Published in final edited form as:

Deafness Educ Int. 2018 ; 20(2): 59–79. doi:10.1080/14643154.2018.1437238.

Numerical and Real-World Estimation Abilities of Deaf and Hearing College Students

Georgianna Borgna¹, Dawn Walton¹, Carol Convertino¹, Marc Marschark^{1,2}, and Jessica Trussell¹

¹National Technical Institute for the Deaf – Rochester Institute of Technology

²School of Psychology, University of Aberdeen

Abstract

Various studies have examined possible loci of deaf learners' documented challenges with regard to reading, usually focusing on language-related factors. Deaf students also frequently struggle in mathematics and science, but fewer studies have examined possible reasons for those difficulties. The present study examined numerical and non-numerical (real-world) estimation skills among deaf and hearing college students, together with several cognitive abilities likely to underlie mathematics performance. Drawing on claims in the literature and some limited evidence from research involving deaf children, the study also considered the possibility that the use of sign language and/or the use of cochlear implants and spoken language might facilitate deaf college students' estimation skills and mathematics achievement more broadly. Results indicated relatively little impact of cochlear implant use or language modality on either estimation skills or overall mathematics ability. Predictors of those abilities differed for deaf and hearing learners. Results suggest the need to guard against overgeneralisations either within the diverse population of deaf learners or between deaf and hearing learners. They further emphasise the need for evidence-based practice in mathematics instruction appropriate for older deaf learners, rather than making assumptions from studies involving younger or narrowly-selected samples.

Researchers and educators working with deaf students usually focus on language and literacy issues, reflecting challenges faced by most deaf learners throughout their academic careers (Easterbrooks & Beal-Alvarez, 2013). In practice, deaf students tend to lag behind their hearing peers across the curriculum (Marschark, Shaver, Nagle, & Newman, 2015; Qi & Mitchell, 2012), but the only other academic domain that has received significant

Correspondence should be sent to Marc Marschark, Center for Education Research Partnerships, National Technical Institute for the Deaf—Rochester Institute of Technology, 52 Lomb Memorial Drive, Rochester, NY 14623 (marc.marschark@rit.edu).

1 Unless otherwise indicated, “deaf” is used broadly here to refer to individuals with sufficient hearing loss to qualify for appropriate support services in school settings.

2 Whether or not self-report measures are valid indicators of individuals' skills in any particular domain is an empirical question. The self-report sign language and spoken language measures used in the present study have been validated in studies by Marschark et al. (2018) and Spencer et al. (2018).

3 Of tangential interest, a MANOVA using scores on the weight, length, volume, and distance dimensions on the units of measurement task as dependent variables yielded a significant effect of group only for volume, $F(2,90) = 4.43$, $p < .05$; Bonferroni-adjusted post-hoc tests indicated that the hearing participants outscored the CI users. The pattern was the same for all four dimensions, however, as hearing participants scored higher than deaf nonusers who scored higher than CI users.

The authors report no conflicts of interest.

investigation is mathematics (see Pagliaro, 2015, for a review). This paper examines students' numerical and non-numerical (real-world) quantity estimation skills and how they might be related to their knowledge of magnitude- and quantity-related vocabulary as well as several aspects of executive function and visual-spatial processing involved in mathematics. Also addressed here are deaf students' sign language abilities and use of cochlear implants (CIs), both of which can be seen as potentially enhancing their mathematics performance, though for different reasons (see below).

Difficulties in mathematics among deaf learners are well-documented from preschool (e.g., Kritzer, 2009; Pagliaro & Kritzer, 2013), through the school years (Ansell & Pagliaro, 2006; Blatto-Vallee, Kelly, Gaustad, Porter, & Fonzi, 2007; Kelly, Lang, & Pagliaro, 2003; Qi & Mitchell, 2012), and into postsecondary education (Blatto-Vallee et al., 2007; Lang & Pagliaro, 2007; Marschark, Morrison, Lukomski, Borgna, & Convertino, 2013). This is not an issue of there being some aspect of mathematics beyond the cognitive abilities of deaf learners. Nunes and colleagues (Nunes, in press; Nunes et al., 2008a, 2008b; Zarfaty, Nunes, & Bryant, 2004; see also Wauters & Dirks, in press) have shown that young deaf learners perform as well or better than hearing peers in several mathematics tasks when presented in ways emphasising the use of nonverbal, visuospatial skills rather than language (cf., Marschark, Paivio, et al., 2017). As learners become older, however, language comes to play a more important role in both mathematics learning and problem-solving, while academic benefits associated with early use of sign language and CIs decline (for a review, see Marschark & Knoors, in press).

Mathematics Performance, Sign Language, and Visual-Spatial Skills

Bauman and Murray (2010) suggested that because of its visuospatial qualities, sign language might be more beneficial than spoken language for explaining mathematical and scientific concepts to deaf learners. Aside from the fact that their example (demonstrating cell mitosis) involved gesture rather than sign language, there does not appear to be empirical evidence for such a link. Kritzer (2009) found lags in understanding number and quantity among deaf preschool children who had "at least good if not fluent exposure to [sign] language in the home" (p. 418), although deaf children with deaf parents performed better than those with hearing parents. Kritzer concluded that simple exposure to sign language might not be sufficient to ensure mathematical success for young deaf children, and that parent-child interactions including number and quantity might be more central (Wauters & Dirks, in press).

Considering older deaf learners, Marschark, Sapere, Convertino, and Seewagen (2005) and Marschark et al. (2013) failed to find significant associations between deaf college students' sign language skills and either their learning from signed mathematics lectures or their mathematics performance. National (U.S.) data drawn from the National Longitudinal Transition Study 2 (NLTS2) further indicate that using spoken language, but neither using sign language nor having deaf parents, is a significant predictor of mathematics achievement among deaf secondary school students (Marschark, Shaver, et al., 2015). Similar findings have been obtained in several other large-sample studies by Convertino, Marschark, Sapere,

Sarchet, and Zupan (2009), Crowe, Marschark, Dammeyer, and Lehane (2017), Dammeyer and Marschark (2016), and Geers, Tobey, Moog, and Brenner (2008).

Even if better mathematical performance cannot be linked directly to deaf students' sign language skills, there might be an association between mathematics performance and their visuospatial skills. For example, in seeking to explain possible sources of the benefits to signers' performance in mathematical tasks observed by Zarfaty et al. (2004), Pagliaro (2015, p. 183) suggested that "It may be, then, that for deaf learners, the geometry concepts and skills are developed sooner and/ or more quickly than those of other areas, perhaps influenced by their visual access to information."

Blatto-Vallee et al. (2007) found significant relations between visual-spatial skills and mathematics performance among deaf and hearing students from middle school to university (sign language skills were not evaluated). At all grade levels, however, hearing students demonstrated significantly greater visual-spatial and mathematics abilities than deaf students. Using seven different visual-spatial tasks, Marschark et al. (2013) also found visual-spatial skills significantly related to mathematics performance for both deaf and hearing college students. Deaf students' performance was significantly predicted by their scores on a visual construction task, whereas hearing students' performance was predicted by their scores on an embedded (hidden) figures task. Consistent with findings of Blatto-Vallee et al., the hearing students in the Marschark et al. study demonstrated significantly better mathematics abilities than their deaf peers and scored as well or better than the deaf students on all seven of the visual-spatial tasks. Deaf students who reported learning to sign later actually outscored those who reported learning to sign as young children on six of the seven visual-spatial tasks (cf., Bauman & Murray, 2010).

Mathematics Performance, Spoken Language, and Cochlear Implant Use

A variety of studies has documented early benefits of cochlear implantation to academic achievement among deaf children. As noted earlier, the academic benefits associated with early access to language through CIs have been found to decline or disappear by secondary school age (e.g., Convertino et al., 2009; Dammeyer & Marschark, 2016; Geers et al., 2008, Marschark, Shaver, et al., 2015). Most relevant studies, however, have focused on literacy, with few examining the long-term impact of CIs on achievement in other domains.

In an analysis of the NLTS2 data from secondary school students in the United States, Marschark, Shaver, et al. (2015) found that use of spoken language but not CI use was a significant predictor of mathematics, reading comprehension, social studies, and science among deaf secondary school students. Convertino et al. (2009) and Crowe et al. (2017) also failed to find CI use to be a predictor of mathematics ability among college-bound, deaf secondary school students as indicated by college entrance examination scores. Crowe et al. found students' self-rated spoken language skills the best predictor of reading and English test scores and a positive predictor of mathematics and science scores. Self-rated sign language skills were negative predictors of both mathematics and science scores.

Foundations of Mathematics Performance

Bull (2008) emphasised that for both deaf and hearing individuals, most mathematical performance depends on foundational skills including mental calculation, speed of number comparison, and estimation skills largely independent of language (see Bull, Marschark, & Blatto-Vallee, 2005; Convertino et al., 2014; Epstein, Hillegeist, & Grafman, 1994; Kritzer, 2009). Consistent with that suggestion, Bull, Blatto-Vallee, and Fabich (2006) found no difference between deaf signers and hearing nonsigners in their performance on a subitizing task involving dots presented in canonical (dice-like) or seemingly random, “skewed” presentations requiring two visual fixations. That finding indicated no difference in the automaticity of numerosity recognition (i.e., “how many?”) by deaf and hearing college students. Bull et al. (2006) also examined the extent to which deaf and hearing college students made use of an internal, visuospatial number line in representing approximate quantities. The use of an internal, analog number line has been well-documented in hearing children and adults, indicating that small magnitudes are associated with the left side of internal space, and large magnitudes are associated with the right side of internal space, the Spatial Numerical Association of Response Codes (or SNARC) effect. Bull et al. found similar performance of deaf and hearing college students on the SNARC task, leading to the conclusion “that there are no obvious differences between deaf and hearing participants in the visual–spatial representational format of magnitude information” (Bull et al., 2006, p. 299; see Marschark, Paivio, et al., 2017).

Bull, Marschark, and Blatto-Vallee (2005) examined activation of numerical information in deaf and hearing college students using relative number magnitude judgments (i.e., judging whether presented digits were greater or less than 5). The two groups were equally accurate in their judgments, but deaf students were significantly slower than hearing students. That finding replicated findings of Epstein et al. (1994), who explored relations among reading, magnitude comparison (i.e., judging which of two numbers was larger), and verification of arithmetic calculations among deaf and hearing college students. They did not find significant group differences in accuracy on either of the latter two tasks, but deaf students were slower than hearing students on both. Epstein et al. did not include information concerning deaf students’ sign language skills, but they found no differences between deaf students who had deaf family members (and thus would have been early if not native signers) and those who did not. Epstein et al. (1994, p. 338) did find a significant correlation between reading achievement and response times in magnitude comparisons, suggesting that such comparisons “may involve more of a verbal component than might be expected.”

Bull et al. (2011) examined another foundational mathematics skill, numerical estimation. Numerical estimation is an early-acquired, everyday mathematical skill involved in everything from knowing how many settings are needed at the dinner table to calculating the tip on a bar bill (Meijas, Mussolin, Rouselle, Gregoire, & Noel, 2012; Nunes, in press). Bull et al. assessed deaf and hearing college students’ numerical estimation skills using the Number-to-Position (NP) task (Siegler & Opfer, 2003), in which individuals were given number lines with the endpoints 0 and 1000 and had to indicate the estimated position of an intervening number (e.g., 6, 289, 874) on each one; performance was measured in terms of the accuracy of number placement. Bull et al. also administered the Numerical Operations

and Mathematical Reasoning subtests from the *Wechsler Individual Achievement Test* (WIAT-II), which assess arithmetical and mathematical reasoning. Hearing students significantly outperformed the deaf students on all three measures. Less accurate performance by deaf than hearing students on the NP task, in particular, indicated the former to have less precise representations of number, an impediment to numeric estimation (Bull, 2008).

More recently, Bull, Marschark, Nordmann, Sapere, and Skene (2017) examined numerical estimation skills among deaf and hearing 5- to 12-year-olds using a non-symbolic magnitude comparison task in which the children had to decide which of two arrays of dots contained more. Measures of mathematics achievement and verbal and visual-spatial working memory also were obtained. Overall, deaf children performed significantly more poorly than their hearing peers on the comparison/estimation task and the verbal working memory task; they also scored significantly lower on the Numerical Operations and Mathematical Reasoning subtests of the WIAT-II. Children who had fluent sign language skills and those who relied on spoken language performed significantly better on the Mathematical Reasoning subtest than those who had basic signing skills, but primary language modality was not related to estimation abilities. Significant correlations between estimation skills and performance on both WIAT-II subtests emphasised its fundamental role underlying mathematical abilities.

Masataka (2006) examined estimation abilities of deaf Japanese adults, all of whom had started to acquire Japanese Sign Language as their first language at the point of their hearing loss diagnoses. Masataka used three estimation tasks, one symbolic and two non-symbolic. One non-symbolic task involved comparing two arrays of dots (containing too many to count) and indicating which had more. The non-symbolic arithmetic estimation task asked participants to subtract a second-presented array of dots from a first-presented array, compare the result to a third array, and decide whether the third array had more or fewer dots than the second array. The symbolic arithmetic estimation task used the same numbers, but presented as Arabic numerals. Masataka found deaf participants equally accurate on the comparison task compared to hearing adults. In contrast to findings of Bull et al. (2017) with a sample of children who had diverse hearing losses and mixed language modalities, the deaf adults in the Masataka study were significantly more accurate than hearing adults on the non-symbolic arithmetic estimation task. However, the deaf adults were significantly less accurate on the symbolic equivalent. Masataka concluded that deaf individuals might have estimation skills comparable to hearing individuals when they can utilise visual-spatial skills, but less so when they have to access magnitude information via symbolic stimuli (Nunes, in press; Pagliaro, 2015; cf., Marschark, Paivio, et al., 2017).

Contrasting with Masataka's (2006) conclusion are findings from Convertino et al. (2014) who assessed magnitude estimation skills using real-world objects rather than dots or other meaningless stimuli. In that study, deaf and hearing college students made estimates of number, length, weight, and volume in a laboratory setting (e.g., How many toothpicks are in this [round clear] container? How much would this [5 gallon] water jug weigh if it was filled with water?). Hearing students were significantly more accurate than deaf students, with no difference between CI users and deaf nonusers. CI users who had received their devices earlier (< 3.5 years of age) were no more accurate than the deaf nonusers, but

performance was not examined as it related to sign language or spoken language skills. Estimation accuracy was related to mathematics achievement as indicated by the American College Test (ACT) mathematics subtest for both groups of deaf students.

The Present Study

Findings reviewed above suggest that while neither sign language nor CI use give older deaf learners any generalised advantage with regard to mathematics or the underlying skills examined in this study, visual-spatial abilities might. In addition to comparing estimation performance of CI users, deaf nonusers, and hearing individuals, all participants in this study therefore were administered two tasks addressing several dimensions of visual-spatial cognitive ability. One was the *General Ability Measure for Adults* (GAMA, Naglieri & Bardos, 1997) which taps several dimensions of nonverbal, visual-spatial reasoning likely to be associated with mathematics ability. In addition, participants completed four subscales of the *Learning, Executive, and Attention Functioning* (LEAF) scale (Kronenberger, Beer, et al., 2014; Castellanos, Kronenberger & Pisoni, 2016) that tap dimensions of executive function likely associated with mathematical and visual-spatial processing. This study also considered the possibility that part of deaf students' difficulties with regard to numerical and non-numerical estimation, as well as other mathematics-related tasks, might lie in their lesser familiarity with the units of measure that describe quantities and magnitudes. Convertino et al. (2014) observed a number of instances in which deaf students were unable to provide the appropriate units associated with their real-world estimates (e.g., "pounds," "inches"). Knowledge of associations between quantity/magnitude terms and properties of length, weight, distance, and volume was evaluated in the present study.

On the basis of research cited earlier involving deaf children, one would expect that CI users might be more familiar with English terms for units of measurement than nonusers who depend primarily on sign language. Evidence that academic advantages associated with CI use during the elementary school years largely dissipate by secondary school would suggest that such differences between CI users and deaf nonusers would be absent at this level.

If sign language truly provides deaf learners with better access to science and mathematics concepts than does spoken language, one might expect deaf college students who are skilled signers to demonstrate better numerical and non-numerical estimation abilities due to their having more frequent and effective experience with tasks requiring estimation. Several studies cited above, however, have indicated no support for the prediction of a significant association between sign language skills and mathematics performance, even if deaf learners' (and hearing learners') visual-spatial skills have been shown beneficial for mathematical performance (Blatto-Vallee et al., 2007; Marschark et al., 2013). Marschark, Paivio, et al. (2017) further found that despite results from previous studies indicating deaf individuals to demonstrate advantages in some visuospatial tasks (Cattani, Clibbens, & Perfect, 2007; Flaherty, 2003; Van Dijk, Klappers, & Postma, 2013a), deaf college students were no more likely than hearing college students to be visual learners (see also, López-Crespo, Daza, & Méndez-López, 2012; Van Dijk, Klappers, & Postma, 2013b). Possible interactions among mathematics-related estimation abilities and knowledge, language skills/

preferences, CI use, and executive function have not yet been explored and constitute the primary focus of this study.

Method

Participants

A total of 93 college students participated in this study. These included 30 hearing students, 33 deaf students who were current CI users, and 30 deaf students who did not use CIs (henceforth “nonusers”). Participants were recruited through posters and personal contact, and were paid for their participation. The CI users reported receiving their implants between the ages of 1 and 16 years with a mean of 6.03 years ($SD = 4.15$ years). This average age of implantation is relatively late by current standards, but it is representative of contemporary CI users in postsecondary education, because pediatric implantation was not as common as it is now when they were very young children (at least in the United States). Participants ranged in age from 17.7 to 23.5 years with a mean of 19 years ($SD = 1.20$); the CI users and deaf nonusers were not significantly different in age.

Materials and Procedure

All participants completed five tasks in the order they are described here; the deaf students also completed a brief communication questionnaire. The only timed test was the GAMA, which participants were given 25 minutes to complete. The GAMA is a nonverbal test that “evaluates an individual’s overall general ability with items that require the application of reasoning and logic to solve problems that exclusively use abstract designs and shapes” (Naglieri & Bardos, 1997, p. 1). It contains 66 items comprising four subscales. As described by Naglieri and Bardos, the Matching subtest, which involves selection of one of six figures that is identical to the target in color, shape, and configuration, requires detailed visual examination and comparison of the figures. The Analogy subtest requires recognition of parallel conceptual relationships between different pairs of figures and the selection of one of six figures that bears the same relationship to a target. The Sequences subtest requires individuals to attend to spatial and sequential arrangements of geometric figures and select one of six figures that completes a logical sequence of geometric designs. The Construction subtest involves selection of one of six figures showing how a set of shapes would appear if assembled, requiring analysis, synthesis, and rotation of the component shapes.

A one-page assessment of participants’ knowledge of units of measurement involved identifying terms associated with length, weight, volume and distance. Each property included a brief description of what it measures and a list of 15 different unit labels was provided (e.g., “*Weight*: how heavy someone or something is. Circle **all** units for weight: feet, pound, mile, inch, pint, kilometer, quart, meter, gallon, ounce, yard, ton, centimeter, liter, grams).

The present form of the NP task included 15 number lines with varying endpoints (smallest endpoints ranging from 0 to 110; largest endpoints ranging from 10 to 10,000). Participants had to estimate and indicate the location of one number (ranging from 6 to 7300) for each number line.

As indicated earlier, four dimensions of executive function were examined using the LEAF (Castellanos et al., 2016; Kronenberger et al., 2014). The LEAF is a questionnaire-based measure containing five questions each about 11 domains of executive function. For the present purposes, the four scales (20 questions) administered to participants were Visual-Spatial Organization (organization and visual-spatial skills), Sustained Sequential Processing (planning, following, and completing sustained tasks), Novel Problem-Solving (independent learning or problem-solving in new or unfamiliar situations), and Mathematics Skills (math and calculation). For each LEAF item, participants rated on a 4-point Likert scale, from “never” to “very often,” how often they had experiences or engaged in behaviours associated with one of the scales (e.g., “I have problems with puzzles or putting things together,” “I think math is hard”). The original LEAF was a parent-report measure. The present study used a language-revised, self-report version of the instrument designed and validated for use with deaf and hearing college students by Marschark, Kronenberger, et al. (2016).

The final task administered to all participants was the real-world estimation task in which participants were asked to estimate the weight, quantity, volume, length, and distance of objects at 10 stations around a laboratory (e.g., “How many pages are in this book?” “How many times would this piece of string go around the outside of that clock on the wall?”).

Deaf participants also completed a brief communication questionnaire. Participants rated their sign language comprehension using a self-report version of the Sign Language Proficiency Interview (SLPI; Rochester Institute of Technology, N.D.). They used a six-point Likert scale corresponding to SLPI rating system descriptors ranging from 0 (e.g., “I either do not know any sign, or I know very few basic signs and have to fingerspell most of my responses to basic questions signed to me”) to 5 (e.g., “I am a skilled signer and can easily understand someone signing to me”). They rated how well they understand spoken language and how well they understand simultaneous communication (SimCom) on 5-point scales from “nothing” to “everything people say.”² They also were asked to indicate their most effective form of communication by responding to the question “Overall, I understand information best through (select one):” Response choices were “sign language,” “spoken language,” and “speech and sign at the same time (SimCom).” Those participants who indicated that they were CI users were asked the age at which they received their first (or only) implant.

Institutional records indicated that most deaf students had taken the American College Test (ACT), whereas most hearing students had taken the SAT. ACT Mathematics scores were available for 41 of the 63 deaf students (21 CI users) and nine of the 30 hearing students. SAT Mathematics scores were available for 11 of the deaf students and 17 of the hearing students.

All participants provided written consent both for data collection proper and for access to their college entrance scores. This study and its methodology were approved by the university’s Institutional Review Board.

Scoring

The GAMA was scored according to the standard rubric (Naglieri & Bardos, 1997), yielding a percentage correct score for each of the four subtests (Matching, Analogy, Sequences, Construction). The NP task was scored in terms of the average deviation (in millimeters) between correct number positions and each participant's estimates of those positions, across the 15 trials. Convertino et al. (2014) scored their real-world, laboratory estimation task in terms of (a) the number of estimations exactly correct, (b) those within 10% of the correct answer, and (c) those within 20% of the correct answer. In fact, all three methods yielded the same results, and exactly correct answers and those within 10% of correct are extremely rare in this task. For the present purposes, therefore, scores on this task were simply the number of times (in 10 trials) each participant was within 20% of the correct answer. The units of measurement task was scored for percent correct. A score for each of the four LEAF scales was obtained by summing students' ratings across the five questions for each (Castellanos et al., 2016). Means and standard deviations for all tasks are provided in Table 1.

Results

Differences Among Groups

Preliminary analyses utilised one-way ANOVAs to examine between-group (CI users, nonusers, hearing) differences on the NP task, the units of measurement task, the real-world estimation task, and college entrance test scores in mathematics. MANOVAs were used to examine between-group differences on the multiple scales of the GAMA and LEAF. All and only those results significant at the .05 alpha level are reported here.

ANOVAs yielded main effects of group on both the NP task, $F(2,90) = 5.66, p < .01$, and the units of measurement task, $F(2,90) = 4.83, p < .01$. Bonferroni-adjusted post-hoc tests indicated that on the NP task, hearing students performed significantly better than both the CI users and the deaf nonusers, who did not differ significantly from each other. On the units of measurement task, the hearing participants significantly outscored the CI users, but there was no significant difference between the CI users and deaf nonusers.³ Analysis of scores on the real-world estimation task also yielded a main effect of group, $F(2,81) = 3.59, p < .05$. Bonferroni-adjusted post hoc tests indicated that the hearing participants were significantly more accurate than the CI users. Neither the hearing participants nor the CI users differed significantly from the nonusers (see Table 1).

MANOVA analyses indicated that there was not a significant effect of group on the GAMA, (Wilks' λ) $F(8,174) = 0.94$, but there was a marginal effect on the LEAF, (Wilks' λ) $F(8,174) = 1.87, p < .07$. Univariate ANOVAs indicated that the latter effect arose from the significant group effect for visual-spatial organization, $F(2,90) = 3.46, p < .05$. Bonferroni-adjusted post-hoc tests indicated that the CI users reported marginally fewer, $p = .055$, difficulties than the hearing participants in executive function related to visual-spatial organization.

Because of the limited overlap in deaf and hearing students' college entrance test scores in mathematics (ACT versus SAT), a comparison based on hearing status was not possible. However, the deaf CI users and nonusers did not differ significantly in their ACT

mathematics scores, $F(1,42) = 2.00$. An ANOVA involving the deaf participants' ACT mathematics scores as the dependent variable and the most effective mode of communication (sign language, spoken language, or both) as a between-subjects variable also failed to yield a significant difference of group, $F(2,41) = 1.36$.

Dividing deaf participants into groups according to their self-reported most effective form of communication—speech, sign, or SimCom—resulted in sample sizes of 15, 23, and 18, respectively. A second set of analyses involving the five task scores as dependent variables, parallel to those above but including only deaf participants, was conducted in which participants' most effective form of communication served as the between-subjects variable. Those analyses failed to yield significant differences related to mode of communication in numerical estimation (NP) task scores, $F(2,60) = 0.51$, their real-world estimation task scores, $F(2,60) = 2.36$, or their scores on the units of measurement task, $F(2,60) = 2.24$. The MANOVA involving LEAF scores failed to yield a significant effect of communication group overall. Tests of simple, between-subjects effects yielded a significant effect for Sequential Processing, $F(2,60) = 3.87$, $p < .05$. Bonferroni-adjusted post hoc tests indicated none of the differences between groups to be significant.

Predicting Estimation and Mathematical Abilities

Examination of possible predictors of participants' estimation abilities involved stepwise multiple regression analyses (probability of F entry .05; probability of removal .10), separately for deaf and hearing participants, alternately using NP task scores and real-world estimation task scores as criterion variables. Predictor variables included those two variables (when not criterion variables) as well as units of measurement task scores, the four LEAF scale scores, the four GAMA scale scores, and participants' college entrance mathematics test scores, where available (ACT for deaf students, SAT for hearing students). Analyses involving the deaf participants also included the several communication variables listed in Table 1. Because neither estimation task yielded significant differences between the CI users and the nonusers or among the three groups based on most effective mode of communication, regression analyses included all deaf participants as a single group, with CI use, age of implantation, and most effective mode of communication as additional predictor variables. Only those predictor variables accounting for significant proportions of variance in a regression equation are reported here.

Deaf participants' performance on the NP task was predicted by their ACT mathematics test scores, indicating better mathematical ability supporting more accurate numerical estimation, and their real-world estimation scores, reflecting a positive association between the two estimation tasks, $r(61) = .44$, $p < .001$ (see Table 2). Hearing participants' NP task scores were predicted by their GAMA Construction scores, and their SAT mathematics test scores, indicating that those hearing individuals with better visual analysis/synthesis skills and better mathematics abilities were more accurate in numerical estimation. Deaf participants' performance on the real-world estimation task was predicted solely by their NP task, again reflecting the positive association between the two estimation tasks. There were no significant predictors of hearing students' performance on the real-world estimation task

(see Table 2). In particular, although the two estimation tasks were significantly related for the deaf students, they were not for the hearing students, $r(28) = .26$, $p = .16$.

Stepwise multiple regression analyses also were used to examine possible predictors of participants' college entrance mathematics test scores. Among the deaf participants, ACT mathematics scores were predicted (positively) by their GAMA Construction scores. Hearing students' SAT mathematics test scores were significantly predicted by their NP task scores, their GAMA Matching scores, their LEAF Problem Solving scores, their GAMA Construction scores, and LEAF Mathematics scores (see Table 3).

Discussion, Conclusions and Limitations

The present study examined deaf and hearing college students' numerical and real-world estimation abilities and possible relations to mathematical achievement more broadly (i.e., indicated by college entrance test scores in mathematics) and several mathematics-related cognitive variables: visual-spatial processing (GAMA), aspects of executive function related to visual-spatial processing and mathematics (LEAF), and knowledge of magnitude/quantity descriptive terms. Consistent with findings from previous studies by Bull, Marschark, and colleagues with both children and college students, hearing participants in the present study generally demonstrated better numerical and real-world estimation skills than their deaf peers. As described by Bull (2008), Pagliaro (2015), and Nunes (in press) such differences are likely to have an impact on daily living and incidental and academic learning, including mathematics achievement. The present results thus emphasize the need for establishing a wider base of strengths among deaf learners in cognitive abilities such as estimation and executive function which likely would improve mathematics abilities as well as the practical application of related skills in day-to-day living. Skills such as real-world or number line estimation may appear to be visual tasks, but could also be related to language experience gained through discussion with parents, teachers, and peers (e.g., queueing up in order of height, sharing candies with siblings or peers; Nunes, in press).

In more general terms, the present results suggest that compared to their hearing peers, deaf college students, as a group, may be more limited in some of their fundamental, mathematics-related abilities, as described by Bull (2008). With regard to college entrance examination scores in mathematics—a standardised achievement test—deaf participants' scores were associated only with better visual analysis/synthesis skills, while hearing participants' scores had a much broader base in foundational skills. The former result largely replicates the finding of Marschark et al. (2013), who found that deaf students' performance in solving ACT mathematics problems containing diagrams was predicted only by their score on a mental construction task similar to the GAMA Construction items. Mathematics entrance scores of hearing students in the present study reflected better numerical estimation skills, better visual examination and comparison skills but lesser reliance on visual analysis/synthesis skills, with more executive function difficulties associated with problem-solving but fewer difficulties associated with mathematics per se. These results therefore appear consistent with the conclusion of Marschark et al. (2013, p. 161) that “deaf students rely more on visual–spatial skills in mathematical problem-solving while hearing students utilise other cognitive processes as well as, or instead of, their visual–spatial abilities.” That

conclusion also appears consistent with the present finding that the numerical (abstract) and non-numerical (concrete) estimation task scores were significantly associated for deaf but not hearing students.

Taken together, the present findings extend those of Marschark, Paivio, et al. (2017) demonstrating that deaf individuals are no more likely to be visual learners than hearing individuals, even if they do demonstrate advantages with regard to some aspects of visuospatial processing (Blatto-Vallee et al., 2007; Cattani et al., 2007; Flaherty, 2003; López-Crespo et al., 2012; Marschark, Spencer, et al., 2015; Van Dijk et al., 2013a; but see Van Dijk et al., 2013b). The findings also are consistent with results of several studies described above indicating that when typical samples of deaf individuals are evaluated (as opposed to studies involving only native signers), deaf learners do not demonstrate any consistent advantage over hearing learners on a variety of visual-spatial tasks, nor do deaf learners who use sign language demonstrate an advantage over those who use spoken language on those tasks (Blatto-Vallee et al., 2007; López-Crespo et al., 2012; Marschark et al., 2013; Marschark, Spencer, et al., 2015).

As described earlier, there is accumulating evidence indicating that benefits to academic achievement during the early school years associated with CI use are attenuated or absent by secondary school age (e.g., Geers et al., 2008; Marschark, Shaver et al., 2015; for a review see Knoors & Marschark, in press). Consistent with such findings, results indicated that CI users and nonusers did not differ in their mathematics abilities as indicated by ACT scores in mathematics, or any other area for that matter. In fact, deaf nonusers performed better, if not significantly so, than CI users on both the numerical and real-world estimation tasks as well as the units of measurement task. There may be longer-term academic advantages for deaf individuals who receive CIs at much younger ages than the participants in the present study, and deaf children in many countries now are receiving CIs at one year of age or even younger. The ages of implantation of participants in the present study were relatively late by current standards, although they accurately reflect the current cohort of college-aged students. However, the fact that age of implantation was not a significant predictor in any of the multiple regression analyses suggests that while that variable may be a relatively important predictor of abilities among young CI users, its potency as a predictor of academic achievement is reduced over the longer-term, as is CI use more broadly.

Similarly, several studies have found young deaf children who have early access to sign language from their deaf parents to demonstrate better reading ability than deaf children of hearing parents, and there is some limited evidence of better reading abilities among younger deaf children educated in bilingual (sign language and spoken/written language) education programs (e.g., Lange, Lane-Outlaw, Lange, & Sherwood, 2013; for a review, see Marschark & Knoors, in press). In both cases, however, studies have focused on deaf children of elementary- and middle school-age, while investigations involving deaf secondary and college students generally have failed to find such advantages. The present study revealed no significant differences in ACT scores, estimation abilities, or knowledge of measurement terminology among deaf participants who indicated that sign language, spoken language, or simultaneous communication (SimCom) was their best form of communication for information access. There is no doubt that individual deaf learners will

benefit more from one mode of communication or another at different points during their educational careers. However, by secondary school and college, earlier group differences linked to their primary mode of communication are no longer apparent. Marschark and Knoors (in press) have described a number of possible reasons for this change relating both to the content, demands, and goals of primary versus secondary/college education and to changing language and cognitive abilities and needs of deaf learners.

One limitation of the present study was the lack of either objective assessments of sign language ability or information about whether any of the deaf participants were native signers. With regard to the former issue, recent studies have indicated that deaf college students' self-ratings of their sign language and spoken language skills usually are correlated with results of objective assessments, even if they sometimes overestimate those skills (Marschark, Machmer, et al., 2018; Spencer et al., 2018). With regard to the latter issue, several studies involving deaf college students have failed to find any advantage in either classroom learning or standardized achievement testing for earlier or native-signing deaf learners over later learners (e.g., Convertino et al., 2009; Crowe et al., 2017; Marschark, Shaver, et al. 2015; Marschark, Spencer, et al. 2015). Native signers (i.e., those with deaf parents) comprise only about 3–5% of the deaf population (Mitchell & Karchmer, 2004). We are unaware of any study that has demonstrated such a difference among secondary or postsecondary deaf learners, and empirical evaluations of the impact on mathematics performance and achievement of different levels of sign language and spoken language skills at different points in time, and ideally longitudinally, remain to be conducted.

The finding of better mathematics abilities by hearing learners compared to deaf learners is neither new nor surprising. Importantly, all of the participants in the present study were sufficiently skilled to gain entrance to university, so the issue here is one of relative differences rather than any all-or-none distinction. The important point is that educators and investigators need to avoid generalisations about academic functioning among deaf learners based on studies of narrowly-selected samples of native signers, successful CI users, or students in a particular educational program. Moreover, results of the present study and the accumulating evidence described earlier clearly indicate that generalisations about older deaf learners, those of secondary school age and beyond, should not be made on the basis of studies involving young deaf children. There are many differences between younger and older deaf learners and our expectations for them, and some of those (yet to be determined) differences appear to have significant impact on performance in the classroom and on standardised achievement tests. The goal should be to identify such differences so that we can build on the strengths of deaf learners and accommodate their needs. Strengths, needs, and academic demands change with age and school setting. Whether the issue is reading comprehension, performance in mathematics classes, or the application of estimation abilities in the real world, deaf students are not simply “hearing students who can’t hear.” Teachers—and deaf students themselves—need to be aware of when and how they learn differently from hearing students if they are to benefit fully from formal and informal educational opportunities.

Acknowledgments

Funding:

This research was supported by grant R01DC012317 from the National Institute on Deafness and Other Communication Disorders. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of NIDCD or NTID.

References

- Ansell E, & Pagliaro CM (2006). The relative difficulty of signed arithmetic story problems for primary level deaf and hard-of-hearing students. *Journal of Deaf Studies and Deaf Education*, 11, 153–170. doi:10.1093/deafed/enj030 [PubMed: 16469969]
- Bauman H-DL, & Murray JJ (2010). Deaf Studies in the twenty-first century: “Deaf-gain” and the future of human diversity In Marschark M & Spencer PE (Eds.), *The Oxford handbook of deaf studies, language, and education*, volume 2 (pp. 210–225). New York, NY: Oxford University Press.
- Blatto-Vallee G, Kelly RR, Gaustad MG, Porter J, & Fonzi J (2007). Visual-spatial representation in mathematical problem-solving by deaf and hearing students. *Journal of Deaf Studies and Deaf Education*, 12, 432–448. doi:10.1093/deafed/enm022 [PubMed: 17548803]
- Bull R (2008). Deafness, numerical cognition, and mathematics In Marschark M, & Hauser P (Eds.), *Deaf cognition: Foundations and outcomes* (pp. 170–200). New York: Oxford University Press.
- Bull R, Blatto-Vallee G, Fabich M (2006). Subitizing, magnitude representation, and magnitude retrieval in deaf and hearing adults. *Journal of Deaf Studies and Deaf Education*, 11, 289–302. doi:10.1093/deafed/enj038 [PubMed: 16601145]
- Bull R, Marschark M, & Blatto-Vallee G (2005). SNARC hunting: Examining number representation in deaf students. *Learning and Individual Differences*, 15, 223–236. doi:10.1016/j.lindif.2005.01.004
- Bull R, Marschark M, Nordmann E, Sapere P, and Skene WA (2017). The approximate number system and domain-general abilities as predictors of math ability in children with normal hearing and hearing loss. *British Journal of Developmental Psychology*. Advance online. doi:10.1111/bjdp.12204
- Bull R, Marschark M, Sapere P, Davidson W, Murphy D, & Nordmann E (2011). Numerical estimation in deaf and hearing adults. *Learning and Individual Differences*, 21, 453–457. doi:10.1016/j.lindif.2011.02.001 [PubMed: 21822363]
- Castellanos I, Kronenberger WG, & Pisoni DB (2016). Questionnaire-based assessment of executive functioning: Psychometrics. *Applied Neuropsychology: Child*. Advance online publication. doi:10.1080/21622965.2016.1248557
- Cattani A, Clibbens J & Perfect TJ (2007). Visual memory for shapes in deaf signers and nonsigners and in hearing signers and nonsigners: Atypical lateralization and enhancement. *Neuropsychology*, 21, 114–121. doi: 10.1037/0894-4105.21.1.114 [PubMed: 17201534]
- Convertino CM, Borgna G, Marschark M, & Durkin A (2014). Word and world knowledge among deaf students with and without cochlear implants. *Journal of Deaf Studies and Deaf Education*, 19, 471–483. doi:10.1093/deafed/enu024 [PubMed: 25145461]
- Convertino CM, Marschark M, Sapere P, Sarchet T, & Zupan M (2009). Predicting academic success among deaf college students. *Journal of Deaf Studies and Deaf Education*, 14, 324–343. doi:10.1093/deafed/enp005 [PubMed: 19357242]
- Crowe K, Marschark M, Dammeyer J, & Lehane C, & Marschark M (2017). Achievement, language, and technology use among college-bound deaf learners. *Journal of Deaf Studies and Deaf Education*. Advance online. doi:10.1093/deafed/enx029
- Dammeyer J & Marschark M (2016). Level of educational attainment among deaf adults who attended bilingual-bicultural programs. *Journal of Deaf Studies and Deaf Education*, 21, 394–402. doi:10.1093/deafed/enw036 [PubMed: 27235699]
- Easterbrooks SR & Beal-Alvarez J (2013). *Literacy instruction for students who are deaf and hard of hearing*. New York: Oxford University Press.

- Epstein KI, Hillegeist EG, & Grafman J (1994). Number processing in deaf college students. *American Annals of the Deaf*, 139, 336–347. [PubMed: 7992779]
- Flaherty M (2003). Sign language and Chinese characters on visual-spatial memory: A literature review. *Perceptual and Motor Skills*, 97(3), pt. 1, 797–802. doi:10.2466/pms.2003.97.3.797 [PubMed: 14738343]
- Geers A, Tobey E, Moog J, & Brenner C (2008). Long-term outcomes of cochlear implantation in the preschool years: From elementary grades to secondary school. *International Journal of Audiology*, 47 (Supplement 2), S21–S30. doi: 10.1080/14992020802339167 [PubMed: 19012109]
- Kelly R, Lang H, & Pagliaro C (2003). Mathematics word problem solving for deaf students: A survey of practices in grades 6–12. *Journal of Deaf Studies and Deaf Education*, 8, 104–119. doi: 10.1093/deafed/eng007 [PubMed: 15448061]
- Kritzer KL (2009). Families with young deaf children and the mediation of mathematically based concepts within a naturalistic environment. *American Annals of the Deaf*, 153(5), 474–483. [PubMed: 19350955]
- Kronenberger WG, Beer J, Castellanos I, Pisoni DB, & Miyamoto RT (2014). Neurocognitive risk in children with cochlear implants. *JAMA Otolaryngology-- Head & Neck Surgery*, 140 (7), 608–615. doi: 10.1001/jamaoto.2014.757 [PubMed: 24854882]
- Lange CM, Lane-Outlaw S, Lange WE, & Sherwood DL (2013). American Sign Language/English bilingual model: A longitudinal study of academic growth. *Journal of Deaf Studies and Deaf Education*, 18, 532–544. doi: 10.1093/deafed/ent027 [PubMed: 23741074]
- López-Crespo GA, Daza MT, & Méndez- López M (2012). Visual working memory in deaf children with diverse communication modes: Improvement by differential outcomes. *Research in Developmental Disabilities*, 33, 362–368. [PubMed: 22119682]
- Marschark M & Knoors H (in press). Sleuthing the 93% solution in deaf education In Knoors H & Marschark M (Eds.), *Evidence-based practice in deaf education*. New York, NY: Oxford University Press.
- Marschark M, Kronenberger WG, Rosica M, Borgna G, Convertino C, Durkin A, Machmer E, Schmitz KL (2016). Social maturity and executive function among deaf learners. *Journal of Deaf Studies and Deaf Education*, 22, 22–34. doi:10.1093/deafed/enw057 [PubMed: 27686092]
- Marschark M, Machmer E, Spencer L, Borgna G, Durkin A & Convertino C (2018). Language and psychosocial functioning among deaf learners with and without cochlear implants. *Journal of Deaf Studies and Deaf Education*, 23, 28–40. doi:10.1093/deafed/enx035 [PubMed: 28977414]
- Marschark M, Morrison C, Lukowski J, Borgna G, & Convertino C (2013). Are deaf students visual learners? *Learning and Individual Differences*, 25, 156–162. doi:10.1016/j.lindif.2013.02.006 [PubMed: 23750095]
- Marschark M, Paivio A, Spencer LJ, Durkin A, Borgna G, Convertino V, & Machmer E (2017). Don't assume deaf students are visual learners. *Journal of Physical and Developmental Disabilities*, 29, 153–171. doi: 10.1007/s10882-016-9494-0
- Marschark M, Sapere P, Convertino C, & Seewagen R (2005). Access to postsecondary education through sign language interpreting. *Journal of Deaf Studies and Deaf Education*, 10, 38–50. doi: 10.1093/deafed/eni002 [PubMed: 15585747]
- Marschark M, Shaver DM, Nagle K, & Newman L (2015). Predicting the academic achievement of deaf and hard-of-hearing students from individual, household, communication, and educational factors. *Exceptional Children*, 8, 350–369. doi: 10.1177/0014402914563700
- Marschark M, Spencer L, Durkin A, Borgna G, Convertino C, Machmer E, Kronenberger WG, & Trani A (2015). Understanding language, hearing status, and visual-spatial skills. *Journal of Deaf Studies and Deaf Education*, 20, 310–330. doi:10.1093/deafed/env025 [PubMed: 26141071]
- Masataka N (2006). Differences in arithmetical subtraction of nonsymbolic numerosities by deaf and hearing adults. *Journal of Deaf Studies and Deaf Education*, 11, 139–143. [PubMed: 16306180]
- Meijas S, Mussolin C, Rouselle L, Gregoire J, & Noel M-P (2012). Numerical and non-numerical estimation in children with and without mathematical learning difficulties. *Child Neuropsychology*, 18, 550–575. doi:10.1016/j.lindif.2011.09.013 [PubMed: 22117818]

- Mitchell RE, & Karchmer MA (2004). Chasing the mythical ten percent: Parental hearing status of deaf and hard-of-hearing students in the United States. *Sign Language Studies*, 4, 138–163. doi: 10.1353/sls.2004.0005
- Naglieri JA & Bardos AN (1997). *General Ability Measure for Adults*. San Antonio, TX: Pearson.
- Nunes T (in press). Thinking in action and beyond In Knoors H & Marschark M (Eds.), *Evidence-based practice in deaf education*. New York, NY: Oxford University Press.
- Nunes T, Bryant P, Burman D, Bell D, Evans D, & Hallett D (2008a). Deaf children's informal knowledge of multiplicative reasoning. *Journal of Deaf Studies and Deaf Education*, 14, 260–277. doi: 10.1093/deafed/enn040 [PubMed: 18948568]
- Nunes T, Bryant P, Burman D, Bell D, Evans D, Hallett D, & Montgomery L (2008b). Deaf children's understanding of inverse relations In Marschark M & Hauser PC (Ed.), *Deaf cognition* (pp. 201–225). New York: Oxford University Press.
- Pagliaro CM (2015). Developing numeracy in individuals who are deaf and hard of hearing educating deaf students in a global context In Knoors H & Marschark M (Eds.), *Educating deaf learners: Creating a global evidence base* (pp. 173–195). New York, NY: Oxford University Press.
- Pagliaro CM & Kritzer KL (2013). The math gap: A description of the mathematics performance of preschool-aged deaf/hard-of-hearing children. *Journal of Deaf Studies and Deaf Education*, 18(2), 139–160. [PubMed: 23307889]
- Qi S, & Mitchell RE (2012). Large-scale academic achievement testing of deaf and hard-of-hearing students: Past, present, and future. *Journal of Deaf Studies and Deaf Education*, 17, 1–18. doi: 10.1093/deafed/enr028 [PubMed: 21712463]
- Rochester Institute of Technology (N.D.). The SLPI at the National Technical Institute for the Deaf. Retrieved 17 January 2018 from <https://www.rit.edu/ntid/slpi/>.
- Siegler RS, & Opfer JE (2003). The development of numerical estimation: Evidence for multiple representations of numerical quantity. *Psychological Science*, 14, 237–243. [PubMed: 12741747]
- Spencer L, Marschark M, Machmer E, Borgna G, Convertino C & Durkin A (2018). Communication skills of deaf and hard-of-hearing college students: Objective measures and self-assessment. Manuscript under review.
- Van Dijk R, Klappers AML, & Postma A (2013a). Superior spatial touch: Improved haptic orientation processing in deaf individuals. *Experimental Brain Research*, 230, 283–289. doi 10.1007/s00221-013-3653-7 [PubMed: 23897133]
- Van Dijk R, Klappers AML, & Postma A (2013b). Haptic spatial configuration learning in deaf and hearing individuals. *PLoS ONE*, 8, e61336. doi: 10.1371/journal.pone.0062374 [PubMed: 23593465]
- Wauters L & Dirks E (in press). Parents count: Enhancing early math skills of young deaf and hard-of-hearing children in the home environment In Knoors H & Marschark M (Eds.), *Evidence-based practice in deaf education*. New York, NY: Oxford University Press.
- Zarfaty Y, Nunes T, & Bryant P (2004). The performance of young deaf children in spatial and temporal number tasks. *Journal of Deaf Studies and Deaf Education*, 9, 315–326. doi: 10.1093/deafed/enh034 [PubMed: 15304434]

Table 1.

Means and standard deviations for task scores and communication variables

	CI Users		Deaf Nonusers		Hearing	
	Mean	SD	Mean	SD	Mean	SD
Real-world Estimation Task (#)	1.80	1.08	2.39	1.64	2.83	1.40
NP Task, Deviation (mm) *	9.96	5.34	9.98	5.26	6.54	2.58
Units of Measurement (%)	.70	.17	.77	.20	.83	.12
GAMA Matching (%)	.82	.13	.81	.16	.86	.13
GAMA Analogy (%)	.73	.12	.72	.14	.78	.09
GAMA Sequences (%)	.51	.14	.47	.15	.54	.20
GAMA Construction (%)	.43	.13	.45	.15	.50	.167
LEAF Visual-Spatial Organization †	3.67	2.24	3.83	1.69	5.00	2.48
LEAF Sequential Processing	3.87	2.18	3.79	1.60	3.43	1.65
LEAF Problem Solving	3.20	2.22	2.56	1.64	2.87	1.61
LEAF Mathematics	5.63	3.88	5.33	3.57	4.33	3.59
Mathematics College Entrance Score	19.00	3.74	19.50	4.69	584.12	93.28
Age of Implantation	5.87	3.88				
Sign Comprehension	3.50	1.28	3.97	1.38		
Speech Comprehension	2.77	.68	1.75	1.12		
SimCom Comprehension	3.23	.68	2.72	.96		

* Higher deviation scores reflect less accurate estimation.

† LEAF scores are summed over five questions per scale. Higher scores indicate greater executive function difficulty.

ACT scores for deaf participants; SAT scores for hearing participants (see text).

Table 2

Regression results predicting numeric (NP) and non-numeric (real-world) estimation scores

	Deaf				Hearing			
	Model 1		Model 2		Model 1		Model 2	
NP Task	β	<i>SE</i>	β	<i>SE</i>	β	<i>SE</i>	β	<i>SE</i>
ACT Math	-0.46	0.25	-0.46	0.15				
Real-world Estimation			0.23	0.36				
GAMA Construction					-0.57	3.29	-.053	2.79
SAT Math							-0.48	0.01
Model summary								
<i>F</i>	5.26 *		6.11 **		7.17 *		8.51 *	
(Degrees of freedom)	1, 19		2, 18		1, 15		2, 14	
<i>F</i> change			5.66				6.99	
(Degrees of freedom)			1, 18				1, 14	
<i>R</i> ²	.22		.40		.32		.55	
<i>R</i> ² change			.19				.25	
Real-World Task	Model 1							
	β	<i>SE</i>						
NP Estimation	0.44 *	0.07						
Model summary								
<i>F</i>	4.46							
(Degrees of freedom)	1, 19							
<i>F</i> change								
(Degrees of freedom)								
<i>R</i> ²	.19							
<i>R</i> ² change								

*
 $p < .05$ **
 $p < .01$

Regression model results predicting composite ACT (deaf students) and SAT (hearing students) scores

Table 3

ACT Math (Deaf Students)	Model 1		Model 2		Model 3		Model 4		Model 5	
	β	SE								
GAMA Construction	0.49	5.85								
Model summary										
<i>F</i>	6.08*									
(Degrees of freedom)	1, 19									
<i>F</i> change										
(Degrees of freedom)										
<i>R</i> ²	.49									
<i>R</i> ² change										
SAT Math (Hearing Students)	Model 1		Model 2		Model 3		Model 4		Model 5	
	β	SE	β	SE	β	SE	β	SE	β	SE
NP Estimation	-0.52	7.97	-0.48	6.92	-0.50	6.15	-0.76	6.24	-0.64	5.08
GAMA Matching			0.47	133.12	0.43	118.76	0.47	99.21	0.55	79.77
LEAF Problem Solving					0.37	9.89	0.42	8.29	0.43	6.46
GAMA Construction							-0.46	97.37	-0.46	75.91
LEAF Numeric									-0.36	3.13
Model summary										
<i>F</i>	5.48*		6.64**		7.21**		9.53**		14.30**	
(Degrees of freedom)	1, 15		2, 14		3, 13		4, 12		5, 11	
<i>F</i> change			5.98		4.78		6.81		8.75	
(Degrees of freedom)			1, 14		1, 13		1, 12		1, 11	
<i>R</i> ²	.27		.49		.62		.76		.87	
<i>R</i> ² change			.22		.14		.14		.11	

* $p < .05$ ** $p < .01$