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Counting Differently: Assessing Mathematics Achievement of Signing Deaf and Hard of Hearing Children Through a Unique Lens

Jon Henner, Claudia Pagliaro, SaraBeth Sullivan, and Robert Hoffmeister

Limited studies exist that connect using signed language with mathematics performance of deaf and hard of hearing children. In the present study, the authors examined 257 participants and compared their results on the Northwest Evaluation Association: Measures of Academic Progress (NWEA MAP) to their results on an assessment of American Sign Language (ASL) skills. It was found that better ASL skills tended to result in better MAP performance. These results are moderated by factors such as age, gender, parental hearing status, and learning disability identification.

Keywords: deaf, language, American Sign Language, ASL, mathematics

For decades, studies have presented the mathematics achievement of deaf and hard of hearing (DHH) students as trailing that of their hearing peers (Traxler, 2000). Many of these academic analyses tend to focus on averages (notably, medians), which can mask the true variability within the data set and create a focus on delays and deficiencies. Hidden from view is a more complex picture of the mathematics abilities of DHH children, including in particular those who perform above the so-called average and those at grade level or above.

Although there are relatively few studies that focus specifically within these broad contexts, those that do find that DHH learners demonstrate equal or superior abilities in numeracy when compared to their age-equivalent hearing counterparts (Arfé et al., 2011; Barbosa, 2013; Zarfaty et al., 2004). DHH learners, preschool through postsecondary (including college-level DHH adults), have demonstrated age-appropriate mathematics skills (Kritzer, 2009; Lange et al., 2013; Pagliaro & Ansell, 2012; Qi & Mitchell, 2012; Traxler, 2000). Little is known, however, about why DHH children succeed in mathematics while others struggle. In the present investigation, a more comprehensive view of student achievement and an exploration of multiple factors that may contribute to mathematics performance

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provide insight and constructive direction to those working with DHH children and youth.

Language and Mathematics

Researchers have long recognized the relationship between language and academic success (Chen & Li, 2008; Cummins, 1982), including success in mathematics (Secada, 1992). To truly learn mathematics, one must engage with it and communicate about it through language. While philosophers argue about whether mathematics itself is a *language* (e.g., Krussel, 1998), we make no such distinction here; mathematics is both a language and a system of operations performed on numbers, patterns, and relationships. Similarly, as with language, one must be involved with mathematics in contexts that have meaning and purpose, at increasingly higher and broader cognitive levels, to succeed in education (Wang et al., 2017). Skills learned in mathematics and language scaffold one another to create an interdependent relationship, allowing the learner to build both capacities simultaneously. These skills develop with age and experience, through infancy (Baldo & Dronkers, 2007; Halvorsen & Molfese, 2016), preschool (Le Fevre et al., 2010; Mix, 2009; Purpura et al., 2011), and the elementary school years (Toll & Van Luit, 2014). Further in one's academic progress, mathematical thinking supports and encourages higher-order thinking and executive function (e.g., organization, problem solving, inference, and supporting arguments) that must be expressed in equally higher-order language. Research shows that children and adults who have language and literacy difficulties often experience numeracy challenges as well (De Smedt et al., 2010; Mann Koepke & Miller, 2013; Simmons et al., 2008).

More recent work in mathematics pedagogy has focused on students whose native language is not the language of instruction (e.g., English Language Learners in the United States). In general, learners with a strong first language (L1) and second language (L2) perform best in mathematics, even better than monolingual learners (Chen & Li, 2008; Hartanto et al., 2018). Among learners who are bilingual, studies show that presentation of mathematics in students' L1 correlates positively with achievement (Bernardo & Calleja, 2005; Perez & Alieto, 2018). But what of those with language deprivation who struggle to achieve across all academic subjects, including mathematics? Poor English-language skills are associated with lower levels of performance in mathematics, particularly as the complexity of mathematics concepts progresses and the language used to describe them becomes more complicated (e.g., Davis & Kelly, 2003; A. Edwards et al., 2013; Hyde et al., 2003; Kelly & Gaustad, 2006; Kelly et al., 2003; Kelly & Mousley, 2001). For example, in a study of DHH adults attending postsecondary institutions (ages 19–34 years), the results showed that those who demonstrated higher levels of written English vocabulary also demonstrated higher levels of facility with mathematics (Kelly & Gaustad, 2006). Most importantly, their scores on the ACT mathematics assessments and the English-language and morphological assessments were correlated not only with each other but also with actual grades from the college-level mathematics classes they took. We recognize that the focus on English and American Sign Language (ASL) limits the generalization of the studies to populations from the United States, yet these studies can likely be generalized to populations of DHH people in other countries, since the conflict between signed and spoken languages is relatively similar in other countries.

Other Factors Affecting Mathematics Achievement

Although the link between language proficiency and mathematics skills is established, language abilities are not the sole predictors of mathematics proficiency. How well students respond to teaching strategies and assessment is contingent on a variety of factors. The basis for this perspective is the Dynamic Systems Theory (de Bot et al., 2007). As de Bot et al. (2007) explained, this theory began as a mathematics theory to explain how variables interact in complex systems (p. 8). When extraordinarily complex systems, such as human beings, are considered, it is found that the examined variables are influenced by numerous other variables, considered and unconsidered. With regard to DHH students, we consider the following variables to be highly influential in learning mathematics: access to language at home (parental hearing status), age, gender, and learning disability.

Access to Language at Home

In typical language acquisition, children acquire the language of their parents as their L1. The timing and quality of language exposure (regardless of modality) is paramount in establishing critical language pathways in a child (Kuhl, 2004; Newport et al., 2001). Delays in this exposure to language (be it spoken or signed), which often occurs with DHH children of hearing parents, can result in varying degrees of language deprivation (Hall, 2017; Humphries et al., 2016; Novogrodsky et al., 2017). More than 90% of DHH children are born to hearing parents. Many of these parents choose to present language to their child via spoken English, most likely unaware of the challenges their child faces in accessing oral language and foregoing any signed language learning. As a result, many of these DHH children experience great difficulty acquiring their parents' spoken (home) language as an L1 (Lederberg et al., 2013). While some may question if studies focusing on language deprivation in deaf children can be generalized to children with only mild to moderate hearing loss, research shows that even those children have higher incidences of language disorders than children who do not present with hearing loss (Tuller & Delage, 2014).

Barriers to L1 acquisition are less evident in culturally Deaf families where the parents are signing Deaf adults. Many DHH children of DHH parents show proficiency in their L1 similar to what would be expected in an environment where oral language is naturally acquired. Having naturally signing DHH parents appears to contribute significantly to the language and mathematics performance of DHH children. Native signing DHH children perform exceptionally well on the United Kingdom General Certificate of Secondary Education exams (GCSEs; Powers, 2003). When examining the scores of young DHH children (ages 4–6 years) on the third edition of the Test of Early Mathematics Achievement (TEMA-3; Ginsburg & Baroody, 2003), Kritzer (2009) found that children with the highest scores tended to have signing DHH parents. Hrastinski and Wilbur (2016), for example, examined the interplay of mathematics skills (drawn from scores on the Northwest Evaluation Association: Measures of Academic Progress [NWEA MAP] scores) and ASL language levels (drawn from teacher judgments and/or school records). Hrastinski and Wilbur's interpretation of the data showed that ASL proficiency was more predictive of level of performance on the NWEA MAP than home language or age of school admission.

Native language proficiency that includes mathematics vocabulary and concept-related language significantly predicts numerical skills (Purpura & Reid, 2016). Ginsburg and Baroody (2003), for example, found that children who had more frequent access to mathematics-specific language demonstrated higher skill levels in mathematics. Use of "math talk" in the home and classroom has positive correlations with number knowledge and numeracy performance (Levine et al., 2010; Susperreguy & Davis-Kean, 2016). Studies have provided evidence of a correlation between socioeconomic status and the preponderance of "math talk" (e.g., Suskind et al., 2016), but many of these studies depend on the word gap framework of Hart and Risley (1995), which Sperry et al. (2019) were unable to replicate. While Golinkoff et al. (2019) have argued that researchers and educators must look past the failed replication and focus on the core issue, which is that early vocabulary scaffolds later education, methods matter too (Golinkoff et al., 2019). However, we caution that emphasis solely on only vocabulary development and reading skills for mathematics achievement, as opposed to grammar and other thinking skills, may not be productive. Much of this discussion can be summed up by Fuchs et al. (2016): "We conclude that pathways to calculation and word-reading outcomes are more different than alike" (p. 8). Fuchs et al. did not mean that reading and mathematics are disjunct, but that they should not be mistaken as being identical skill sets.

Many DHH children do not have full access to language environments that saturate them in language. For them, more language input would be beneficial. The relationship between mathematics and language extends to natural signed languages[1] (Barbosa, 2013; Hrastinski & Wilbur, 2016; Lange et al., 2013; Madelena et al., 2020). Use of "math talk" with Deaf preschoolers at home by their parents has also been linked to improved mathematics performance (Pagliaro & Kritzer, 2017).

The present study extends the exploration by Hrastinski and Wilbur (2016) of ASL skills and mathematics skills by folding into its conceptual models additional variables that research suggests might influence mathematics achievement, such as age, gender, and learning disability status.

Age

Age is a typical controlling variable in acquisition studies because as children age, their cognitive capacities improve. Typically, their understanding of numeracy, number cognition, and ability to handle complex mathematics ideas and operations improve with age (Pagliaro, 2015). We have used age as a controlling variable in most of our analyses using the American Sign Language Assessment Instrument (ASLAI) data set (Hoffmeister et al., 2013; see Henner et al., 2016, and Novogrodsky et al., 2017, for more discussion about our use of age as a controlling variable).

Gender

Gender appears to have a slight effect on mathematics outcomes, favoring boys, particularly among older age groups. While we emphasize that gender should have no effect on mathematics abilities, gender scholars demonstrate that cultures that devalue mathematics abilities in girls and women show depressed mathematics scores among those groups (Seymour, 1995). Meta-analyses on the effects of gender on mathematics achievement of hearing children suggest a small but significant difference between boys and girls in the upper high school grades, where boys demonstrate higher accuracy on more complex mathematics (Lindberg et al., 2010; Reilly et al., 2015).

Gender influences in studies with DHH students differ from those in studies with hearing students. For DHH children educated within an ASL-English bilingual model for at least 4 years in grades 2–9, Lange et al. (2013) found that gender did not have a significant effect on mathematics achievement. Similar findings were observed by Kluwin (1994) and Powers (2003), who both determined that gender was not significantly related to scores on the mathematics portion of the GCSE in the United Kingdom (Powers, 2003), nor on the Stanford Achievement Test–Hearing Impaired Edition in the United States (Kluwin, 1994). It is important to note that beyond these data from DHH high school graduates (Kluwin, 1994; Powers, 2003), there is no known further research examining gender and mathematics skills of DHH students in grades 9–12 in the United States. There is not yet a rich understanding of how gender might influence the mathematics achievement of DHH children. However, we cannot discredit the possibility that DHH children will be affected by *stereotype threat* or embodied beliefs about race, class, gender, and disability, among other identities, that manifest not only in society but in the parents and teachers who create mathematics learning environments (Shapiro & Williams, 2012). If DHH children are exposed to stereotype threats, then male DHH participants will demonstrate similar superior performance on mathematics assessments. However, we stress that we believe that language skills (ASL and/or English) are more determinative of the mathematics success of DHH students than gender.

Learning Disability

Learning disabilities can affect test scores in mathematics and reading. For example, in a study on learning disabilities in young hearing children (kindergarten and grade 1), researchers found that they had a significant effect on measured mathematics knowledge, specifically skills related to number sets and number estimations, but not counting knowledge (Geary et al., 2007). This suggests that learning disabilities may affect some mathematics skills more than others. Slightly older children (grade 2) who had different types of learning disabilities (mathematics based, reading based, or both) all demonstrated below-average mathematics abilities in comparison with their peers who had no learning disabilities (Cirino et al., 2015).

For DHH children, Allen (1986) found that cognitive learning disabilities were a strong predictor of lower outcomes on the mathematics computation portion of the Stanford Achievement Test–Hearing Impaired for DHH test takers in 1974 and 1983 ($p < .001$). In 2003, Powers determined that learning disabilities led to significantly lower results on the GCSEs for high school graduates in the United Kingdom in both 1995 ($p < .026$) and 1996 ($p < .006$). These findings indicate that learning disabilities influence the mathematics performance of high school graduates. More recently, Lange et al. (2013) found that the presence of a "secondary disability" significantly correlated with the mathematics scores ($p < .05$) of DHH children (grades 2–9) educated within an ASL/English bilingual approach for at least 4 years. Thus, there is some indication that the presence of a learning disability can significantly affect mathematics outcomes for DHH students from grade 2 through high school graduation, as is also seen with hearing students. While there are fairly limited studies on dyscalculia in DHH people, we can, on the basis of the literature on hearing peers, expect similar results (Butterworth, 2008; Reigosa-Crespo et al., 2012).

In the present study, we postulated that a lack of meaningful access to language may have critical implications for mathematics development. In the context of the data set collected for the study, we hypothesized that native signing participants who had experienced less language deprivation and more access to mathematics-specific language would perform better on a mathematics achievement assessment than the non-native signing participants. This study extends previous studies, especially the work of Hrastinski and Wilbur (2016), by exploring the impacts of ASL proficiency, language nativity, age, gender, and learning disability on the mathematics achievement of DHH children. Specifically, we sought to answer two questions:

1. How do the MAP mathematics achievement scores of the DHH participants compare to the appropriate hearing-normed mean RTI units for the ages?
2. What factors (e.g., age, gender, language input [signing status], ASL vocabulary, and learning disability) influence how DHH students perform on the MAP mathematics subtest?

Method

Participants

Data for the present analysis were collected from 257 DHH participants, aged 8–18 years, who were tested with the ASLAI (Hoffmeister et al., 2013) as part of routine language testing at various schools for the deaf across the United States. Data collection was partially funded by a grant from the U.S. Institute of Education Sciences that lasted from 2010 to 2015. Data collection after the grant ended was facilitated by individual contracts with the schools. Consent prior to 2014 was acquired for participants by means of parent consent forms. After 2014, consent was given through a "blanket consent" in which parents were required to opt out of testing, as it included all students in each of the schools. Schools that allowed blanket consent were given detailed individual and group results that could be used to craft individualized education program goals for ASL language support. The data set used in the analysis has been used in several other papers, which were published by the Boston University Center for the Study of Communication and the Deaf, including Henner et al. (2019) and Novogrodsky et al. (2017); however, the questions we sought to answer in the present study were markedly different.

Thirty-two percent of the participants (*N* = 82) were considered native signers, in that at least one parent was Deaf. The other 68% (*N* = 175) were considered to be non-native signers (i.e., both parents were hearing). Table 1 shows the distribution of participants by age and signing status.

Overall, the number of native participants decreased as age increased. The inverse was true for the number of non-native participants. This finding seems to align with that of Henner et al. (2016) that large numbers of non-native students tend to transfer to schools for the deaf after the age of 10 years. As there is no definitive explanation for why the native student population decreases at schools for the deaf after age 12, additional research is necessary to determine the reasons for this change.

Of the 257 participants, 54% (*n* = 140) were female and 46% (*n* = 117) were male; 31% (*n* = 79) were Asian American or Pacific Islander, 8% (*n* = 21) were Black, 26% (*n* = 68) were White, and 35% (*n* = 89) were Latinx. Participants were assigned a student rating that allowed schools to categorize participants them as follows:

1. had no diagnosed learning disability and none were suspected

Table 1. Distribution of the Sample (N = 257) by Age and Signing Status

Age (years)												
	8	9	10	11	12	13	14	15	16	17	18	Total
Native signers	15	13	12	9	8	3	7	4	4	4	3	82
Non-native signers	8	9	8	10	10	16	21	18	19	28	28	175

2. had no diagnosed learning disability but one was suspected
3. had a diagnosed learning disability

Ratings were provided by the schools and were generally made by someone who was familiar with the participant. Forty-two percent (n = 107) of the participants were rated as having no disability, and no additional ones were suspected (rating 1). Forty-five percent (n = 116) of the participants were rated as having no disability, and one was suspected but not identified (rating 2). Thirteen percent of the participants (n = 34) had a formally identified learning disability (rating 3). However, no information was collected about the kind of learning disability each of the participants with that diagnosis had, nor about how the learning disability was identified. Table 2 shows the distribution of ratings between native and non-native participants.

The data show that native signers were disproportionately represented in category 1 (no disability), while non-native signers were disproportionately represented in category 2 (suspected learning disability).

We did not collect information about degree of hearing loss because that information was not applicable to the study in the absence of qualitative information about how the individual participants were able to use their available hearing. That kind of information requires the use of assessments such as the Speech, Spatial, and Qualities of Hearing Scale (Gatehouse & Noble, 2004). The way we collected data was from the schools, which did not give us access to the kind of information that would enable us to use the scale.

Measures

American Sign Language Assessment Instrument (ASLAI)

The ASLAI is a computerized task assessment of ASL language proficiency. The tasks that make up the battery measure ASL vocabulary, syntax, reasoning, and literacy proficiency in DHH children aged 3–18 years. The instrument has been normed on over 2,000 DHH children over the past 10 years. The basic structure of the ASLAI is multiple choice, with one stimulus and four possible responses from which participants may select an answer: Figure 1 presents an example from the Antonyms task. The picture on the left shows the stimulus. The four pictures on the right show possible responses from which the test taker must choose the correct signed response.

We collected data on participant ASL vocabulary abilities using two of the tasks from the ASLAI battery: Antonyms (Novogrodsky et al., 2014a) and Synonyms (Novogrodsky et al., 2014b). These tasks were chosen because they represent in breadth and depth a good measure of overall ASL vocabulary knowledge. Both tasks are described in detail in Novogrodsky et al. (2014a, 2014b).

Table 2. Distribution of Disability Ratings Among the Sample Population

	Ratings		
	1 (no disability)	2 (suspected learning disability)	3 (confirmed learning disability)
Native signers ($N = 82$)	55% ($n = 45$)	33% ($n = 27$)	12% ($n = 10$)
Non-native signers ($N = 175$)	35% ($n = 62$)	51% ($n = 89$)	14% ($n = 24$)

Figure 1. Example of the ASLAI Platform

Note. This figure shows what the American Sign Language Assessment Instrument (ASLAI) platform looks like. It has six boxes in two rows. The first box is a stimulus item and shows a White woman in a purple shirt signing HATE. The next four boxes arranged in a square are the responses. The same woman signs all four responses. The images are freeze-frames of different signs.

Each task is presented in five stages: (a) a global instruction phase; (b) a task instruction phase, in which specific directions are given for a particular task (e.g., finding a sign of similar meaning to the prompt for antonyms); (c) a practice phase, in which the test taker is shown a model prompt and answer; (d) a task phase, in which the test taker proceeds through the questions; and (e) a review phase, in which participants can go back and change their answers if they need to. Responses are scored under an assigned ID number and automatically included in the database in real time.

Northwest Evaluation Association: Measures of Academic Progress (NWEA MAP): Mathematics Test

The NWEA MAP is a computer-based English print format, adaptive assessment designed to provide information on student academic growth over time (see nwea.org). The MAP assessment consists of four assessment batteries: (a) MAP for reading, English language use, and mathematics; (b) science; (c) primary grades for reading and mathematics; and (d) end-of-course assessments in mathematics. Because all questions are presented in English print, the ability to read and knowledge of English are required. Adaptive tests scale to student abilities. Correct answers track participants to more challenging questions. Missed questions track students to easier questions. Results are presented in RIT values, which represent Rasch Units. The RIT value represents the level of task difficulty at which participants could get the correct answer at least half the time, that is, the level of difficulty at which getting the correct answer is not due to chance. The RIT value is designed so that schools can analyze student growth from year to year. RIT scores range between 100 and 300 and are presented via beginning-of-year norms, middle-of-year norms, and end-of-year norms. A student's score (100–300) depends on their age and the content area. Content area scores are not considered equivalent: A 180 in reading and a 180 in mathematics are not comparable scores.

For the present analysis, only data from the Mathematics assessment was used. Additional detail about the use of the MAP with DHH children can be found in Hrastinski and Wilbur (2016).

Procedure

Participants completed the ASLAI tasks in groups of 15–20. Testing time for the battery ranged from 3 to 4 hours, depending on the age of the student. Testing at schools typically took up to 1 week. Smaller schools could be finished in 3 days, while larger schools could take up to 10 days, depending on logistics. Data from the tasks were immediately sent to CRT databases and encrypted to ensure participant confidentiality.

Results

1. How do the MAP mathematics achievement scores of the DHH participants compare to the appropriate hearing-normed mean RTI units for the ages?

We first asked how the MAP mathematics scores of the DHH participants compared to the appropriate normed mean RTI units for their hearing peers. While in general we do not believe that DHH children should be compared to hearing peers because DHH children often have more challenges in acquiring both spoken and written English, which can lead to downstream effects, we do so here to demonstrate that different lenses are needed for analyzing data from DHH children.

The NWEA draws norms from 72,000–153,000 student test results from over 1,000 different schools (Thum & Matta, 2015). The sampling is designed to represent the variety of students in the United States. MAP mathematics RTI norms exist for grade levels K–11. As ASLAI scores are by age rather than grade, we converted the MAP grades to age equivalents, based on those used on the third edition of the Test of Early Mathematics Ability (TEMA-3; Ginsburg & Baroody, 2003) and calculated MAP mathematics RTI norms for ages 5–16 years. Although the TEMA-3 only goes up to age 8 (second grade, 7 years old; third grade, 8 years old), we felt that we could expand how we used the TEMA-3 age equivalents to match age to grade for ages greater than 8 years.

The student sample in the present analysis ranged from ages 8 to 18 years; thus, we recognize that there is not a perfect match between the MAP mathematics RTI norms and our own data set. These differences are reflected in the design of Table 3.

For our analysis, we chose a descriptive approach using the end-of-year norms as the metric of comparison for DHH mean scores. These results are presented in Table 3. We also calculated two additional columns, the low bound of the end-of-year mean RTI (end-of-year mean RTI – end-of-year RTI standard deviation) and the high bound of the DHH mean

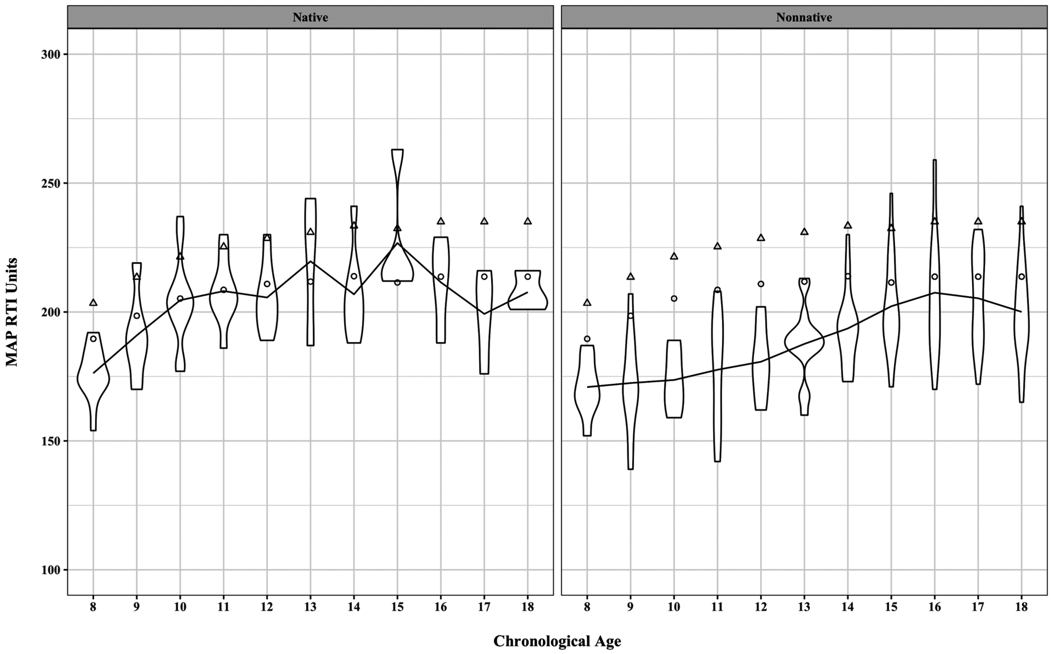
Table 3. Comparison of End-of-Year Mean RTI and Standard Deviation for Hearing and Deaf and Hard of Hearing (DHH) Populations

Grade	Age, years	End-of-year mean RTI	End-of-year RTI standard deviation	DHH mean RTI	DHH RTI standard deviation	End-of-year mean RTI (low bound; end-of-year mean RTI – *SD*)	DHH mean RTI (high bound; DHH mean RTI + *SD*)
K		159.1	13.69				
1		180.8	13.63				
2	7	192.1	13.54				
3	8	203.4	13.81	174.39	10.48	189.59	184.87
4	9	213.5	14.97	183.36	19.43	198.53	202.79
5	10	221.4	16.18	192.2	21.45	205.22	213.65
6	11	225.3	16.71	192.05	23.75	208.59	215.80
7	12	228.6	17.72	191.78	18.41	210.88	210.19
8	13	230.9	19.11	192.68	20.08	211.79	212.76
9	14	233.4	19.52	196.93	16.65	213.88	213.58
10	15	232.4	20.96	206.68	21.42	211.44	228.10
11	16	235	21.3	208.17	22.58	213.70	230.75
N/A	17			204.56	17.04		221.60
N/A	18			200.77	17.93		218.70

RTI (DHH mean RTI + DHH RTI standard deviation). These two columns show mathematically the extent of any overlap between -1 standard deviation for general norms and +1 standard deviation for the DHH students in our sample population. Thus, a wider range is covered than just the typically reported absolute mean or median. The standard deviation "indexes the variability of scores" (Cohen et al., 2003, p. 24). What that means is that the standard deviation frames how the mean is dependent on clusters of data points on either end and that these clusters can pull the mean back or forth depending on how many data points are in these clusters and where they are relative to the mean.

The data indicate that from ages 8 to 16 years the RTI norms of our DHH sample were less than the RTI norms of the norming population of the MAP mathematics subtest. Additionally, the norms for DHH students who were aged 17 were less than the norms for the last available MAP RTI norms. The data also show a flattening of scores for DHH participants from ages 10 to 13. During these 4 years, mean RTI scores hover around 192. However, when the upper bound of DHH mean RTI scores is compared to the lower bound of the general normed RTI scores, a different picture of DHH mathematical abilities emerges. The DHH upper bound scores were higher than the normed lower bound scores at every age except 8, 12, and 14. For the latter two age groups, the difference between the normed RTI lower bound and the mean RTI upper bound for DHH students was a matter of decimal points. In Figure 2 we visualize the distribution of data using density plots. Density plots show not only the number of data points through size, but

Figure 2. RTI Score Distribution by Age and Signing Status



Note. Circles represent the lower bound RTI score and triangles represent the Measures of Academic Progress (MAP) normed score. These are two graphs of the responses next to each other. The *y* axis is labeled "MAP RTI Units" and ranges from 100 to 300. The *x* axis is labeled "Chronological Age" and ranges from 8 to 18. The left graph is for native signers and the right graph is for non-native signers. The data are plotted with violin charts, with a line going through the mean score.

also the range of scores. Within the density plot, we also show lines connecting the mean RTI scores for native and non-native signers. The circles are the normed RTI unit lower bounds for the MAP mathematics subtest, and the triangles are the normed RTI units.

The data in Figure 2 show different distributions of MAP RTI scores depending on access to language at home (SIGNING STATUS). We found that the mean RTI units were higher overall for native signers than for non-native signers. The range of scores for native signers shows that many of these students scored at least within the range of the MAP RTI lower bounds and the normed MAP RTI score. Most of the native participants had scores that approximated the MAP RTI lower bounds for ages 10, 11, 12, 16, and 17 years. The data also show that some native signers reached and exceeded the MAP RTI normed score from ages 9 through 15. While non–native signers appeared to have lower scores than native signers across the board, they did reach the normed MAP RTI lower bound scores for ages 9 and 13–18. Ages 14, 15, and 18 met and exceeded the MAP RTI normed score.

On the basis of this initial analysis, we wanted to further examine the DHH students who were meeting and exceeding both the normed MAP RTI lower bounds and the MAP RTI norms. First, we examined the percentages of native and non-native signers with scores higher than both the normed MAP RTI lower bounds and the MAP RTI norms. Second, we did a profile analysis of the type of DHH student who could meet MAP RTI norms based on the background data we had on each student.

Table 4 presents the percentages of native and non-native signers who had scores

Table 4. Distribution of Percentage Reached for Normed Measures of Academic Progress (MAP) RTI Lower Bound and RTI Scores, by Signing Status

	Percentage reached	
	Normed MAP RTI lower bound	Normed MAP RTI score
Native signers (*N* = 82)	34% (*n* = 28)	11% (*n* = 9)
Non-native signers (*N* = 175)	19% (*n* = 33)	2% (*n* = 4)

higher than both the normed MAP RTI lower bounds and the MAP RTI norms.

We then looked at each of the students who scored at or above their age group's normed MAP RTI scores to see if any patterns emerged. Thirteen students reached this criterion, and we considered these participants to be "achieving." Data for these 13 participants are listed in Table 5. The data indicate that the average age for *achieving* DHH participants was 12.9 years. These students were largely native signers and more likely to be male (8) than female (5). Eight of the participants had no diagnosed learning disability. Two were suspected of having a learning disability, but were not diagnosed. One had a formally diagnosed learning disability. All *achieving* DHH participants, with one exception, had very high ASL vocabulary scores, with 8 (62%) of them having scores higher than 90%. Of the five scores lower than 90%, three were from participants aged 10 and younger. One 15-year-old, non-native male signer demonstrated low ASL vocabulary proficiency but high mathematics skills. However, that specific participant also scored above MAP reading RTI norms (224 vs. 222.9),

Table 5. Participants Who Scored Above the Norms for Measures of Academic Progress (MAP) Math ematics

Participant	Chronological age (years)	Signing status	Gender	Ethnicity	Student rating	MAP math RTI score	ASL vocabulary (x 100)
1	18	Non-native	F	Asian	3	241	100
2	16	Non-native	M	White	2	259	92.5
3	16	Non-native	M	White	1	254	96
4	15	Native	M	White	1	263	100
5	15	Non-native	M	White	1	246	17.5
6	14	Native	M	Latinx	1	241	100
7	13	Native	M	Latinx	1	244	89
8	12	Native	F	White	2	230	96
9	11	Native	M	White	1	230	92
10	10	Native	F	White	1	229	96
11	10	Native	M	White	1	237	89
12	9	Native	F	White	1	218	71
13	9	Native	F	White	1	219	89

Note. ASL = American Sign Language.

indicating strong proficiency in printed English.

To sum, the likely high-performing DHH student was a middle school male student without a learning disability and with native ASL signing skills and high ASL vocabulary abilities. We stress that the gender results do not mean that males are better at mathematics than females but are a likely result of societal stereotypes encouraging males to pursue mathematics learning.

2: *What factors (e.g., age, gender, language input [signing status], ASL vocabulary, and learning disability) influence how DHH students perform on the MAP mathematics subtest?*

Our second research question focused on factors that affect performance on the MAP mathematics subtest for DHH children. We looked at five factors: (a) chronological age, (b) signing status (native vs. non-native), (c) ASL vocabulary abilities, (d) identified gender (male vs. female), and (e) learning disability (none, suspected but not diagnosed, and diagnosed learning disability). We predicted that each factor would have the following effects on the MAP mathematics RTI scores:

- As chronological age rises, RTI scores will also rise.
- Native signers will have higher average scores than non-native signers.
- DHH children with better ASL vocabulary will show higher RTI scores.
- Males will have higher average scores than females.
- Those without any learning disabilities will have better scores than both those suspected of having one, but not identified with one, and those identified with a learning disability.
- Those suspected of having a learning disability, but not identified with one, may have better scores than those identified with a learning disability and should lag behind students without a known or suspected learning disability

To answer our second question, we used a random effects mixed-model approach following Baayen et al. (2008). The random effects mixed-model approach has been used successfully in several other studies published by our team, including Henner et al. (2019) and Novogrodsky et al. (2017). Results (see Table 6) show that all of the five factors listed above were significant predictors of MAP mathematics scores.

1. Age: As chronological age increased, MAP RTI units also increased by an average of 2.49 points per year, Chi-Sq(1) = 47.76, $p < .001$.
2. Signing status: Native signers outperformed non-native signers by an average of 6.78 RTI units, Chi-Sq(1) = .004, $p < .01$.
3. ASL vocabulary: Vocabulary knowledge lent itself to a slope of 38.51 RTI units depending on the mean scores of the Antonym and Synonym tasks, Chi-Sq(1) = 68.41, $p < .001$.
4. Gender: Males outperformed females by an average RTI score of 5.38, Chi-Sq(1) = 5.38, $p < .005$.
5. Learning disability: Disability diagnosis predicted average RTI scores, Chi-Sq(2) = 18.73, $p < .001$. Those suspected of a diagnosis, but without a formal diagnosis, had RTI scores on average 7.34 less than those without a disability. Those who had a formal learning disability diagnosis had scores 12.5 points less than those of participants without a disability.

Discussion

Three questions guided the present study. We begin our discussion with research question 1: *How do the MAP mathematics*

Table 6. Mixed-Effect Regression Analysis Using Measures of Academic Progress (MAP) as the Dependent Variable and Age, Signing Status, Native/Non-native, Vocabulary, Gender, and Student Rating as Independent Variables

	Estimate (beta)	Standard error	*t*	Chi-square	*p*
Fixed effects					
Age	2.49	.034	7.25	47.76	< .001
Signing status (native)				.004	.009
Non-native	-6.78	2.33	-2.90		
Vocabulary	38.51	4.13	9.31	68.41	< .001
Gender (female)					
Male	5.38	1.89	2.84	.005	.001
Student rating (no disability)				18.73	< .001
Suspected disability	-7.34	2.15	-3.41		
Diagnosed learning disability	-12.50	3.11	-4.01		
Random effects	Variance	Standard deviation			
Intercept	78.25	8.8			

achievement scores of the DHH participants compare to the RIT units for the ages?

We wanted to investigate if there was an overlap between the standard deviations in the scores of DHH and hearing participants and if there were DHH data points within the overlap. Within this overlap, the scores of DHH students ($M + SD$) met or exceeded the scores of hearing students ($M - SD$) in every single comparison except one. The main exception occurred in the 8-year-old group, yielding a 5-point difference, a very slight difference when the scale is considered. This is remarkable, considering that DHH students learn mathematics in variable language environments (and often in a second language, as hearing educators typically are not fluent in ASL, DHH students' first or natural language), or from teachers who may also not be skilled in teaching mathematics (Kelly et al., 2003; Pagliaro, 1998). Lack of fluency in ASL affects the teaching of mathematics in that for many mathematics concepts there is not a one-to-one correspondence between English words and ASL signs, a situation that requires nonfluent ASL educators to resort to English, or worse, to artificially create a sign for a mathematics concept (Henner et al., 2017; Müller de Quadros & Hoffmeister, 2020). Furthermore, DHH students must contend with possible language deprivation in addition to the same pressures hearing students experience that can deflect mathematics acquisition curves (e.g., learning disabilities, gender expectations).

Our efforts may indicate that while on the surface it appears that DHH students do not do as well as their hearing counterparts on the MAP mathematics subtest, an analysis of variability demonstrates that DHH students do better than the expected narrative. In our sample for the present study, 61 DHH students (24%) surpassed the $M - SD$ score of hearing students and 13 (5%) did better than the age-related mean score for hearing participants. Thus, our results show that the focus should not be solely on simple means analyses when DHH students' performance in mathematics is being determined. Instead, other approaches to the data must be considered that give a clearer picture of DHH students' performance. Most importantly, the data must be contextualized, as DHH people are not a homogenous group. If the goal of specialized education is to focus on the needs of the individual, then the individuality each participant brings to the research data set must be considered. Essentialized statements, such as that referring to reading (i.e., "DHH people read at a fourth-grade level") must be replaced with information that describes the complexity and nuance of how the academic scholarship and skills of DHH participants are measured relative to their life experiences of being deaf or hard of hearing in a hearing society that makes little allowance for full access to language.

Research question 2. *What factors (e.g., age, gender, language input [signing status], ASL vocabulary, and learning disability) influence how DHH students perform on the MAP mathematics subtest?* The issue of variability compels us to drill deeper into the DHH population and move away from treating DHH students as a group, as is done in almost all research studies. DHH students' identities are not simply Deaf, deaf, or hard of hearing; DHH students are made up of multiple identities and multiple unique experiences. Thus, we looked at multiple factors the literature has shown to be significant, including participants' age at testing, identified gender, suspected or identified learning disability, ASL (vocabulary) knowledge, and signing status of parents (e.g., native/non-native signer/language user). Age and gender were chosen as independent controlling variables due to typical age-related developmental patterns and culture-centric influences on gender. Specifically, we considered the explicit and implicit discouragement of mathematics learning and involvement in STEM (science, technology, engineering, mathematics) for girls and women. We were additionally curious to see if a group of DHH children who did not have full access to the community language and its culture would show similar effects. Below, we discuss the results for specific factors.

Age

As expected, there was a significant effect of age on performance on the MAP mathematics subtest. Older participants generally performed better than younger participants. A closer breakdown of the scores by age and parental hearing status is seen in Figure 2. In general, the MAP mathematics scores improved for each year cohort. While we cannot generalize these findings beyond the participant group researched here, we did notice that some years did not see any improvement in scores, and some years saw the mean scores trending downward. We suspect that flat trending scores represent a transition to harder mathematics subject areas (e.g., trigonometry, algebra). This may also indicate the impact of language fluency on the presentation of mathematical concepts. A teacher's inability to use ASL fluently restricts the amount, type, and level of mathematics concepts that can be presented to DHH students, especially in the higher grades. As a possible indicator of this phenomenon, anecdotally speaking, we point out that downward trending scores show that participants who were proficient in mathematics likely transferred to schools where there would be opportunities to participate in advanced classes in which ASL-fluent instructors could deliver appropriate mathematics content. We would also not rule out the possibility that these DHH students transferred to integrated classrooms (with hearing students) with skilled interpreters, a development that would further support the idea that ASL fluency has an impact on the delivery of mathematical concepts.

Gender

The data presented a significant effect of gender, with male-identifying participants scoring higher overall on the MAP assessment than female-identifying participants. The results align with demonstrated gender effects in mathematics performance. We stress that our results do not show that males are better than females at mathematics, even in DHH populations. What our results do demonstrate is that cultural norms that support male achievement in mathematics trickle into DHH groups, regardless of language barriers and community differences. It appears that cultural norms regarding males and females are strong enough that DHH children pick up on them even within variable language environments. It is possible that DHH students' mathematics teachers, most of whom are women, may reflect their own cultural biases and feelings of mathematics inadequacy onto their students, a phenomenon called *stereotype threat* (see Tomasetto et al., 2011, for a discussion of stereotype threat in parents, and Shapiro & Williams, 2012, for a general discussion of stereotype threat).

Parental Hearing Status

While recent efforts show that in many areas parental hearing status is not as significant as the early input of ASL (see Henner et al., 2019, for a discussion), it is still often used as a controlling variable. On the whole, DHH children who have full *access* to language at home do better than DHH children who do not. In the present study, our results showed that parental hearing status did have a significant effect on the mathematics abilities of the DHH children. Of the 13 participants whose performance surpassed the normed MAP RTI scores, 9 had Deaf parents. Yet as the density graphs in Figure 2 indicate, the distribution of scores for native and non-native groups overlaps substantially. The data, however, are stratified in that while non-native signers were able to do as well on the MAP mathematics subtest as their native signing peers, the latter seemed to have an advantage. One possible explanation for these results is provided by research by Pagliaro and Kritzer (2010, 2017) that showed the importance of engaging in explanatory discussion of mathematics and numeracy concepts around children. DHH children with Deaf signing parents have access to an increase in "math talk," which has been shown to correlate with better mathematics performance by hearing students (Klibanoff et al., 2006). As always, we emphasize that disparities in the scores between DHH children with good access to language at home and those with limited access to language at home are not insurmountable. Given a signed language–rich environment at school with peers and adults who also provide signed language input, DHH children who have signed language access at home can improve their proficiency to the point where they are on par with native signing peers (Henner et al., 2019). One concern evidenced from the data is that while White participants made up only 26% of the sample population, they represented 78% of the 13 who scored above the MAP norms. The disparity in mathematics achievement shown even within this small group will require further research, as it is reflective of similar educational challenges faced by hearing children of color (see Berry et al., 2014 for a discussion of this topic).

ASL Vocabulary

To further demonstrate the impact of ASL (language) fluency, we analyzed the role of ASL vocabulary knowledge in mathematics scores. Research by Hrastinski and Wilbur (2016) showed that ASL proficiency translates into better scores on the MAP mathematics subtest. Results from the present study support this finding with nearly quadruple the participants, demonstrating a clear connection between ASL vocabulary proficiency and mathematics scores on the MAP. The findings also add to the general mathematics research showing the positive relationship between early and full access to a true language and mathematics knowledge. To sum up, we believe that our results will encourages the use of fluent ASL in the deaf education mathematics classroom. These results also fit neatly with demonstrations by Andin et al. (2019) showing that there is no real difference between signed language phonology and a spoken language phonology in how the brain processes numeracy. For the brain, language is language and mathematics is mathematics.

Learning Disabilities

Finally, we compared the performance on the MAP mathematics subtest of three groups of DHH participants: those without an identified learning disability, those suspected of having one, and those identified as having one. As predicted, those with an identified learning disability did not perform as well as those without an identified learning disability. DHH participants suspected of having a learning disability also did not do as well as those who were not identified as having one, but better than those identified as having a learning disability. However, having a learning disability or being suspected of having one does not automatically mean that mathematics achievement is impossible for DHH children. One participant who scored better than the normed RTI for their age group was identified as having a learning disability, and another high scorer was suspected of having one. Having a learning disability does not necessarily have an effect on how well one learns mathematics.

When considering these results, readers should keep two points in mind. First, the label *learning disability* covers a wide range of challenges, many of which have little to do with mathematics. Thus, we do not know the specifics of the learning disability identification or suspicion in our sample of students. A student can have a reading learning disability (e.g., dyslexia) and not a mathematics learning disability (e.g., dyscalculia), for example. Although having a reading disability can affect the measurement of mathematical knowledge since almost all measurement tasks are in English print (in societies where English is the primary language), the point stands. Second, the process of identifying learning disabilities in DHH students is controversial given that the identification process assumes a typical language-accessible environment. Many of the identifiable behaviors associated with learning disabilities are actually related to language deprivation in the DHH population (see Walker et al., 2017 for a discussion of this topic). More to the point, Walker et al. (2017) showed that teachers of the deaf are often inaccurate when determining what constitutes a learning disability in DHH children. Additionally, deaf children tend to be diagnosed with disabilities related to learning and attention at greater rates than hearing children (Bailly et al., 2003; Greco et al., 2009). Without additional kinds of testing, preferably ethnographic (see Hou & Kusters, 2020, for a discussion of ethnographic assessment), we cannot know if the participants in the present study had an identified learning disability that would require specific and knowledgeable interventions to promote mathematics achievement, or if the participants may have been language deprived but presented as having a learning disability. Either situation requires extensive and individualized targeted education plans.

Still, our results suggest that DHH students who are suspected of having or are identified as having learning disabilities struggle in their classrooms more so than DHH students without an identified learning disability. Teachers can make note of strategies that are more or less successful with each student and adopt a more universal design for learning in their classroom by varying the approaches and products used in instruction. Classrooms are often made up of students with a wide range of needs and learning modes (Hitchcock & Stahl, 2003). Lesson plans with varied activities, select grouping of students, and matching products meeting differential learning styles can better address students' individual needs. Additionally, teachers should ensure that DHH students have access to the appropriate linguistic support in classrooms. This requires that teachers themselves be fluent in ASL or that qualified, fluent ASL educational interpreters, knowledgeable in mathematics, are appropriately paired with the DHH child. However, we strongly stress that educational interpreters should not be considered when students are at risk of language deprivation (Caselli et al., 2020). It is critical to learning to have an accessible language environment.

Final Thoughts, Limitations, and Recommendations for Future Research

In a direct comparison of the mean MAP mathematic scores, the 257 DHH students who participated in the present study did not, as a group, perform at the level of the normed mean RTI units. However, we argue that this result needs to be contextualized. *Some* performed better than hearing counterparts. *Some* scored at or slightly below norms. Overall, the results were variable, as the outcomes of research with DHH populations tend to be.

Our goal was to find ways to examine data through a different lens. The literature to date has tended to focus on gaps between DHH children and hearing children without taking into consideration factors that will influence performance such as language deprivation; inaccessible environments; insufficient signing skills of parents, teachers, and administrators; and low cultural expectations. An application of Dynamic Systems Theory to this research population reveals the need to examine the different factors that can influence mathematical performance in our studied population. Accordingly, we looked for other ways to analyze the data in order to find ways to represent the mathematics achievement of a group of DHH students and to determine what factors might have contributed to the results.

We began the present article by examining how researchers tend to present and interpret the mathematics performance of DHH students as lagging behind that of hearing peers. Yet, as we have stressed repeatedly, researchers often forget that DHH youth are not just deaf or hard of hearing. As learners within the larger general population, DHH students vary by gender/sex, age, race, culture, language, and disability. They may be contending with family situations that can derail learning, or educational approaches that do not support their individuality, full access to their language, or their emotional well-being. Many educators hold low expectations of DHH students, accepting the standardized measured levels of achievement as standard "for deaf kids." As a result, the lack of learning is attributed to the fact that they are DHH and not to observable characteristics of teaching and the environment. Despite these challenges, we know that some DHH children do as well as or better than their hearing peers academically. Some of their success may be attributed to resilience (Listman et al., 2011), but resilience is an individual trait that is not attributable to all DHH students. We believe that all DHH students have the capacity to learn and to succeed. To understand how to better analyze the data we acquired from our participants, so that we might gain insight into successful DHH youth, we employed Dynamic Systems Theory, which helped us reframe our thinking and consider the results we received in a more global context. The variables we chose were limited by what was available in the data set. It is important to remember that any measurement model cannot control for all observed and unobserved factors.

Because we used the mathematics subtest of the MAP and focused more on standard deviation overlap instead of rigid comparisons of the mean, our results demonstrated that many of the study participants scored close to or in the overlap of standard deviations, indicating performance approximating that of their hearing peers. Viewing achievement levels this way provides a very different picture by which teachers should plan mathematics instruction, not from an insurmountable deficit view but from a positive expectation of DHH student performance.

Although looking at standard deviation overlaps is another way to interpret the data, it still does not provide a reasonable explanation for why some DHH students struggle in mathematics. While the present study cannot provide an adequate explanation for this phenomenon, we provide a different, possible solution by examining performance data and suggestions for capitalizing on DHH students' mathematic abilities. Researchers studying DHH populations need to continue to explore mathematical modeling that contextualizes their assessment performance while contextualizing data results. However, we all must be aware that purely quantitative results do not provide qualitative reasoning for why DHH individuals perform on assessments the way they do.

We suggest that teachers plan mathematics lessons for DHH students that support and build upon the achievement these students display, while also recognizing the DHH learner's unique needs (Pagliaro, 2015). Capitalizing on linguistically accurate signed communication with DHH students is essential to support this instruction (Kurz & Pagliaro, 2020). In addition, given our results that solidly show that ASL vocabulary knowledge translates into likely success in mathematics, we strongly support the results of Hrastinski and Wilbur (2016) and promote teacher fluency not only in signed languages overall, but in the application of mathematics concepts through signed languages (Kurz & Pagliaro, 2020; Pagliaro & Kurz, 2021).

Because our results indicate that better signing skills in DHH children are more likely to result in higher mathematics performance, we additionally suggest that DHH children be exposed to a *fully accessible* and *true* language early, and from more fluent models in the home environment and the school. While as a field, we in deaf education cannot control whether parents of DHH children acquire enough signed language to become proficient signers, we can ensure that DHH children have access to qualified fluent signing teachers of DHH and qualified fluent signed language interpreters. We encourage those professionals who work with signing DHH students not only to become fluent ASL signers but to make use of the vast repository of STEM signed language corpora (e.g., ASL Clear, aslclear.org; Atomic Hands, atomichands.com) and literature (Kurz & Pagliaro, 2020) from which they can better learn how to incorporate specific scientific and mathematical concepts into age-appropriate instruction. From a teacher training perspective, our work evidences the need to implement training to attain ASL-fluent teachers and specific training in how to teach and present mathematical knowledge to signing DHH students of all ages. As a specific support, we encourage current and future educators of the deaf to consider ways in which they can improve their signed language abilities so that they can use the available properties of ASL to demonstrate both entry-level and higher-order STEM concepts.

Note on Terminology

1. We use the phrase "natural signed languages" to distinguish between community emergent signed languages like ASL and British Sign language from constructed and artificial signed systems developed by researchers, laypeople, and educators, such as Signing Exact English, which fall under the umbrella term *Manually Coded English*.

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