressions involves boundaries (for example, where an exponent in an expression begins and ends). A common preventive strategy for communicating the locations of boundaries, such as where a fraction, exponent, root, or other structure begins and ends, is to add words such as "begin root … end root." (Both MathSpeak and SimpleSpeak use such strategies.) However, particularly in longer expressions, those words can build up to the point that the verbal load makes it difficult to keep the expression in short-term memory. Accordingly, ClearSpeak endeavors to replace at least some of the wording (particularly begin/end language) with alternatives, such as prosodic cues (primarily pauses, although changes to the speech rate have been considered) that do not require verbal memory, to the extent that such cues can be effective replacements and/or help mitigate memory-load problems that occur when the language must be retained. In our second feedback study (see Frankel & Brownstein, in press), we investigated the effectiveness of various combinations of prosodic cues and end language, and used the results to further refine the ClearSpeak rules and preferences.

The First Feedback Study

The balance of this report describes the first feedback study, conducted in March 2012, and its results. This study was the first of a series of studies guiding the specification and implementation of ClearSpeak. Unlike the standardization, customization, and externalization requirements, which could be assessed *prima facie*, determining which styles best met the requirements of similarity to classroom speech and ease of decoding expressions needed empirical investigation. Hence, the primary purpose of the first study was to determine whether, for SVIs who were in or had completed Algebra 1 and for Algebra 1-type math expressions, ClearSpeak surpassed the other two styles with respect to those remaining requirements. And although positive subjective reaction to a speech style was not an overriding requirement, we believed that such a reaction would be highly desirable because such reactions would increase the likelihood that students would be willing to use the speech. Accordingly, the primary research questions were:

1. Does ClearSpeak promote equal or better decoding of mathematical expressions as compared with the other two styles?
2. Do students react at least as or more positively in a variety of respects to ClearSpeak as to the other styles? For example, how do the styles compare on overall student preference and on students' perceptions of familiarity and understandability?

We attempted to answer the first question by presenting students with objective math and math-recognition questions in which the mathematical expressions were presented purely in audio in the various speech styles (see Appendix A, questions 1, 9, 18, 26, 36, 46, and 47). To answer the second question, we presented them with feedback questions (the remaining questions in Appendix A) about how familiar and understandable they found the speech in each case. In end-of-section and end-of-study questions, we asked them to indicate an overall assessment of each style, which of the three styles they most preferred, and which they least preferred. We also sought specific suggestions for improving ClearSpeak in later phases. Further breakouts of these research questions and how the study went about answering them are described below (see the section, Quantitative Results by Research Question).

Participants

Sixteen students with visual disabilities (blindness or low vision) who were taking or had completed Algebra 1 participated in the study. All but one student (who was blind) completed all three sections. A summary of the participants' most relevant

Table 1 Participant Characteristics

Visual status	Current math class	Other disabilities	Preferred math access method
Blind: 8 Low vision: 8	Algebra 1: 4 Math models[a]: 2 Algebra 2: 7 Calculus: 2 Other: 1	Autism: 1 Hearing impairment: 1 Orthopedic: 1 Learning disability in math: 1 Speech impairment: 1 TBI: 1	Hard copy braille: 5 Braille + reader: 3 Reader: 1 Large print/screen enlargement: 6 Regular print: 1

Note. TBI = traumatic brain injury.
[a]Math Models is a course given in this particular school between Algebra 1 and Algebra 2.

characteristics is presented in Table 1. We did not collect data on age, grade, sex, or ethnicity; none of which were expected to be relevant. It is perhaps notable that audio was not a preferred math access method for most of the participants: It was listed by two of the blind students and by one student with both low vision and a math learning disability. That fact reflects the limited audio support that has (prior to our project) been available for math.

Sampling Procedures

Participants, all of whom were blind or had low vision, were taking or had completed Algebra 1, were fluent in English, and did not have significant cognitive disabilities, were recruited through two participating schools for the blind. We slightly exceeded our recruiting goal of 15 students, but as already noted, one of the students began but did not complete the study. Students were given $25 in gift cards for completing the study. Institutional Review Board approval and signed informed consent forms were obtained prior to data collection.

Research Design

Each student was assigned to receive three parallel sections of items. In each section, the math expressions were spoken in a different one of the three styles—ClearSpeak, MathSpeak, or SimpleSpeak. In order to cancel possible order effects, the order of styles was varied systematically. After answering each math question, the student was asked several feedback questions about the math statement and math question.

Instruments

The study used three instruments.

First, the student background questionnaire asked students to self-report their math- and vision-related background and their history with using various forms of AT for math.

Second, the student background questionnaire for teachers was a parallel instrument to the questionnaire for students. It presented teachers with the same questions (on behalf of their students) that the students had answered for themselves. Central topics of the two questionnaires included the following:

- student's current "best" mode for accessing math (print, braille, read aloud, AT);
- perceived usefulness for the student of the various modes for accessing math (print, braille, read aloud, AT);
- student's proficiency with fractions, exponents, and parentheses (grouping); and
- the degree to which the student uses visual versus nonvisual methods of accessing math.

Third, the math and feedback instrument comprised three sections (see Appendix A for one full section), each of which consisted of the following:

- Seven math statements (expressions or equations), each accompanied by one or two "math questions." In most cases, these were not typical math "problems," but rather questions to determine how successful the student was at decoding the math statements. The math statements represented key secondary school algebra topics (fractions, exponents, grouping). The purpose of each math statement is included as annotations to the sample instrument provided in Appendix A.

- For each math question, there were several feedback questions designed to gather information about the student's perceived level of understanding of the structure of the math statement (i.e., how easily they could decode the statement) and about the student's subjective reaction to how the math was spoken
- A section summary question regarding the student's willingness to hear math spoken the way it was in that section

After all three sections were completed, students were asked three final summary questions about the way math was spoken in all three sections.

Note that the three sections are described as parallel. To be more specific, the feedback questions were identical, and the math statements and questions were "clones"—differing only in superficial aspects so as to minimize any memorization effects between items as participants progressed from one section to the next for the three speech styles. Efforts were made to maintain the same level of difficulty among the clones. However, to control for possible unintended differences in difficulty among clones, the assignment of instrument variants (i.e., group of cloned expressions) to speech styles was systematically varied (see the section, Study Manipulation). Sample expressions and their clones, including information about how the expressions were spoken in the different speech styles, are included in Appendix B.

Delivery Method

The math and feedback instrument consisted of two parts: a textual component and a prerecorded audio component. All of the math expressions were provided in audio only. The audio component was delivered via MP3 players; the textual component was delivered via Word file (which students could use with their screen reader, including entering their own responses into the document) and hardcopy print (for use with a live reader/scribe). This division into screen readable/scribe readable text and prerecorded audio was employed for three reasons: (a) the integration of MathPlayer audio into screen readable Word documents was not yet ready for use (it is functional as of this writing and was used in the final pilot), (b) the rules and preferences were under development and needed to be simulated via entry of exact speech to be read by the screen reader, and (c) we wished to ensure that all students, regardless of degree of usable vision, received the expressions only in audio, which allowed us to isolate the effects of the audio presentation from any visual information that might otherwise be available to students with some vision. Because students with vision are accustomed to using it, however, being required to work without vision plausibly increased the difficulty of the tasks for such students (and as will be seen in the discussion of results, students with low vision had lower levels of success than students with blindness).

Details of how the audio portions were developed are provided in the section, Development of Audio. The student experience can be seen from the annotated instrument presented in Appendix A. That instrument includes both math and feedback questions. The feedback questions were designed to assess decoding success and students' subjective reactions to the speech.

Development of the Items

To develop the items, we worked with two of our expert consultants, Susan Osterhaus and Maylene Bird (both of whom teach math to blind/low vision students). Appendix A includes descriptions of the reasons behind the selection of each math statement and associated math question. In creating the math questions to accompany the statements, we sought questions that would help identify errors in recognition of the math structures in the statements, as opposed to questions that would assess students' mathematical ability. Following the general precepts of evidence-centered design (Hansen & Mislevy, 2008) in order to make sure the test items could provide evidence to support the claims to be made on their basis, we developed the following criteria for expressions to be used in the study:

- Similarity to expressions typically found in high school algebra
- Inclusion of structures that would be understood by a sighted student who is currently taking the second half of an Algebra 1 class or a subsequent math class
- Complexity sufficient to offer potential accessibility difficulties attendant to spoken presentation; that is, not be so simple that students would instantly understand them, no matter how they were spoken
- Simplicity sufficient to allow students to understand them without intensive effort
- Support for math questions that require little or no computation (so as to focus on decoding, not computation)

- Speech that is significantly different for at least two of the three speech styles being tested (and preferably, different for all three)
- Support math questions that can help to diagnose aspects in which the speech style succeeds or fails to make the math expression clear, as opposed to those that assess whether the student can do the mathematics required to work with the expression (i.e., if students fail to correctly identify the denominator of a fraction, it is possible that the speech did not make the relevant boundaries sufficiently clear)

Because the first ClearSpeak rules to be developed focused on fractions, exponents, and multiplication/parentheses—all common and essential in Algebra 1—the expressions and associated questions for the study focused on these structures. The "math questions" were crafted to call upon the lowest level of math knowledge needed in order to assess the students' understanding of each expression's structure and content (i.e., whether the student successfully decoded the expression). Among the feedback questions to which students responded were requests to describe how they arrived at their answers. That information in many cases helped us to pinpoint portions of the expression that were or were not spoken understandably or allowed us to infer that a student did (or did not) correctly identify the expression regardless of whether the student answered the math question correctly.

The resulting items included some constructed-response questions (e.g., evaluate the expression, reduce the fraction) and some multiple-choice questions in which the distracters reflect incorrect understandings of the statements that could result from the ways the statement is spoken in the various speech styles. For example, a student would be more likely to select a particular distracter if the student had drawn a particular incorrect conclusion about the scope of an exponent in the statement. After the expressions and questions were created, we created clone versions to prevent memorization effects between speech styles. Clones were carefully constructed to change only surface features and to maintain equal difficulty. All items and clones were carefully developed and reviewed by two test developers (Brownstein and Frankel) and two teachers/consultants (Osterhaus and Bird). See Appendix A for a sample instrument and Appendix B for a smaller sampling of expressions and clones showing the speech used for each style.

Development of Audio

The math expressions in the instruments were developed in Microsoft Word 2007 with MathType 6.8. For each clone group, one document was produced for the ClearSpeak implementation and another for the MathSpeak and SimpleSpeak implementations. For the ClearSpeak implementation, exact speech was inserted to prototype what would become rules or preferences as ClearSpeak development matured. MathSpeak and SimpleSpeak spoke according to each style's already established rules. Note that at the time of the study, the MathSpeak implementation included what was initially thought to be an intentional part of the speech style but later was considered a bug because it was not, in fact, intended: In three of the seven math expressions, on which four of the eight math questions were based, it added the phrase "nested one deep," indicating a nesting level. Although this speech pattern was not intended, some other implementations of MathSpeak do announce nesting levels for fractions within fractions (gh, 2004–2006), and the version of MathSpeak against which ClearSpeak was compared in this study was the implementation that had been in the published version of MathPlayer at the time of the study.

Once the expressions and intended speech were finalized, a computer's default voice was set to Microsoft Anna, the standard text-to-speech voice that comes with Windows 7. (Anna is not the highest quality voice, but we do not have distribution licenses for higher quality voices, so it was the only available selection.) The free, open-source Audacity sound editor was used to capture the audio produced by having the computer speak each expression in each speech style and in each clone version. Some sound editing was done to all files in all speech styles in order to correct cases of particularly poor pronunciation: Places in the sound stream where Anna pronounced a number or symbol (e.g., "x") correctly replaced instances where Anna pronounced the symbol incorrectly ("thex" for "x" and "dwy" for "y"). We felt comfortable performing this editing, which was done uniformly across all expressions and styles, because we wanted students to be able to focus as much as possible on the vocabulary and prosody, rather than on pronunciation issues that would be solved in later implementations by integration with the Window-Eyes and NVDA screen readers, each of which can use a variety of speech engines and voices. At the start of each audio math statement, we added audio introductions, such as, "Math statement for questions one through eight," spoken via JAWS, using its default voice and speech engine (Eloquence Reed), and recorded. At the end of each math statement, we inserted a tone to signal students to pause the audio to answer the questions before moving to the next audio clip. So, for each math expression, a student would hear the following:

1. Introduction (e.g., "Math statement for questions one through eight")
2. The spoken expression
3. End tone

The final audio files were loaded onto MP3 players and tagged so that the clips would play in the correct order and display appropriate labels on players. The audio files are available for download. See Appendix E for links.

Study Manipulation

There were three instrument variants; each used a different set of clones of the expressions. The section given first was always Clone Group 1, the second section was Clone Group 2, and the third was Clone Group 3. Each clone group was given to different groups of students in each of the speech styles. Students were randomly assigned to receive a given section order: Six students, including the one who did not finish the study, received the order and clone group assignment SimpleSpeak (Clone Group 1), MathSpeak (Clone Group 2), ClearSpeak (Clone Group 3); five received the order/assignment MathSpeak (Clone Group 1), ClearSpeak (Clone Group 2), SimpleSpeak (Clone Group 3); and five students received the order/assignment ClearSpeak (Clone Group 1), SimpleSpeak (Clone Group 2), MathSpeak (Clone Group 3).

Qualifications of Study Administrators

Study administrators were either project consultants who worked at one of the cooperating schools or cooperating school personnel. For students who took notes in braille, the study administrator transcribed those notes into print so that we could consider them when we analyzed the data.

Session Procedure

First, students completed the background questionnaires with the help of the study administrator who also collected parallel information from the student's math and VI teachers.

Next, administrators provided the students with the correct instrument, based on the random order assignment. Form 1 used the order SimpleSpeak (Section S), MathSpeak (Section M), and ClearSpeak (Section C). Form 2 was ordered M, C, S; Form 3 was ordered C, S, M. The beginning of the instrument explained the purpose of the study and described the procedure to the students.

Last, administrators guided the students through the three sections of the form, including the math questions, the feedback questions, and the end-of-section questions and then the end-of-study questions. As needed, administrators assisted with audio playback and scribing student responses for those students who did not enter their own responses into the Word document.

Data Analysis

The instrument files were returned to us electronically by the study administrators and pasted or transcribed into a spreadsheet by a staff member. Because one student completed only two of the three sections (SimpleSpeak and MathSpeak only), that student's data were not used in the analysis. We organized the spreadsheets and, based on the answer key for the math questions, entered information about whether each answer was correct or incorrect. In a small number of cases, a student's answer to the math question was technically incorrect but correct for the purposes of analysis (or "adjusted correct"); even more rarely, an answer could be technically correct but incorrect for the purposes of analysis. For example, consider the expression $16\,x^9 + 12\,x^{13} + 5\,x^7 + 1$, about which students were asked to type in an answer to the question, "What is the biggest exponent in the math statement?" If a student entered $12\,x^{13}$ or x^{13} instead of just 13, that would be technically incorrect but adjusted correct (and so was treated as correct for analysis) because it showed that the student correctly identified the biggest exponent, even though the student did not express it as directed. For the math statement $(2)\,(4)\,(5+1)\,(3)$, students were asked to give the value of the math statement and to explain how they arrived at that value. In some cases, the student's explanation clearly indicated that the student correctly identified the numbers and the operation of multiplication, but that the student multiplied incorrectly. Again, such a response was technically incorrect but adjusted and counted as correct because it showed that the student correctly decoded the math expression. For those students who wrote down (using braille or by typing into the document) what they thought they heard, we determined whether their written expression matched the spoken expression. In some cases evaluating this transcription resulted in a technically correct answer being adjusted incorrect or vice versa. Although analyses were performed on both technical correctness and adjusted correctness, for the purposes of reporting, we are including only the analyses based on adjusted correctness because that is the measure that addresses students' level of success in decoding the math expressions. To avoid repeating "adjusted correct," whenever "correct" is used in this document it refers to the "adjusted" correctness measure. For ClearSpeak, there were six adjustments out of 105 total responses; for SimpleSpeak, three adjustments out of 105 total responses, and for MathSpeak, four adjustments out of 105 total responses.

Results

This section describes how our results bear on each of two research questions:

1. Decoding Comparison: Does using ClearSpeak result in equal or better decoding of mathematical expressions representative of Algebra 1 content, as compared with the other two styles tested? That is, as implemented in MathPlayer, how does the ClearSpeak prototype style compare with the pre-existing styles SimpleSpeak and MathSpeak with regard to students' ability to decode the representative math statements as measured by degree of success on the math questions (Appendix A)?
2. Favorability Comparison: Do students subjectively react at least as or more positively to ClearSpeak, as compared with the other two styles? That is, as implemented in MathPlayer, how does the ClearSpeak prototype style compare with the pre-existing styles SimpleSpeak and MathSpeak with regard to students'(a) overall level of favorable attitude, as expressed in terms of familiarity and ease of understanding (see Questions 4, 6, and similar questions in Appendix A), (b) level of confidence in their understanding of the math statement (see Question 5 and similar questions in Appendix A), and (c) for the subset of questions that involved somewhat more difficult math problem solving, level of confidence that they had answered the math question correctly (math confidence; see Questions 34, 44, 55, 57, and 66 in Appendix A)?

As we will describe in detail in this section, our results supported very promising answers to both of these central questions. We found that expressions spoken with the ClearSpeak style performed better than expressions using the other two styles, both with regard to success with the math decoding questions and with regard to measures of favorable attitude (confidence that they understood the expression and found the speech familiar) and confidence in their ability to handle the math ("math confidence"). In addition, for all these summary measures, ClearSpeak showed the least variability in response between students with blindness and those with low vision.

Quantitative Results by Research Question

Because of the small sample, quantitative analysis is descriptive only.

Decoding Comparisons

Table 2 shows the mean scores for the math items, which were a proxy measure of whether the student comprehended the math statement sufficiently to engage with it mathematically, that is, whether the student successfully decoded the statement. Each of the 15 students answered eight math questions for each of the three speech styles, and were scored

Table 2 Mean Math Decoding Scores

ClearSpeak			SimpleSpeak			MathSpeak		
All	Blind	Low vision	All	Blind	Low vision	All	Blind	Low vision
0.89	0.91	0.88	0.70	0.78	0.64	0.56	0.67	0.46

Note. 0 = incorrect; 1 = correct; $N = 15$ students (7 blind, 8 with low vision), 8 questions per student per speech style. The scores are averaged across all items for all ($N = 15$), blind only ($n = 7$) and low vision only ($n = 8$).

Table 3 Students' Opinions of Favorability of Expressions (Based on Familiarity and Understandability) Using Each Speech Style

Feedback	ClearSpeak	SimpleSpeak	MathSpeak
Familiarity			
Very familiar	48%	24%	24%
Somewhat familiar	50%	50%	31%
Not very familiar	2%	9%	23%
Very unfamiliar	0%	16%	22%
Understandability			
Very easy to understand	52%	17%	16%
Somewhat easy to understand	33%	37%	38%
Somewhat hard to understand	13%	24%	23%
Very hard to understand	3%	22%	22%

Note. $N = 15$ students (7 blind, 8 with low vision), 7 questions per section.

Table 4 Students' Opinions of Confidence in Understanding of Expressions Using Each Speech Style

Feedback	ClearSpeak	SimpleSpeak	MathSpeak
Very sure understood	71%	42%	39%
Somewhat sure understood	24%	37%	33%
Not sure understood	5%	7%	11%
Definitely did not understand	0%	14%	17%

Note. $N = 15$ students (7 blind, 8 with low vision), 7 questions per section.

1 (correct) or 0 (incorrect) for each question. The figures shown represent the mean scores on all of the math items for all students, blind students, and students with low vision for each of the three styles. Note that while the blind students' mean scores were higher than those of students with low vision, the difference between those groups was smallest for math statements spoken according to the ClearSpeak style.

Favorability Comparisons

In addition to comparing correct responses to the math questions, we analyzed students' feedback responses indicating degree of perceived familiarity with the speech used, whether they found it easy to understand, and the degree of confidence that they had in fact understood the expression. Table 3 shows the students' responses for *favorability*, which combines familiarity and understandability:

- Favorability: Percent of students characterizing "the way the computer spoke the math statement" as *very familiar*, *somewhat familiar*, *not very familiar*, or *very unfamiliar* for the seven instances per student per speech style (one per math statement) of that question; and percent of students characterizing "the way the math statement was spoken by the computer" as *very easy*, *somewhat easy*, *somewhat hard*, or *very hard* to understand for the seven instances per student per speech style (one per math statement) of that question

Table 4 shows their responses regarding confidence that they understood the expressions. The percentages shown are based on the feedback questions given after each math question and represent the responses for all students for all of the expressions in each of the three styles:

- Confidence in understanding: Percent of students answering the question "How sure are you that you understood the math statement?" with *very sure*, *somewhat sure*, *not sure*, *definitely did not understand* for the seven instances per student per speech style of that question.

The data were further analyzed to compute scores for favorability (familiarity and ease of understanding) and confidence in understanding (sure they understood it).

Favorability scores for each expression were based on students' answers to two questions: (a) "Which of the following best describes the way the math statement was spoken by the computer?" (*very easy to understand*, *somewhat easy to*

Table 5 Average Favorability, Confidence in Understanding, Math Confidence, and Mean Math Decoding Scores Averaged Across All Items

Group	ClearSpeak	SimpleSpeak	MathSpeak
Favorability: Range 0 to 6			
All	4.75	3.25	2.96
Blind	4.92	3.96	3.65
Low vision	4.61	2.63	2.36
Confidence in understanding: Range −1 to 3			
All	2.64	1.87	1.64
Blind	2.53	2.04	1.85
Low vision	2.73	1.72	1.46
Math confidence: Range 0 to 5			
All	3.93	2.68	1.88
Blind	3.80	3.45	2.86
Low vision	4.03	2.00	0.95
Mean math decoding scores: Range 0 to 1			
All	0.89	0.70	0.56
Blind	0.91	0.78	0.67
Low vision	0.88	0.64	0.46

Note. All ($N = 15$); Blind ($n = 7$); Low vision ($n = 8$).[a]
[a]A version of this table appears in Frankel et al. (2013).

understand, *somewhat hard to understand*, or *very hard to understand*) and (b) "The way the computer spoke the math statement was (*very familiar*, *somewhat familiar*, *not very familiar*, *very unfamiliar*)." The answers were scored as follows: 3 points were assigned for *very easy/very familiar*, 2 for *somewhat easy/familiar*, 1 for *somewhat hard/not very familiar*, 0 for *very hard/very unfamiliar*. Because this score was based on the sum of two questions, the range of available scores was 0 to 6 per student per math statement.

Confidence in understanding scores for each expression were was based on the question: "How sure are you that you understood the math statement?" (*very sure*, *somewhat sure*, *not sure*, or *definitely did not understand*). Again *very sure* counted 3 points, *definitely did not understand* counted 0 points, and the two intermediate choices counted 2 points or 1 point, respectively. In addition, for the math statements about which more difficult math questions were asked, the students were also asked, "Once you understood what the computer was saying for the math statement, the math question itself was (*very easy*, *somewhat easy*, *somewhat difficult*, *very difficult*, *couldn't figure out what the computer was saying*)?" For cases where a student answered that they could not figure out what the computer was saying, a point was subtracted from the confidence in understanding score because we took this as a strong indication that the speech in an applicable case was not understood by the student. Because this score was based primarily on one question (with a potential adjustment from an additional question), the range of available scores was −1 to 3 per student per math statement.

Math confidence scores were also calculated. Although every attempt was made to minimize the amount of actual math manipulation or calculation required to answer the "math questions" (the purpose of which was to gauge whether the student understood the expression well enough to work with it—that is, to test decoding—not whether the student could do the actual computation), some of the more complex expressions required more actual math than others. For those questions (based on Math Statements 4–7), a math confidence score was generated from responses to the questions (a) "Once you understood what the computer was saying for the math statement, the math question itself was (*very easy*, *somewhat easy*, *somewhat difficult*, *very difficult*, *couldn't figure out what the computer was saying*)?" (see Questions 34, 44, 55, 57, and 66 in Appendix A) and (b) "Do you think you answered the math question correctly (*yes*/*no*)?" (see Questions 35, 45, 56, 58, and 67 in Appendix A). For the first question, the 0–3 point scale was used as previously described; for the second question "yes" was assigned 2 points and "no" 0 points. One math statement involved two math questions and two sets of two math confidence questions. So that it could be compared conveniently to the others, the scores generated from the answers to the two sets of math confidence questions were averaged. The range of available scores per student per math statement for math confidence was 0–5.

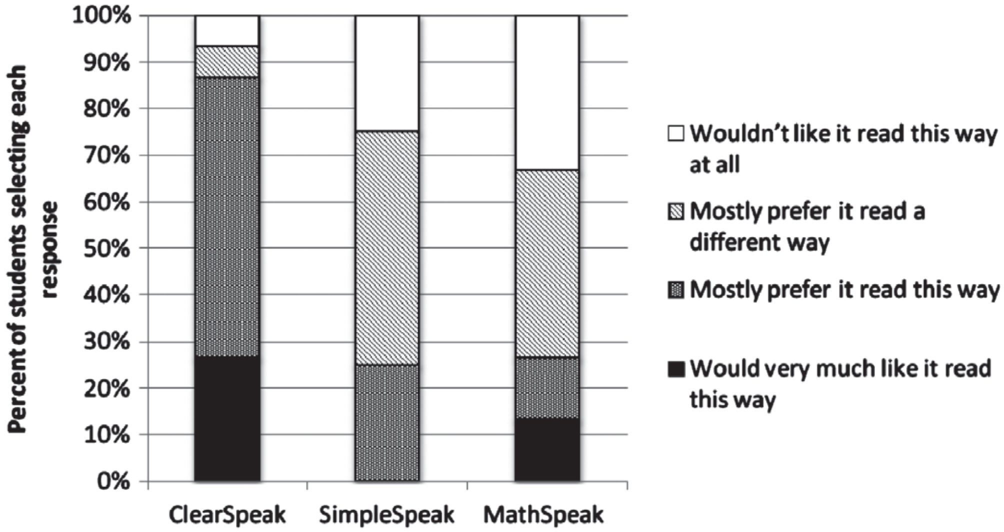

Figure 1 Section summary responses. Percentage of students providing each response ($N = 15$).

Mean scores for all students for all expressions for favorability, confidence in understanding, and math confidence are shown in Table 5, which also includes for convenience the mean math decoding scores from Table 2.

Table 5 shows that mean scores for each measure were notably higher for ClearSpeak than for SimpleSpeak or MathSpeak for all students taken together and for both groups when visual status (blind or low vision) was broken out. We also noted that differences between mean scores on all measures for students with blindness compared with mean scores for all measures for students with low vision were relatively small for ClearSpeak and much larger for SimpleSpeak and MathSpeak. We also computed quantitative results by expression and provide those results in Appendix C. Those data show that differences between speech styles are minimal for some expressions (see Tables C1 through C3) and substantial for others (see Tables C4 through C7). Students' answers to the free-response questions helped to explain the data (see the Qualitative Findings section).

Students' overall impressions of the speech styles were captured through the section summary and final summary questions. In the end-of-section questions, they were asked regarding each speech style, "Assuming that you are using a computer to speak math, how much would you like it to speak the way it spoke in this section?" Responses are summarized in Figure 1, which shows that, directly after the ClearSpeak section, almost all students would *mostly* or *very much* like math spoken according to the ClearSpeak style, while very few students felt that way about SimpleSpeak or MathSpeak at the end of their respective sections.

After working through the sections devoted to all three of the speech styles, students were asked to indicate which style overall they thought most helped them to understand the math statements and which style they thought helped least. These results are summarized in Figure 2, which shows that two thirds of the students thought that overall ClearSpeak was the most helpful and none thought it the least helpful of the three styles. Nearly all students thought MathSpeak was the least helpful. SimpleSpeak fell in between.

Qualitative Findings

Taken together, the results described previously support key aspects of our trajectory for development of ClearSpeak. As seen in Figures 1 and 2, students tended to indicate an overall preference for ClearSpeak over the other two styles. They also, as seen in Tables 3 through 5, tended to provide higher favorability and confidence scores and were more likely to answer the math questions correctly when the math was spoken using ClearSpeak. Because ours is a development project, an additional important goal of the first feedback study beyond that of validating our overall approach to ClearSpeak was to obtain specific feedback on speech patterns that were or were not helpful, in order to guide further development. To that end, we examined the responses to the free-response questions.

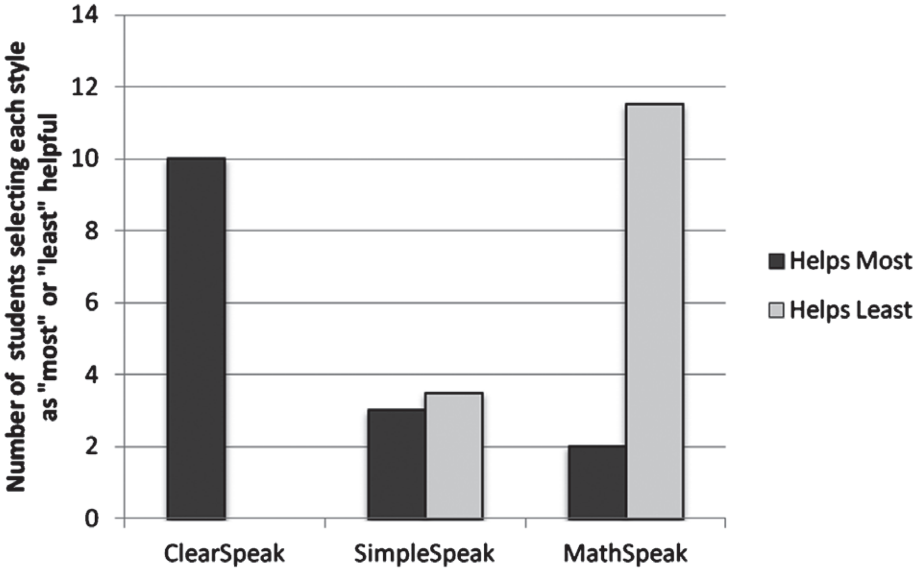

Figure 2 Styles considered most and least helpful ($N = 15$). *Note.* One student selected two of the styles as least helpful, which was counted as one-half point for each of the two styles so selected.

Providing support for our overall assumption that classroom-like speech would promote easier decoding and more positive subjective reactions, students frequently expressed a preference for speech they considered classroom-like when they encountered it in the spoken math in the study. For example:

> "I like how it sounds just like my morning math class."
>
> "[Liked] terms used in my math class"
>
> "I didn't know what nested one deep means. I've never heard that in class before" [in reference to MathSpeak].
>
> "All around just easier to understand with the change of terms and familiar language used in everyday math classes"
>
> "The numerator and denominator stuff sounds like elementary school. I don't like it. Just use open and close for fractions. I hear that in class."

Overall, students' responses showed that they held a variety of views regarding many of the details of ClearSpeak's implementation, including use of pauses, the speed at which the math was spoken, the use of parentheses versus implied "times" (e.g., should the expression $2(x + 3)$ or the expression $(2)(3)(4)$ be spoken with each opening and closing parenthesis, with "times" to indicate multiplication, or with some combination of both?), and some of the terminology employed. We had not explicitly formulated research questions around these issues and did not attempt to count or code these free-form responses, but we did find them worthy of note and consideration. Comments centered on issues of pauses, speed, terminology, approach to implied "times," and voice selection. Each of these topics is discussed briefly in this section.

Pauses

The speech rules for all three styles include some pauses, but pauses are more carefully structured in ClearSpeak; in addition, speech engines sometimes pause unpredictably. Some students felt that the pauses were helpful (though perhaps more as providing a "breather" than, at least consciously, as ways to convey mathematical meaning); others thought some of the pauses broke up the flow of the math. The extent to which the styles' pausing strategies may have more subtly affected students' perceptions or decoding performance cannot be determined, but it could have affected the students' overall perceptions of the styles. Overall, students had difficulty understanding how the (intentional) pauses were meant to work, which suggests that although ClearSpeak should be understandable with little or no direct instruction, some training or practice in its conventions is likely to be helpful. The second feedback study, which is described in Frankel & Brownstein (in press), further explores the effectiveness of two elements of prosody: pauses and speech rate changes.

Speed

Many students found the speed to be too fast, but a few found it too slow for their liking. Starting with the implementation of Word integration with Window-Eyes (used in the second feedback study) and carrying forward into the implementation with NVDA (NonVisual Desktop Access; used in subsequent studies), users can now take control of the speech rate. In addition, the implementation of interactive navigation within expressions (now complete and the focus of the third feedback study) gives users added control over their pace. Most students were writing expressions down (using braille or paper) as they heard them (see Question 2 and similar questions in Appendix A), and slower speed and/or more control over the pace make that easier for them to accomplish. There are also preliminary indications (from the third feedback study) that navigation support reduces the need to write expressions down by allowing users to explore expressions' mathematical structure.

Terminology

Students generally commented favorably on ClearSpeak's language of "raised to" and "powers" and unfavorably on terms like "superscript" and "baseline" (used in MathSpeak) or "super" (used in SimpleSpeak). Many stated that they did not know what the latter terms meant.

One such example was the expression

$$x^9 \cdot \frac{y^5}{y^2} \cdot \frac{z^{-7}}{z^{-3}},$$

which was spoken in MathSpeak as "x superscript 9 baseline dot start fraction nested one deep y superscript 5 baseline over nested one deep y squared end fraction nested one deep dot start fraction nested one deep z superscript minus 7 baseline over nested one deep z superscript minus 3 end fraction nested [pause] one deep."

One student commented, "I still don't understand what 'nested one deep' and 'superscript' mean. I think I may understand that superscript means 'to the power of something' and subscript is to the base of something. Like x^7, the 7 is the superscript and x7, the 7 is the subscript."

The corresponding SimpleSpeak speech was "x to the 9 dot fraction y to the fifth over y squared end fraction dot fraction z super negative 7 end super over z super negative 3 end super end fraction."

For the SimpleSpeak version, students frequently objected to the term "super."

The ClearSpeak version was "x raised to the power 9 [pause] times [pause] the fraction with numerator y raised to the power 5 and denominator y raised to the power 2 [pause] times [pause] the fraction with numerator z raised to the power negative 7 and denominator z raised to the power negative 3."

Student comments on the ClearSpeak versions were generally positive, particularly with regard to the use of "power." However, some thought "raised to the" added unnecessary words. The "raised" has since been removed from the speech rule for expressions with fairly simple use of exponents, such as the current example. See Brownstein et al. (2015a), p. 17. Students' expressed preferences for the ClearSpeak approach to exponents is consistent with the expression-breakouts seen in Appendix C: expressions where the most salient differences between speech styles were in how they handled more complicated exponents (see Table C7) showed a strong advantage for ClearSpeak over both of the other two styles.

As mentioned in the section, ClearSpeak and the Speech Style Requirements, ClearSpeak focuses on classroom-like speech and mathematical meaning (hence "power," "times," "f of") instead of on print symbols such as "superscript" (as one student called the latter, "a strange symbol being read") or on braille symbols. Overall, students commented favorably on the symbol-sparse terminology: "I liked that it didn't give me a lot of strange signs, just the problem like you'd hear it read by a person." That MathSpeak can use difficult terminology was implicitly recognized by Bouck, Meyer, Joshi, and Schleppenbach (2013) in their explorations of MathSpeak as a means of accessing algebra. Part of their research methodology involved explicit instruction with the MathSpeak language and a review of algebraic terminology such as *coefficient* and *term*. Our first feedback study, by contrast, provided no explicit instruction in the language or special terminology of each speech style (since ClearSpeak avoids the use of terms expected to be unfamiliar), but it did include at the beginning of each section examples of the same expressions rendered in the speech style to be used in the section.

Parentheses and Implied "Times"

ClearSpeak speaks parentheses as "open/close paren" or "open/close parenthesis," only where needed for mathematical clarity, using "times" in place of parentheses that indicate only multiplication, as in (3)(2). SimpleSpeak speaks all parentheses ("open/close"), as does MathSpeak ("left parenthesis/right parenthesis"). Students' preferences among these were mixed. For example, some thought SimpleSpeak's "open/close" was too terse, and students wondered what was being opened or closed (were they parentheses, brackets, braces, etc.?) Of those who commented, more students commented favorably on ClearSpeak's "open parenthesis/close parenthesis" as compared to MathSpeak's "left parenthesis/right parenthesis." Students were mixed on whether "times," the parentheses, or both should be spoken in cases where parentheses denote multiplication.

Voice

Microsoft Anna (see the section, Development of Audio) was selected only because it was readily available at the time of this study, not for suitability for speaking math. We edited out the worst pronunciation problems; however, students frequently mentioned the voice as something they would like to have changed (although some indicated they liked it), and some mentioned a preference for the "standard JAWS voice" (Eloquence Reed). The second feedback study used the Eloquence speech engine implemented in Window-Eyes. With the enhanced screen reader integration now available, students can use any speech engine supported by supported screen readers (currently NVDA and Window-Eyes) and any voices available on their computers that are supported by the speech engines recognized by the screen reader.

Discussion

As we described in the Results section, it is clear from this first study that the answers to our primary research questions—how does ClearSpeak compare to MathSpeak and SimpleSpeak with regard to both students' ability to decode the math statements and students' subjective reactions to the speech style—were favorable to ClearSpeak. Soiffer, who implemented the ClearSpeak style in MathPlayer, is also responsible for maintaining the other styles implemented in MathPlayer. As a result of the feedback received on SimpleSpeak and MathSpeak and following the first study, Soiffer corrected the MathSpeak "nested one deep" speech pattern and implemented several enhancements to SimpleSpeak (e.g., replacing "super" with "to the power") based on some of the ClearSpeak rules developed in this phase of the project. The ClearSpeak rules tested in this study have now been finalized, implemented in MathPlayer, and documented in Brownstein et al. (2015a).

Limitations

As previously mentioned in the Development of Audio section, an undesirable speech pattern ("nested one deep") later determined to be unintended was part of the MathSpeak renditions of three of the seven math expressions. Four math questions, plus their associated feedback questions, were based on these expressions (Questions 26, 36, 46, and 47). This speech pattern (which was adjusted in MathPlayer's MathSpeak implementation after the study concluded) likely contributed to students' difficulty with MathSpeak: Several students mentioned that particular phrasing as being confusing. The expressions in which this speech pattern occurred showed the greatest disadvantage for the MathSpeak style (see Tables C4, C5, and C6). However, we do not think the "nested one deep" speech pattern accounts fully for MathSpeak's disadvantage when compared to ClearSpeak, because the disadvantage was present, though to a lesser extent, in the remainder of the expressions (see Tables C1, C2, C3, and C7).

Subsequent Work

As previously noted, screen reader and Word integration has been accomplished and used in a second study that focused on certain prosodic elements, including pauses and change of speech rate (Frankel & Brownstein, in press). The interactive navigation feature has also been developed, integrated with the Window-Eyes and NVDA screen readers and Word, and evaluated in a third feedback study. A study of the authoring tools for teachers and other content creators, as well as a final pilot that incorporates assessments of both authoring and spoken math tools, was also conducted. Frankel et al. (in press) reported on the final pilot with teachers for the authoring tools and the final pilot with students for the spoken math tools.

Acknowledgments

We are grateful to Susan Osterhaus and Maylene Bird of the Texas School for the Blind and Visually Impaired for their assistance with the development of ClearSpeak and of the research instruments and with administering the instruments to some of the participating students. The research reported here was supported by the Institute of Education Sciences, US Department of Education, through Grant R324A110355 to the Educational Testing Service. The opinions expressed are those of the authors and do not represent views of the Institute of Education Sciences or the US Department of Education.

Notes

1 In this document, we use the term *math expression* to refer to any combination of mathematical symbols.

2 An open interval is an interval that does not contain its endpoints, depicted on a number line with open circles at the endpoints, or as an ordered pair of numbers (Wolfram MathWorld, 2015).

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Appendix A. Sample Instrument (Annotated)

The instrument that follows is the base instrument. As noted in the main body of this report, there were two additional parallel sections of the instrument, using items cloned from the instrument shown here. It is also important to recall that as delivered to students, the visual math expressions shown here for convenient reference were replaced by instructions to play a corresponding audio file. Students or the study administrators would play the specified audio files on the MP3 players that we provided or on their computers using a software media player and they were permitted to replay the audio clips as desired. This was done because we wanted all students, regardless of visual status, on a level playing field that focused on the audio experience. The audio files are available for download. See Appendix E for links.

We have also added to each math and feedback question a brief explanation (boxed for ease of identification) of the testing purpose behind the question and in some cases the intent behind the ClearSpeak audio implementation. For the feedback questions, purposes are provided only for the first instance of a feedback question; subsequent matching feedback questions applied to different expressions have the same essential purpose. Those explanations were not included in the instrument given to students or study administrators.

Before You Start:

This section starts with three examples of math statements. In each case, you will first hear the example, and then a short description of the math in the example. The purpose of these examples is to give you a chance to get used to the speech style used in each section. Note that each section uses the same three math statements, but each section speaks them in the style used in that section, so the same statements will sound somewhat different in each style.

Example 1:

$$\frac{3}{x+2} - 5$$

Example 1 is a fraction minus an integer. The fraction has the number 3 in the numerator and the expression x plus 2 in the denominator. The integer is 5.

Example 2:

$y\,(x-2)$

Example 2 is the variable y multiplied by the expression x minus 2. There are parentheses around the expression x minus 2.

Example 3:

$5^7 + 4^{-3}$

Example 3 is the sum of two numbers. Each number consists of a base and an exponent. The first number has base 5 and exponent 7. The second number has base 4 and exponent negative three.

You may replay the examples and explanations as much as you wish. When you are ready, continue on to begin this section.

Questions 1–8 Are About This Math Statement:

$5\,(3x \quad - 12) + 2x\,(4x \quad - 6)$

Math Question

1. In the math statement, the number 5 is multiplied by which of the following?
   a. $(3x - 12) + 2x$
   b. $3x - 12$
   c. $(3x - 12) + 2x\,(4x - 6)$
   d. $3x$

> Purpose: An easy expression to help students get comfortable working with the instrument. It also tests comprehension of parentheses used for multiplication and different ways of speaking the parentheses. The incorrect answer choices reflect what someone listening to the expression might think is multiplied by the initial number (in this case, 5) if the speech failed to make the parenthetical groupings clear.

Feedback Questions

2. What, if anything, did you do to help yourself understand the math statement and answer the math question? (Mark all that apply.)
   a. Didn’t need to do anything
   b. Wrote it down using braille
   c. Wrote it down some other way
   d. Played it back again. If so, did you play it back
      1) Just a few times
      2) many times

> Purpose: obtain information about the student’s process and whether students augmented the audio experience with written materials.

3. How much experience do you have with this type of math statement?
   a. none
   b. a little
   c. a moderate amount
   d. a lot

Purpose: Determine whether the particular type of math in the expression was familiar or unfamiliar to the student. If a student was unfamiliar with (in this case) use of parentheses, that could be a confounding factor in their ability to understand what the expression is.

4. Which of the following best describes the way the math statement was spoken by the computer:
   a. Very easy to understand
   b. Somewhat easy to understand
   c. Somewhat hard to understand
   d. Very hard to understand

Purpose: Assess the student's opinion regarding how understandable the speech is.

5. How sure are you that you understood the math statement?
   a. Very sure
   b. Somewhat sure
   c. Not sure
   d. Definitely did not understand

Purpose: Assess the student's opinion regarding how understandable the speech is, and the extent to which students were confident of their answers to the math question versus just guessing.

6. The way the computer spoke the math statement was
   1. Very familiar
   2. Somewhat familiar
   3. Not very familiar
   4. Very unfamiliar

Purpose: Assess the student's opinion regarding how familiar the speech is.

7. What did you particularly like about the way the computer read the math statement? Type your response in the space below.

8. What would you change about the way the computer read the math statement, in order to make it easier to understand? Type your response in the space below.

Purpose for questions 7 and 8: Gather specific information about what works/could be changed about the speech for that expression.

Questions 9–17 Are About This Math Statement:

$(2)\,(4)\,(5 + 1)\,(3)$

Math *Questions*

9. Compute the value of the math statement. Type your answer in the space below.

> Purpose: Also an easy expression, intended to compare speaking the parentheses (vs. speaking “times”—that is, attending to the expression’s meaning rather than to its explicit representation). ClearSpeak speaks only the parentheses around “5 + 1,” and instead of speaking the others, signals the multiplication by speaking “times.” The other two styles speak all of the parentheses (MathSpeak as “left/right parenthesis” and SimpleSpeak as “open/close”). To determine whether the students comprehended the expression, they were asked to compute its value. The numbers were selected to make the computation portion of the item as simple as possible so that comprehension could be the focus.

10. Explain the steps you took in computing the value of the math statement. Type your explanation in the space below.

Feedback Questions

11. What, if anything, did you do to help yourself understand the math statement and answer the math questions? (Mark all that apply.)
    a. Didn’t need to do anything
    b. Wrote it down using braille
    c. Wrote it down some other way
    d. Played it back again. If so, did you play it back
        1) Just a few times
        2) many times
12. How much experience do you have with this type of math statement?
    a. none
    b. a little
    c. a moderate amount
    d. a lot
13. Which of the following best describes the way the math statement was spoken by the computer:
    a. Very easy to understand
    b. Somewhat easy to understand
    c. Somewhat hard to understand
    d. Very hard to understand
14. How sure are you that you understood the math statement?
    a. Very sure
    b. Somewhat sure
    c. Not sure
    d. Definitely did not understand

15. The way the computer spoke the math statement was

    a. Very familiar
    b. Somewhat familiar
    c. Not very familiar
    d. Very unfamiliar

16. What did you particularly like about the way the computer read the math statement? Type your response in the space below.

17. What would you change about the way the computer read the math statement, in order to make it easier to understand? Type your response in the space below.

Questions 18–25 Are About This Math Statement:

$16x^9 + 12x^{13} + 5x^7 + 1$

Math Question

18. What is the biggest exponent in the math statement? Type your answer in the text box below.

> Purpose: Tests differences in speech for positive exponents. While ClearSpeak again interprets the meaning of the expression by speaking of "powers," the other styles focus on the literal symbols, referencing "superscript" or "super" and "baseline" or "end super." Students were asked only to identify the "biggest exponent," not to perform any computation or problem solving.

Feedback Questions

19. What, if anything, did you do to help yourself understand the math statement and answer the math question? (Mark all that apply.)

    a. Didn't need to do anything
    b. Wrote it down using braille
    c. Wrote it down some other way
    d. Played it back again. If so, did you play it back

        1) Just a few times
        2) many times

20. How much experience do you have with this type of math statement?

    a. none
    b. a little
    c. a moderate amount
    d. a lot

21. Which of the following best describes the way the math statement was spoken by the computer:

    a. Very easy to understand
    b. Somewhat easy to understand

c. Somewhat hard to understand
d. Very hard to understand

22. How sure are you that you understood the math statement?

    a. Very sure
    b. Somewhat sure
    c. Not sure
    d. Definitely did not understand

23. The way the computer spoke the math statement was

    a. Very familiar
    b. Somewhat familiar
    c. Not very familiar
    d. Very unfamiliar

24. What did you particularly like about the way the computer read the math statement? Type your response in the space below.

25. What would you change about the way the computer read the math statement, in order to make it easier to understand? Type your response in the space below.

Questions 26–35 Are About This Math Statement:

$$\frac{12+3}{15+2}+3+\frac{7}{92}+6$$

Math Question

26. Which of the following best describes the math statement?

    a. Integer plus fraction plus integer plus integer plus fraction plus integer
    b. Fraction plus integer plus fraction plus integer
    c. Fraction plus integer plus fraction
    d. Fraction plus fraction plus integer
    e. Integer plus fraction plus fraction plus integer

Purpose: Tests the ability to distinguish the components in expressions involving a combination of integers and fractions. (Students are asked to characterize the expression and given options like “fraction plus integer plus fraction plus integer.”) The ClearSpeak version does not say “end fraction,” but rather uses long pauses at the appropriate places, and the phrase “the integer” before each integer to disambiguate the expressions using language that was natural in the context (the use of this should decrease memory load).

Feedback Questions

27. What, if anything, did you do to help yourself understand the math statement and answer the math question? (Mark all that apply.)

    a. Didn’t need to do anything
    b. Wrote it down using braille

c. Wrote it down some other way
d. Played it back again. If so, did you play it back
   1) Just a few times
   2) many times

28. How much experience do you have with this type of math statement?
    a. none
    b. a little
    c. a moderate amount
    d. a lot
29. Which of the following best describes the way the math statement was spoken by the computer:
    a. Very easy to understand
    b. Somewhat easy to understand
    c. Somewhat hard to understand
    d. Very hard to understand
30. How sure are you that you understood the math statement?
    a. Very sure
    b. Somewhat sure
    c. Not sure
    d. Definitely did not understand
31. The way the computer spoke the math statement was
    a. Very familiar
    b. Somewhat familiar
    c. Not very familiar
    d. Very unfamiliar
32. What did you particularly like about the way the computer read the math statement? Type your response in the space below.
33. What would you change about the way the computer read the math statement, in order to make it easier to understand? Type your response in the space below.
34. Once you understood what the computer was saying for the math statement, the math question itself was
    a. very easy
    b. easy
    c. hard
    d. very hard
    e. couldn't figure out what the computer was saying
35. Do you think you answered the math question correctly?
    a. yes
    b. no

    Why or why not? Type your response in the space below.

Questions 36–45 Are About This Math Statement:

$$\frac{x-2}{x^2}+\frac{3}{8x}+\frac{5}{y^3-1}$$

Math Question

36. Which of the following is the denominator of a fraction in the math statement?

    a. $x^2 + 3$

    b. x^2

    c. $8x + 5$

    d. y^3

> Purpose: Tests whether the speech enables students to detect where each fraction ends. Both MathSpeak and SimpleSpeak use "end fraction," while ClearSpeak uses pauses between the fractions, as well as explicitly identifying the numerator and denominator (fraction with numerator … and denominator …).

Feedback Questions

37. What, if anything, did you do to help yourself understand the math statement and answer the math question? (Mark all that apply.)
    a. Didn't need to do anything
    b. Wrote it down using braille
    c. Wrote it down some other way
    d. Played it back again. If so, did you play it back
        1) Just a few times
        2) many times
38. How much experience do you have with this type of math statement?
    a. none
    b. a little
    c. a moderate amount
    d. a lot
39. Which of the following best describes the way the math statement was spoken by the computer:
    a. Very easy to understand
    b. Somewhat easy to understand
    c. Somewhat hard to understand
    d. Very hard to understand
40. How sure are you that you understood the math statement?
    a. Very sure
    b. Somewhat sure
    c. Not sure
    d. Definitely did not understand
41. The way the computer spoke the math statement was
    a. Very familiar
    b. Somewhat familiar

c. Not very familiar
d. Very unfamiliar

42. What did you particularly like about the way the computer read the math statement? Type your response in the space below.

43. What would you change about the way the computer read the math statement, in order to make it easier to understand? Type your response in the space below.

44. Once you understood what the computer was saying for the math statement, the math question itself was

    a. very easy
    b. easy
    c. hard
    d. very hard
    e. couldn't figure out what the computer was saying

Purpose: To attempt to distinguish between math-related difficulties and decoding-related difficulties.

45. Do you think you answered the math question correctly?

    a. yes
    b. no

    Why or why not? Type your response in the space below.

Purpose: we were interested in how students' perceptions of success might be related to their actual success.

Questions 46–56 Are About This Math Statement:

$$\frac{x^9 y^5 z^{-7}}{y^2 z^{-3}}$$

Math Questions

46. Which of the following is the math statement, rewritten without a denominator? (Remember that $\frac{r^s}{r^t} = r^{s-t}$.)

    a. $x^9 y^3 z^{-4}$

    b. $x^7 y^3 z^{-4}$

    c. $x^9 y^7 z^{-4}$

    d. $x^9 y^3 z^{-10}$

47. The math statement is equivalent to which of the following?

a. $x^9 \cdot \frac{y^5}{y^2} \cdot \frac{z^{-7}}{z^{-3}}$

b. $\frac{1}{x^9} \cdot \frac{y^2}{y^5} \cdot \frac{z^{-3}}{z^{-7}}$

c. $x^9 \cdot \frac{y^{5z-7}}{y^{2z-3}}$

d. $x^{9y} \cdot \frac{5z^{-7}}{y^2 z^{-3}}$

> Purpose: Tests negative exponents. ClearSpeak uses more natural "raised to the power" language, rather than the "sup … end sup" of SimpleSpeak and "sup … base" of MathSpeak. In ClearSpeak the language used is the same for all the exponents. This should make comprehension easier. ClearSpeak also speaks the implied times. This expression did require some actual calculation in order to assess comprehension, so students were asked both to simplify the expression by selecting the expression that rewrites the original without a denominator, and to select an equivalent expression.

Feedback Questions

48. What, if anything, did you do to help yourself understand the math statement and answer the math questions? (Mark all that apply.)
    a. Didn't need to do anything
    b. Wrote it down using braille
    c. Wrote it down some other way
    d. Played it back again. If so, did you play it back
        1) Just a few times
        2) many times
49. How much experience do you have with this type of math statement?
    a. none
    b. a little
    c. a moderate amount
    d. a lot
50. Which of the following best describes the way the math statement was spoken by the computer:
    a. Very easy to understand
    b. Somewhat easy to understand
    c. Somewhat hard to understand
    d. Very hard to understand
51. How sure are you that you understood the math statement?
    a. Very sure
    b. Somewhat sure

c. Not sure
d. Definitely did not understand

52. The way the computer spoke the math statement was

    a. Very familiar
    b. Somewhat familiar
    c. Not very familiar
    d. Very unfamiliar

53. What did you particularly like about the way the computer read the math statement? Type your response in the space below.

54. What would you change about the way the computer read the math statement, in order to make it easier to understand? Type your response in the space below.

55. Once you understood what the computer was saying for the math statements, math question 46 (rewriting the statement without the denominator) was

    a. very easy
    b. easy
    c. hard
    d. very hard
    e. couldn't figure out what the computer was saying

56. Do you think you answered the math question 46 correctly?

    a. yes
    b. no

    Why or why not? Type your response in the space below.

57. Once you understood what the computer was saying for the math statements, math question 47 (determining which of the answer choices was equivalent to the statement) was

    a. very easy
    b. easy
    c. hard
    d. very hard
    e. couldn't figure out what the computer was saying

58. Do you think you answered the math question 47 correctly?

    a. yes
    b. no

    Why or why not? Type your response in the space below.

Questions 59–68 Are About This Math Statement:

$2^{y+1} + 4$

Math Question

59. What is the exponent in the math statement?

   a. $y + 1 + 4$

   b. $y + 1$

   c. y

   d. $(y + 1) \cdot 4$

> Purpose: Tests complicated exponents and boundaries. Speech for complicated exponents in ClearSpeak puts the exponents between “raised to the” and “power,” rather than the “sup,” etc. of the other systems, which should disambiguate using familiar language that integrates well with the context and should require less memory load.

Feedback Questions

60. What, if anything, did you do to help yourself understand the math statement and answer the math question? (Mark all that apply.)
    a. Didn’t need to do anything
    b. Wrote it down using braille
    c. Wrote it down some other way
    d. Played it back again. If so, did you play it back
        1) Just a few times
        2) many times
61. How much experience do you have with this type of math statement?
    a. none
    b. a little
    c. a moderate amount
    d. a lot
62. Which of the following best describes the way the math statement was spoken by the computer:
    a. Very easy to understand
    b. Somewhat easy to understand
    c. Somewhat hard to understand
    d. Very hard to understand
63. How sure are you that you understood the math statement?
    a. Very sure
    b. Somewhat sure
    c. Not sure
    d. Definitely did not understand

64. The way the computer spoke the math statement was
    a. Very familiar
    b. Somewhat familiar
    c. Not very familiar
    d. Very unfamiliar
65. What did you particularly like about the way the computer read the math statement? Type your response in the space below.
66. Once you understood what the computer was saying for the math statement, the math question itself was
    a. very easy
    b. easy
    c. hard
    d. very hard
    e. couldn't figure out what the computer was saying
67. Do you think you answered the math question correctly?
    a. yes
    b. no

    Why or why not? Type your response in the space below.
68. What would you change about the way the computer read the math statement, in order to make it easier to understand? Type your response in the space below.

Section Summary Question

Assuming that you are using a computer to speak math, how much would you like it to speak the way it spoke in this section?

a. I would very much like the computer to read it this way
b. I would mostly prefer the computer to read it this way
c. I would mostly prefer the computer to read it a different way
d. I wouldn't want the computer to read it this way at all

Purpose: Assess student's general favorability toward the speech style used in a given section.

End of study questions, asked at the conclusion of all three sections:

1. After having worked with three different ways of speaking math, overall, which one do you think most helps you understand the math statements?
    a. The first one
    b. The second one
    c. The third one
2. Overall, which of the three styles do you think least helps you understand the math statements?
    a. The first one

b. The second one
c. The third one

3. Do you have any other comments about the speech styles or suggestions on how to make computers speak math better?

Purpose: Assess student's preferred and least preferred speech style; gather additional suggestions for further development.

Appendix B. Examples of Clones

This appendix provides the following:

- Three clone versions of two of the expressions used in the instrument
- Text indicating how, for the Clone Group 1 version of each of the two expressions, the speech varied for the three different speech styles. Each style controls both wording and the length and placement of pauses. Pause length could not be measured precisely (it is adjusted dynamically based on the speech rate), and so instead the lengths are approximated for illustrative purposes as (VS) (S), (M), and (L) for very short, short, medium, and long pauses, respectively.

Clone Group 1 Version of Math Expression 1

$16x^9 + 12x^{13} + 5x^7 + 1$

Clone Group 1 Version of Math Expression 1, as Spoken in the Three Speech Styles:

ClearSpeak

16 (M) x to the 9th power (L) plus 12 (M) x to the 13th power (L) plus 5 (M) x to the 7th power (L) plus 1

MathSpeak

16 (VS) x superscript (S) 9 baseline plus 12 (S) x superscript (M) 13 baseline plus 5 (S) x superscript (M) 7 baseline (VS) plus 1

SimpleSpeak

16 (S) x to the 9th (S) plus 12 (VS) x to the 13th (M) plus 5 (VS) x to the 7th (VS) plus 1

Clone Group 2 Version of Math Expression 1

$19x^6 + 14x^{13} + 7 + 35x^{18}$

Clone Group 3 Version of Math Expression 1

$16x^9 + 12x^{15} + 5x^7 + 1$

Math Question (Same for All Clone Groups)

What is the biggest exponent in the math statement?

Clone Group 1 Version of Math Expression 2

$$5\,(3x - 12) + 2x\,(4x - 6)$$

Clone Group 1 Version of Math Expression 2, as Spoken in the Three Speech Styles:

ClearSpeak:

5 times (L) open parenthesis (M) 3 x (S) minus 12 (M) close parenthesis (L) plus 2x times (L) open parenthesis (M) 4 x (S) minus 6 (M) close parenthesis.

SimpleSpeak:

5 (M) open (M) 3x minus 12 (M) close (M) plus 2 x (M) open (M) 4 x minus 6 (M) close

MathSpeak:

Five (M) left parenthesis (M) 3x minus 12 (S) right parenthesis (M) plus 2 x (S) left parenthesis (M) 4 x minus 6 (S) right parenthesis

Clone Group 2 Version of Math Expression 2

$$4\left(2y - 12\right) + 3y\,\left(5y - 8\right)$$

Clone Group 3 Version of Math Expression 1

$$6\,(3x - 9) + 4x\,(2x - 15)$$

Appendix C. Results by Expression

The tables represent the responses of 15 students to seven math expressions in each of the three speech styles. An explanation of the most salient differences in wording for the styles is given after each table. We did not attempt to transcribe the different pause durations used in each style because although pauses were manually and systematically defined for ClearSpeak, the pause lengths used in the other two styles are determined by assorted algorithms in the computer code and so cannot easily be documented. See Appendix A for the questions accompanying each expression. See also the section on Study Manipulation for information about how clones, section order, and speech style were systematically varied. The audio files are available for download. See Appendix E for links.

Table C1 Means and Standard Deviations (SD) for the Expression for Questions 1 – 8
Clone 1: $5\,(3x-12)+2x\,(4x-6)$
Clone 2: $4\,(2y-12)+3y\,(5y-8)$
Clone 3: $6\,(3x-9)+4x\,(2x-15)$

Mean or SD	ClearSpeak	SimpleSpeak	MathSpeak
Favorability: Range 0 to 6			
Mean	5.13	3.47	3.73
SD	0.99	1.96	1.79
Confidence in understanding: Range −1 to 3			
Mean	2.67	2.53	2.53
SD	0.49	0.74	0.52
Math confidence: Range 0 to 5[a]			
Mean	n/a	n/a	n/a
SD	n/a	n/a	n/a
Correct math responses: Range 0 to 1			
Mean	0.93	0.87	0.87
SD	0.26	0.35	0.35

Note. $N = 15$.
[a]Math confidence computed only for the more difficult math expressions.

In ClearSpeak, the implied "times" was spoken and the parentheses were spoken as "open parenthesis" and "close parenthesis." In SimpleSpeak, the implied "times" was not spoken, and parentheses were spoken as "open" and "close." In MathSpeak, the implied "times" was not spoken, and parentheses were spoken as "left parenthesis" and "right parenthesis."

Table C2 Means and Standard Deviations (SD) for the Expression for Questions 9 – 17
Clone 1: $(2)\,(4)\,(5+1)\,(3)$
Clone 2: $(5)\,(3+1)\,(9)\,(2)$
Clone 3: $(4)\,(3)\,(2+3)\,(5)$

Mean or SD	ClearSpeak	SimpleSpeak	MathSpeak
Favorability: Range 0 to 6			
Mean	5.2	3.87	4.07
SD	0.94	1.68	1.91
Confidence in understanding: Range −1 to 3			
Mean	2.73	2.47	2.73
SD	0.80	0.52	0.46
Math confidence: Range 0 to 5[a]			
Mean	n/a	n/a	n/a
SD	n/a	n/a	n/a
Correct math responses: Range 0 to 1			
Mean	0.93	1.00	0.73
SD	0.26	0.00	0.46

Note. $N = 15$.
[a]Math confidence computed only for the more difficult math expressions.

In ClearSpeak, the implied "times" was spoken; speech was suppressed for the parentheses not required for grouping, and the parentheses required for grouping were spoken as "open parenthesis" and "close parenthesis." In SimpleSpeak, the implied "times" was not spoken, and all parentheses were spoken as "open" and "close." In MathSpeak, the implied "times" was not spoken, and all parentheses were spoken as "left parenthesis" and "right parenthesis."

Table C3 Means and Standard (SD) for the Expression for Questions 18–25

Clone 1: $16\,x^9 + 12\,x^{13} + 5\,x^7 + 1$

Clone 2: $19x^6 + 14x^{13} + 7 + 35x^{18}$

Clone 3: $16x^9 + 12x^{15} + 5x^7 + 1$

Mean or SD	ClearSpeak	SimpleSpeak	MathSpeak
Favorability: Range 0 to 6			
Mean	5.00	4.13	3.33
SD	1.00	1.68	1.45
Confidence in understanding: Range −1 to 3			
Mean	2.73	2.47	2.20
SD	0.59	0.64	0.94
Math confidence: Range 0 to 5[a]			
Mean	n/a	n/a	n/a
SD	n/a	n/a	n/a
Correct math responses: Range 0 to 1			
Mean	1.0	1.0	0.87
SD	0.0	0.0	0.35

Note. $N = 15$.

[a]Math confidence computed only for the more difficult math expressions.

In ClearSpeak, exponents were spoken as “to the [n]th power.” In SimpleSpeak, they were spoken as “to the [n].” In MathSpeak, they were spoken as “superscript [n] baseline.”

Table C4 Means and Standard Deviations (SD) for the Expression for Questions 26–35

Clone 1: $\frac{12+3}{15+2} + 3 + \frac{7}{92} + 6$

Clone 2: $3 + \frac{7}{12} + \frac{3+15}{6+12}$

Clone 3: $6 + 10 + \frac{9+2}{18} + \frac{2+14}{6+5}$

Mean or SD	ClearSpeak	SimpleSpeak	MathSpeak
Favorability: Range 0 to 6			
Mean	4.60	3.40	1.73
SD	1.40	1.45	1.67
Confidence in understanding: Range −1 to 3			
Mean	2.60	2.07	0.40
SD	0.63	1.22	1.30
Math confidence: Range 0 to 5			
Mean	4.40	3.20	1.87
SD	0.99	2.24	2.13
Correct math responses: Range 0 to 1			
Mean	0.93	0.73	0.47
SD	0.26	0.46	0.52

Note. $N = 15$.

In ClearSpeak, fractions and integers were spoken as “the fraction with numerator [numerator] and denominator [denominator] plus the integer [integer].” In SimpleSpeak, the fractions with sums in the numerator or denominator were spoken as “fraction [numerator] over [denominator] end fraction”; the other fractions were spoken with ordinals in the denominator. Integers were spoken as “[integer].” In MathSpeak, they were spoken as “start fraction nested one deep [numerator] over nested one deep [denominator] end fraction nested one deep”; the other fractions were spoken with ordinals in the denominator. Integers were spoken as “[integer].”

Table C5 Means and Standard Deviations (SD) for the Expression for Questions 36–45

Clone 1: $\frac{x-2}{x^2} + \frac{3}{8x} + \frac{5}{y^3-1}$

Clone 2: $\frac{y-1}{y^3} + \frac{4}{9x} + \frac{5}{x^2-3}$

Clone 3: $\frac{x-7}{x^3} + \frac{9}{12y} + \frac{4}{y^2+6}$

Mean or SD	ClearSpeak	SimpleSpeak	MathSpeak
Favorability: Range 0 to 6			
Mean	4.53	3.73	1.93
SD	1.13	1.67	2.02
Confidence in understanding: Range −1 to 3			
Mean	2.67	1.73	0.73
SD	0.62	1.33	1.75
Math confidence: Range 0 to 5			
Mean	4.33	3.67	1.80
SD	1.11	1.95	2.31
Correct math responses: Range 0 to 1			
Mean	1.00	0.80	0.40
SD	0.00	0.41	0.51

Note. $N = 15$.

The fractions were spoken in each style as they were in the expressions for Questions 26–25. In all speech styles, the exponents were spoken as "squared" or "cubed."

Table C6 Means and Standard Deviations (SD) for the Expression for Questions 46–56

Clone 1: $\frac{x^9\, y^5\, z^{-7}}{y^2\, z^{-3}}$

Clone 2: $\frac{x^7\, y^{-5}\, z^9}{y^{-2}\, z^3}$

Clone 3: $\frac{x^8\, y^6\, z^{-9}}{y^2\, z^{-4}}$

Mean or SD	ClearSpeak	SimpleSpeak	MathSpeak
Favorability: Range 0 to 6			
Mean	4.27	1.80	2.00
SD	1.62	1.90	1.85
Confidence in understanding: Range −1 to 3			
Mean	2.53	0.43	0.57
SD	0.64	1.45	1.25
Math confidence: Range 0 to 5			
Mean	2.43	1.17	1.06
SD	0.82	1.41	1.15
Correct math responses: Range 0 to 1[a]			
Mean	0.43	0.20	0.17
SD	0.42	0.37	0.31

Note. $N = 15$.
[a] Average of two math questions.

There were two math questions for this expression. In ClearSpeak, the fractions were spoken as "fraction with numerator [numerator] and denominator [denominator]." Within the numerator and denominator, the exponents were spoken as "[variable] raised to the power [exponent]" (the negative exponents added the term "negative"). In SimpleSpeak, the fractions were spoken as "fraction [numerator] over [denominator] end fraction." Within the numerator and denominator, the positive exponents were spoken as "[variable] to the [ordinal exponent]" and negative exponents were spoken as "[variable] super negative [exponent] end super." In MathSpeak, the fractions were spoken as "start fraction nested one deep, [numerator] over nested one deep [denominator] end fraction nested one deep," and the exponents were spoken as "superscript [exponent] baseline."

Table C7 Means and Standard Deviations (SD) for the Expression for Questions 59–68

Clone 1: $2^{y+1}+4$

Clone 2: $2^{z+3}+5$

Clone 3: $2^{w+4}+3$

Mean or SD	ClearSpeak	SimpleSpeak	MathSpeak
Favorability: Range 0 to 6			
Mean	4.53	2.33	3.93
SD	1.41	2.06	1.62
Confidence in understanding: Range −1 to 3			
Mean	2.53	1.40	2.33
SD	0.64	1.45	1.11
Math confidence: Range 0 to 5			
Mean	4.53	2.67	2.73
SD	0.64	2.16	2.12
Correct math responses: Range 0 to 1			
Mean	1.00	0.33	0.40
SD	0.00	0.49	0.51

Note. $N = 15$.

In ClearSpeak, the exponent was spoken as “raised to the [exponent] power.” In SimpleSpeak, it was spoken as “super [exponent] end super.” In MathSpeak, it was spoken as “superscript [exponent] baseline.”

Appendix D. Excerpt From Master Expressions List

Table D1 Fractions

Preference	Identifier	Example	Speech
Auto	Frac001	$\frac{1}{2}$	One half
Auto	Frac002	$\frac{12}{32}$	12 over 32
Auto	Frac002b	$\frac{2x}{3y}$	2x over 3y
Auto	Frac002d	$\frac{\frac{1}{2}}{\frac{1}{3}}$	One half over one third
Auto	Frac004	$\frac{x+y}{2}$	The fraction with numerator x plus y, and denominator 2
Auto	Frac006	$\frac{x+y}{x-y}+\frac{2}{3}$	The fraction with numerator x plus y, and denominator x minus y, plus two thirds
Auto	Frac007	$\frac{\text{miles}}{\text{gallon}}$	Miles over gallon
Over	Frac009	$\frac{1}{2}$	1 over 2
Over	Frac013	$\frac{x+y}{x-y}$	x plus y over x minus y
OverEndFrac	Frac017	$\frac{1}{2}$	1 over 2 end fraction
OverEndFrac	Frac018	$\frac{12}{32}$	12 over 32 end fraction
OverEndFrac	Frac021	$\frac{x+y}{x-y}$	x plus y over x minus y end fraction

Table D1 Continued

Preference	Identifier	Example	Speech
OverEndFrac	Frac022	$\frac{x+y}{x-y}+\frac{2}{3}$	x plus y over x minus y, plus, 2 over 3 end fraction
GeneralEndFrac	Frac025	$\frac{1}{2}$	The fraction with numerator 1 and denominator 2, end fraction
GeneralEndFrac	Frac026	$\frac{12}{32}$	The fraction with numerator 12, and denominator 32, end fraction
GeneralEndFrac	Frac027	$\frac{x+y}{x-y}$	The fraction with numerator x plus y, and denominator x minus y, end fraction
GeneralEndFrac	Frac030	$\frac{x+y}{x-y}+\frac{2}{3}$	The fraction with numerator x plus y, and denominator x minus y, end fraction, plus, two thirds, end fraction
General	Frac032	$\frac{1}{2}$	The fraction with numerator 1, and denominator 2
General	Frac036	$\frac{x+y}{x-y}$	The fraction with numerator x plus y, and denominator x minus y
FracOver	Frac040	$\frac{1}{2}$	The fraction 1 over 2
FracOver	Frac045	$\frac{x+y}{x-y}+\frac{2}{3}$	The fraction x plus y over x minus y, plus, the fraction 2 over 3
FracOver	Frac046	$\frac{\text{miles}}{\text{gallon}}$	The fraction miles over gallons
FracOver	Frac047	$\frac{2\text{ miles}}{3\text{ gallons}}$	The fraction 2 miles over 3 gallons
Per	Frac054	$\frac{\text{miles}}{\text{gallon}}$	miles per gallon
Per	Frac055	$\frac{2\text{ miles}}{3\text{ gallons}}$	2 miles per 3 gallons
Ordinal	Frac056	$\frac{1}{2}$	One half
Ordinal	Frac057	$\frac{12}{32}$	12 thirty seconds
EndFrac	Frac065	$\frac{12}{32}$	12 over 32 end fraction
EndFrac	Frac066	$\frac{2+3}{13}$	The fraction with numerator 2 plus 3, and denominator 13 end fraction
EndFrac	Frac068	$\frac{x+y}{x-y}$	The fraction with numerator x plus y, and denominator x minus y end fraction
EndFrac	Frac067	$\frac{x+y}{x-y}+\frac{2}{3}$	The fraction with numerator x plus y, and denominator x minus y, end fraction, plus two thirds
EndFrac	Frac070	$\frac{\text{miles}}{\text{gallon}}$	miles over gallon end fraction

Table D2 Fractions With Text in Numerator and/or Denominator

Preference	Identifier	Example	Speech
Auto		$\frac{\text{rise}}{\text{run}}$	rise over run
Auto		$\frac{\text{successful outcomes}}{\text{total outcomes}}$	successful outcomes over total outcomes

Table D3 Fractions Within Fractions

Preference	Identifier	Example	Speech
Auto	NestFrac001	$\frac{\frac{1}{2}}{\frac{1}{3}}$	one half over one third
Auto	NestFrac002	$\frac{\frac{1}{2}}{\frac{1}{3}}$	the fraction with numerator 1, and denominator 2 over one third
Auto	NestFrac003	$\frac{\frac{1}{2}}{3}$	one half over 3
Auto	NestFrac004	$\frac{1}{\frac{2}{3}}$	1 over two thirds
Auto	NestFrac005	$\frac{\frac{11}{32}}{\frac{16}{51}}$	the fraction with numerator 11 over 32, and denominator 16 over 51.
Auto	NestFrac007	$\frac{1+\frac{4}{x}}{2}$	the fraction with numerator 1 plus 4 over x and denominator 2
Auto	NestFrac008	$\frac{3}{2+\frac{4}{x}}$	the fraction with numerator 3 and denominator 2 plus 4 over x
Auto	NestFrac010	$\frac{1+\frac{2}{3}}{1-\frac{2}{3}}$	the fraction with numerator 1 plus two thirds, and denominator 1 minus two thirds
Auto	NestFrac012	$\frac{\frac{x+1}{x-1}+1}{x+1}$	the fraction with numerator, the fraction with numerator x plus 1 and denominator x minus 1 plus 1, and denominator x plus 1
Auto	NestFrac017	$1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\cdots}}}$	1 plus the continued fraction with numerator 1 and denominator 1 plus the fraction with numerator 1 and denominator 1 plus the fraction with numerator 1 and denominator 1 plus dot dot dot
EndFrac	NestFrac019	$\frac{\frac{1}{2}}{\frac{1}{3}}$	one half over one third, end fraction

Table D3 Continued

Preference	Identifier	Example	Speech
EndFrac	NestFrac020	$\frac{\frac{1}{2}}{\frac{1}{3}}$	the fraction with numerator 1, and denominator 2 over one third, end fraction
EndFrac	NestFrac021	$\frac{\frac{1}{2}}{3}$	one half over 3, end fraction
EndFrac	NestFrac022	$\frac{1}{\frac{2}{3}}$	1 over two thirds, end fraction
EndFrac	NestFrac023	$\frac{\frac{11}{32}}{\frac{16}{51}}$	the fraction with numerator 11 over 32, and denominator 16 over 51, end fraction
EndFrac	NestFrac025	$\frac{1+\frac{4}{x}}{2}$	the fraction with numerator 1 plus 4 over x and denominator 2, end fraction
EndFrac	NestFrac026	$\frac{3}{2+\frac{4}{x}}$	the fraction with numerator 3 and denominator 2 plus 4 over x, end fraction
EndFrac	NestFrac028	$\frac{1+\frac{2}{3}}{1-\frac{2}{3}}$	the fraction with numerator 1 plus two thirds, and denominator 1 minus two thirds, end fraction
EndFrac	NestFrac030	$\frac{\frac{x+1}{x-1}+1}{x+1}$	the fraction with numerator, the fraction with numerator x plus 1 and denominator x minus 1, plus 1, and denominator x plus 1, end fraction
EndFrac	NestFrac032	$1+\frac{x}{1+\frac{2}{x}}$	1 plus the fraction with numerator x, and denominator 1 plus 2 over x, end fraction
EndFrac	NestFrac035	$1+\cfrac{1}{1+\cfrac{1}{1+\cfrac{1}{1+\cdots}}}$	1 plus the continued fraction with numerator 1 and denominator 1 plus the fraction with numerator 1 and denominator 1 plus the fraction with numerator 1 and denominator 1 plus dot dot dot, end fraction

Table D4 Fractions With Functions

Preference	Identifier	Example	Speech
Auto	Fracfunct001	$\frac{f(x)}{g(x)}$	f of x over g of x
Auto	Fracfunct002	$\frac{f(x)+g(x)}{g(x)}$	the fraction with numerator f of x plus g of x, and denominator g of x
Auto	Fracfunct003	$\frac{f(x+1)}{g(x)}$	the fraction with numerator f of, open paren, x plus 1, close paren, and denominator g of x
Auto	Fracfunct004	$\frac{f(x)}{2}$	the fraction with numerator f of x, and denominator 2
Auto	Fracfunct005	$\frac{2}{f(x)}$	2 over f of x

Table D4 Continued

Preference	Identifier	Example	Speech
Auto	Fracfunct007	$\frac{\sin x}{\cos x}$	sine x over cosine x
Auto	Fracfunct009	$\frac{\sin x + \cos x}{\cos x}$	the fraction with numerator sine x plus cosine x, and denominator cosine x
Auto	Fracfunct 010	$\frac{\sin 2x}{\cos 3x}$	Sine 2x, over, cosine 3x
Auto	Fracfunct 011	$\frac{\sin\left(x+y\right)}{\cos\left(x+y\right)}$	the fraction with numerator, the sine of, open paren, x plus y, close paren, and denominator, the cosine of, open paren, x plus y, close paren
Auto	Fracfunct012	$\frac{f\,(2x)}{g\,(3x)}$	f of 2x over g of 3x
Auto	Fracfunct013	$\frac{\log x}{\log y}$	log x over log y
Auto	Fracfunct015	$\frac{\log_{10} x}{\log_5 y}$	the log base 10 of x over the log base 5 of y
Auto	Fracfunct017	$\frac{\log\,(x+1)}{\log y}$	the fraction with numerator, the log of, open paren x plus 1, close paren, and denominator log y

Appendix E. Fully Accessible Version of This Report

For a version of this report that is fully accessible using the tools described, download the Microsoft Word document located at https://www.ets.org/Media/Research/RR-16-23.docx. You will also need the following tools:

- MathPlayer: http://www.dessci.com/en/products/mathplayer/download.htm
- MathType: http://www.dessci.com/en/products/mathtype/default.htm
- MathPlayer is free; MathType is a paid product but is available for free trial. If screen reader integration is desired, download the free NVDA screen reader: http://www.nvaccess.org/download/
- Additional tools, tutorials, and related information can be found at http://www.clearspeak.org.

Note that the math expressions in this document will, when used with the tools indicated, speak according to the current MathPlayer settings, including any user-configurations and speech-style selections. That speech will not necessarily match the recorded audio provided in the study. The recorded audio used in the study can be downloaded at the following links:

- http://www.ets.org/Media/Research/RR-16-23_ClearSpeak_Audio.zip
- http://www.ets.org/Media/Research/RR-16-23_MathSpeak_Audio.zip
- http://www.ets.org/Media/Research/RR-16-23_SimpleSpeak_Audio.zip

Suggested citation:

Frankel, L., Brownstein, B., Soiffer, N., & Hansen, E. (2016). *Development and initial evaluation of the ClearSpeak style for automated speaking of algebra* (Research Report No. RR-16-23). Princeton, NJ: Educational Testing Service. http://dx.doi.org/10.1002/ets2.12103

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