Learning and Individual Differences 32 (2014) 246–253

Contents lists available at ScienceDirect

Learning and Individual Differences

journal homepage: www.elsevier.com/locate/lindif

Deaf signers use phonology to do arithmetic

Josefine Andin *, Jerker Rönnberg, Mary Rudner

Linnaeus Centre HEAD, Swedish Institute for Disability Research, Department of Behavioural Sciences and Learning, Linköping University, SE-581 83 Linköping, Sweden

ARTICLE INFO

Article history:
Received 22 April 2013
Received in revised form 16 January 2014
Accepted 20 March 2014

Keywords:
Deaf signers
Arithmetic
Phonology

ABSTRACT

Deaf students generally lag several years behind hearing peers in arithmetic, but little is known about the mechanisms behind this. In the present study we investigated how phonological skills interact with arithmetic. Eighteen deaf signers and eighteen hearing non-signers took part in an experiment that manipulated arithmetic and phonological knowledge in the language modalities of sign and speech. Independent tests of alphabetical and native language phonological skills were also administered. There was no difference in performance between groups on subtraction, but hearing non-signers performed better than deaf signers on multiplication. For the deaf signers but not the hearing non-signers, multiplicative reasoning was associated with both alphabetical and phonological skills. This indicates that deaf signing adults rely on language processes to solve multiplication tasks, possibly because automatization of multiplication is less well established in deaf adults.

1. Introduction

Deaf students generally lag several years behind hearing peers in arithmetic (e.g. Traxler, 2000), a delay that has been shown to occur even before formal schooling starts (Kritzer, 2009) and persist throughout adulthood (Bull et al., 2011). However, there are no differences in general cognitive ability that can explain this. Recent work has demonstrated a link between sign language skills and reading ability in deaf signers (Mayberry, del Giudice, & Lieberman, 2011; Rudner et al., 2012) indicating that native language skills may support academic achievement in general. In this study we investigate the relation between phonology and arithmetic.

Whereas phonological skill refers to the ability to process the sublexical structure of language, arithmetic skill refers to the ability to combine numbers. Simple arithmetic refers to operations of addition, subtraction, multiplication and division with smaller values of numbers. Generally, the same components of arithmetical processing cause problems for both hearing and deaf students (Norell, 1998), but there are several areas in which differences between the groups can be seen. Hearing non-signers perform better than deaf signers on relational statements, including expressions such as *less than*, *more than* and *four times as many as* (Kelly, Lang, Mousley, & Davis, 2003; Serrano Pau, 1995), arithmetic word problems that require reading a text in which the arithmetic problem is stated (Hyde, Zevenbergen, & Power, 2003), fractions (Titus, 1995) and multiplicative reasoning (Nunes et al., 2009). On the other hand, deaf children outperform hearing children on problems that involve spatial arrays of figures (Zarfaty, Nunes, & Bryant, 2004). Simple arithmetic is related to linguistic ability in the form of phonological skills, at least for hearing individuals (De Smedt, Taylor, Archibald, & Ansari, 2010). Many of the mathematical domains that are identified as problematic for deaf individuals are related to linguistic abilities, and relational statements as well as arithmetic word problems are related to reading skills (Serrano Pau, 1995). It is possible that the use of phonological abilities in simple arithmetic processing differs between deaf and hearing persons. If so, this might help explain the performance differences in simple arithmetic between the two groups. The overall aim of this study is to investigate the relations between simple arithmetic and first language phonological skills in adult deaf signers and hearing non-signers.

1.1. Sign language phonology

Development of phonological skills is closely related to access to language during childhood, irrespective of whether that language is speech or sign based (Mayberry & Lock, 2003). Sign languages are visual, natural and fully fledged languages with their own vocabulary and grammar used in deaf communities (for a review see Emmorey, 2002). Sign languages are produced manually and perceived visually, in contrast to spoken languages which are produced orally and perceived audio-acoustically. Otherwise, sign languages are fully comparable to spoken languages and can be described using the same linguistic terms as spoken languages, which means that sign languages possess phonology, morphology, syntax and prosody (Emmorey, 2002; Klima & Bellugi, 1976; Sandler & Lillo-Martin, 2006). Although sign languages are not representations of either spoken or written language, sign languages make use of manual alphabets (fingerspelling) to represent letters and

* Corresponding author at: Linköping University, SE-581 83 Linköping, Sweden. Tel.: +46 13 282165; fax: +46 13 282145.
E-mail addresses: josefine.andin@liu.se (J. Andin), jerker.ronnberg@liu.se (J. Rönnberg), mary.rudner@liu.se (M. Rudner).

http://dx.doi.org/10.1016/j.lindif.2014.03.015

orthography when producing e.g. place names or proper names. In Swedish Sign Language (SSL) there is a substantial overlap between the phonologies of the manual alphabet, manual numerals and word signs, particularly as regards handshape, although the manual alphabet and manual numerals display less movement and diversity of location compared to word signs (Bergman, 2012). Sign languages differ considerably in regard to the extent to which fingerspelling is used. For example, in American sign language (ASL) fingerspelling is used extensively and constitutes up to 35% of signed discourse, whereas in Italian Sign Language (LIS) fingerspelling is used very sparsely (Morere & Roberts, 2012; Padden & Gunsauls, 2003). SSL, which is in focus in the present study, has a one-handed manual alphabet and resembles ASL in its extensive use of fingerspelled words and signs (Padden & Gunsauls, 2003). In SSL, fingerspelling can be used for proper names and foreign words, to describe how a word is spelled and to fill lexical gaps. Furthermore, fingerspelling is used in 'fingerspelled signs', which are loan words from Swedish that have been incorporated in the SSL vocabulary (Bergman & Wikström, 1981). SSL fingerspelled signs may comprise either all the letters of the Swedish word or only its consonants, demonstrating just how morphologically different they are from word signs. Sometimes the fingerspelled sign does not have the same function in SSL as the original word has in Swedish, e.g. a loan word that is a noun in Swedish can be a verb in SSL. Despite morphological differences, these fingerspelled signs are used as regular lexical signs and can be inflected in the same way as other lexical signs in SSL. Because fingerspelled signs are extensively used in SSL, native deaf children encounter fingerspelling explicitly and the manual alphabet implicitly early in their language development, probably many years before their hearing peers start to bother about letters (Bergman, 2012). In the present study we focus on the phonological feature of handshape where the overlap of the manual alphabet, manual numerals and sign words is at its greatest.

Phonology can be defined as the level of linguistic structure that organizes the medium through which language is transmitted (Sandler & Lillo-Martin, 2006). Thus, for spoken languages, phonology can be described as the combination of sounds to form utterances. For signed languages, phonology refers to how components of the signs are put together with respect to handshape, orientation, location and movement (Sandler & Lillo-Martin, 2006). Signs that share at least one of these features are thus considered to be phonologically similar (Klima & Bellugi, 1976; Sandler & Lillo-Martin, 2006). In SSL this can be exemplified by the manual numeral for the digit "6" and the fingerspelled letters "B" and "Q" (Fig. 1). These three hand configurations all share the same handshape and are thus considered to be phonologically similar, despite the fact that the orientation of the hand configuration for "Q" is different from that of the two others. Despite the differences in the surface description of phonology for speech and sign, it can be described in the same terms at a theoretical level. Phonology is used in similar ways in spoken and in signed language, e.g. it is the basis of poetry (Klima & Bellugi, 1976; Sutton-Spence, 2001) and nursery rhymes (Blondel & Miller, 2001). Further, the processing of sign-based and

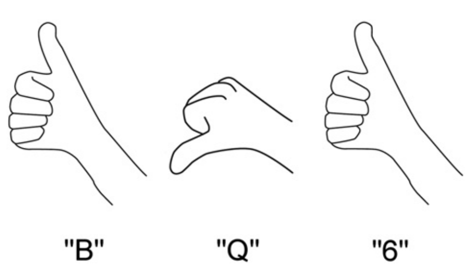

Fig. 1. Sign language phonology. Fingerspelled letters B, and Q and the manual numeral for the digit 6 share the same handshape, and Q is distinguished from the two others by a different orientation. The three signs are all phonologically similar.

speech-based phonology appears to be supported by generally similar neural networks in left hemisphere language areas (MacSweeney, Waters, Brammer, Woll, & Goswami, 2008). MacSweeney et al. (2008) used a picture-based phonological task that involved accessing either the English or British Sign Language (BSL) lexical labels of picture pairs and judging whether the English words rhymed and whether the signs shared a location. Despite the general similarity of the neural activation patterns for BSL and English in deaf and hearing signers and hearing non-signers, some differences were identified. Similarly, in a study investigating the neural correlates of processing phonology in a working memory context it was found that despite overall similarities across modalities, there were significant differences (Rudner, Karlsson, Gunnarsson, & Rönnberg, 2013). In the study by Rudner et al. (2013), phonological similarity in sign language was based on handshape. Behavioural results suggest that a closer relationship between semantics and phonology in signed compared to speech-based languages may influence the functional role of phonology in cognitive processing (Marshall, Rowley, & Atkinsson, 2013; Vigliocco, Vinson, Woolfe, Dye, & Woll, 2005). For example, during a sign-based phonological fluency task, adult deaf signers displayed particularly rich clustering of items according to both semantics and phonology (Marshall et al., 2013).

1.2. Arithmetic and language

Success in mathematics requires a wide range of abilities ranging from lower level arithmetical skills to linguistic skills, especially reading skills (Bull, Blatto-Vallee, & Fabich, 2006; Serrano Pau, 1995). Bull et al. (2006) have shown that there are no major differences between deaf and hearing adults on lower level arithmetical skills such as subitizing, magnitude processing or magnitude automatization that can explain deaf students' mathematical difficulties. However, they did find that the deaf individuals had a reduced efficiency in retrieval of magnitude information, concluding that the efficiency with which deaf individuals process numerical information, but not the numerical representations per se, differ between deaf and hearing individuals, which may influence overall performance on mathematical tasks (Bull, Marschark, & Blatto-Vallee, 2005). Further, it has been suggested that deaf individuals tend to have weaker association between concepts (Marschark, Convertino, McEvoy, & Masteller, 2004) and a tendency to rely on item-specific processing rather than relational processing (see review in Marschark, 2003) that might lead to delay in the establishment of arithmetic number representations and affect higher level arithmetical competence, such as simple arithmetic. Further, it has been shown that deaf children in Swedish schools for deaf and hard-of-hearing children often make use of a "double counting" strategy, in which both hands are used to represent different digits simultaneously, when modelling problems (Foisack, 2003). Such a strategy may be appropriate up to a point, but it does not lead to the development of the arithmetic fact based strategies that are important for learning multiplication tables and establishing automaticity. This may lead to greater reliance on phonological processing during multiplication for deaf than hearing individuals.

Simple arithmetic can be roughly divided into two separate conceptual domains; additive reasoning that include problems solved by addition and subtraction, and multiplicative reasoning that includes problems solved by multiplication and division (Nunes et al., 2009). However, newer data points to a relatively lower functional dependency between multiplication and division compared to addition and subtraction (Robinson & LeFevre, 2012; Venneri & Semenza, 2011). Multiplication has been shown to rely on speech based phonology, whereas subtraction uses a visual-analogue magnitude code (Lee & Kang, 2002). Bull et al. (2005) have shown that deaf individuals have access to the visual-analogue magnitude code, but it is probable that they have a less efficient access to speech based phonology. Further, hearing children make sense of the world around them by simultaneous coordination of auditory and visual information (Marschark, 2006). Deaf children make sense of the world in a similar way when learning to sign, as parents provide simultaneous information about the sign and its referent through manipulation of sign location. However, when more elaborate skills, such as reading or arithmetic, are introduced in school or kindergarten, deaf children need to correlate two sequentially displayed visual stimuli (the sign and its referent). This increases cognitive load and interferes with tasks requiring phonological processing. Therefore, deaf individuals would be expected to perform less well than hearing individuals in both phonological and multiplication tasks. Indeed, Nunes et al. (2009) showed that deaf children underperform on multiplicative reasoning compared to hearing children. In the current study we aim to investigate for the first time the relation between first language phonology and multiplication in adult deaf signers and hearing non-signers.

1.3. Aim of the study

The aim of this study is to investigate the relation between phonological and arithmetic skills in adult deaf sign language users and hearing non-signers. In particular we investigate the relation between phonological skill and subtraction (additive domain) and multiplication (multiplicative reasoning). We hypothesise that deaf signers will perform worse than hearing non-signers on multiplication but not on subtraction and that there will be a stronger relationship between multiplication and phonology for deaf signers than for hearing non-signers.

2. Methods

2.1. Participants

Eighteen deaf adults (fourteen women and four men; mean age 27.7, SD 4.13) and eighteen adult hearing, native Swedish speakers (thirteen women and five men; mean age 28.1, SD 5.50) were recruited to the study. All deaf participants considered SSL to be their primary language and they used SSL daily. None of them reported an ability to use spoken language in everyday life through speech and/or speech reading. However, all of them were bilingual to the extent that they could communicate through written Swedish. They were all deaf from birth (17 participants) or before six months of age (1 participant). Three deaf participants had deaf parents who signed with them from birth and another two had an older deaf sibling and parents, who had already started to learn SSL, who signed with them from birth. An additional seven deaf participants had hearing parents who started to sign with them before or around the age of one. The remaining six deaf participants were exposed to sign language from around two years of age. Thus, all deaf participants were exposed to sign language before the age of three. Mean reported age of sign language acquisition was 12 months ($SD = 10$). None of the deaf participants reported acquisition of a functional spoken language prior to learning SSL. Because parents of deaf children in Sweden are offered free sign language tuition, all hearing parents of the deaf participants in this study were well prepared to use adequate sign language in communication with their deaf child. Hence, all signing participants can be described as early signers who acquired sign language in the infancy developmental epoch (Mayberry, Chen, Witcher, & Klein, 2011; Mayberry & Lock, 2003), with a native or native-like knowledge of SSL.

The participants in the speaking group were unfamiliar with SSL and recruited to match the signing group on age, education, gender and non-verbal intelligence.

All participants had completed mandatory Swedish education, which at the time meant nine years for the hearing group and ten years for the deaf group, and Swedish high school (three to four years for both groups). The deaf participants had all been enrolled in deaf schools where sign language was the primary teaching regime. Six of the hearing participants and six of the deaf participants had a university degree or equivalent education (e.g. sign language teachers). This means that all participants have language and mathematic skills on at least high school level. For this study multiplication table skills are especially important, a skill which should be mastered by grade 3 (SKOLFS 2010:37, SKOLFS 2010:250). The careful matching further resulted in no statistically significant differences between the groups regarding age ($t(34) = .239$, $p = .813$, $r = .08$) and non-verbal IQ (Ravens standard progressive matrixes; $t(34) = 1.87$, $p = .070$, $r = .31$).

The study was approved by the regional ethics committee in Linköping (Dnr 190/05). Written informed consent was given by all participants.

2.2. Tasks and procedures

The cognitive test battery used in this study was made up of four separate sets of tests. All tests were the same for deaf and hearing subjects unless otherwise stated. All participants performed the tests individually and in the same order, as presented below, except for one of the deaf participants who performed test number 3 last due to technical problems. A professional accredited sign language interpreter was present during testing of the deaf participants to provide them with a verbatim translation of test instructions and an opportunity to ask questions if needed. During the same test session, participants were also enrolled in a short-term memory experiment. Results on this experiment, together with the overall results on Operation Span (see below), is reported in Andin et al. (2013).

2.2.1. Simple symbol processing

Low level phonological and arithmetic knowledge were assessed by a simple symbol processing test constituted by basic alphabetical and numerical knowledge subtests. The material for each of the subtests consisted of a matrix with ten rows and ten columns. In each cell of the matrix, there was either a letter (for the alphabetical subtest; all letters of the Swedish alphabet was used) or a number (for the numerical subtest; numbers 1 to 20 were used). On each row the participants were asked to circle the characters that were not in alphabetical or numerical order. One point was given for each correctly circled letter or number and a reduction of one point was given for each incorrectly circled letter or number. Separate scores were calculated for the letter and number subtests. The maximum score was 17 on each subtest. There was no time limit for the test.

2.2.2. Complex symbol processing

Both low level phonological and arithmetic knowledge and high level phonological and arithmetical processing were further investigated with a computerised test called complex symbol processing. This test contained six conditions: a phonological task, subtraction, multiplication, letter order, digit order and a visual control task. Both groups completed all tasks using the same stimulus material. However, for the phonological task the instructions differed for the two groups. Deaf signers were asked about hand-shape and hearing non-signers about rhyme. Because all deaf signers were bilingual to some extent, it is conceivable that the rhyming trials could cause interference. However, the deaf participants were not informed about the rhyming task and to ensure that interference from rhyming trials did not take place, an error analysis was performed. The six tasks are described in Table 1. The tasks were constructed such that the stimulus format was the same for all tasks but cognitive processing demands differed. Keeping the format equal for all conditions allows for better comparisons across conditions. In particular, it controls the visuospatial processing load of looking at the stimuli. This is important because visuospatial processing differences may exist between deaf and hearing individuals (Bavelier, Dye, & Hauser, 2006). Thus, retaining the same stimulus format across conditions facilitates investigation of differences between groups. Each stimulus consisted of three digit-letter pairs (e.g. B2 K4 G8). The digits used were 0 to 9. The letters were chosen taking into account their

Table 1
Overview of the six conditions in the complex symbol processing task.

Condition	Determine…	Example 1 2V 3B 6M	Example 2 4D 5L 1Ö
Digit order	…if the digits appear in numerical order.	“Yes” e.g. 2, 3, 6	“No”
Letter order	…if the letters appear in alphabetical order.	“No”	“Yes” e.g. D, L, Ö
Multiplication	…if there is a digit that when multiplied with one of the other digits equal the third.	“Yes” e.g. $2 \times 3 = 6$	“No”
Subtraction	…if there is a digit that when subtracted from one of the other digits equal the third.	“No”	“Yes” e.g. $5 - 1 = 4$
Phonological similarity	…if any of the three letter-digits pairs rhyme.[a]	“Yes” e.g. 3 and B	“No”
	…if any of the three letter-digit pairs have the same hand-shape.[b]	“Yes” e.g. 2 and V has the same hand-shape in SSL	“No”
Control condition	…if any of the letters have two dots over them.	“no”	“Yes” e.g. Ö

[a] Hearing subjects.
[b] Deaf subjects.

phonological characteristics in Swedish and the Swedish manual alphabet, so that equal numbers of unique digit-letter pairs could be created which either rhymed in Swedish or shared a handshape in the Swedish manual alphabet and the set of Swedish manual numerals. These letters were: b, d, e, g, h, k, l, m, o, p, q, t, u, v, x, z, å and ö (see Fig. 2 for an overview of the ten pairs used for each language). All subtraction and multiplication tasks were of small problem size, with products and sums smaller than 10 (Campbell & Xue, 2001).

Four separate sets of material with 60 trials each were created. The sets were balanced with regard to number of trials per condition, order of conditions and the amount of correct and incorrect trials. Each participant was randomly assigned to perform two of the four

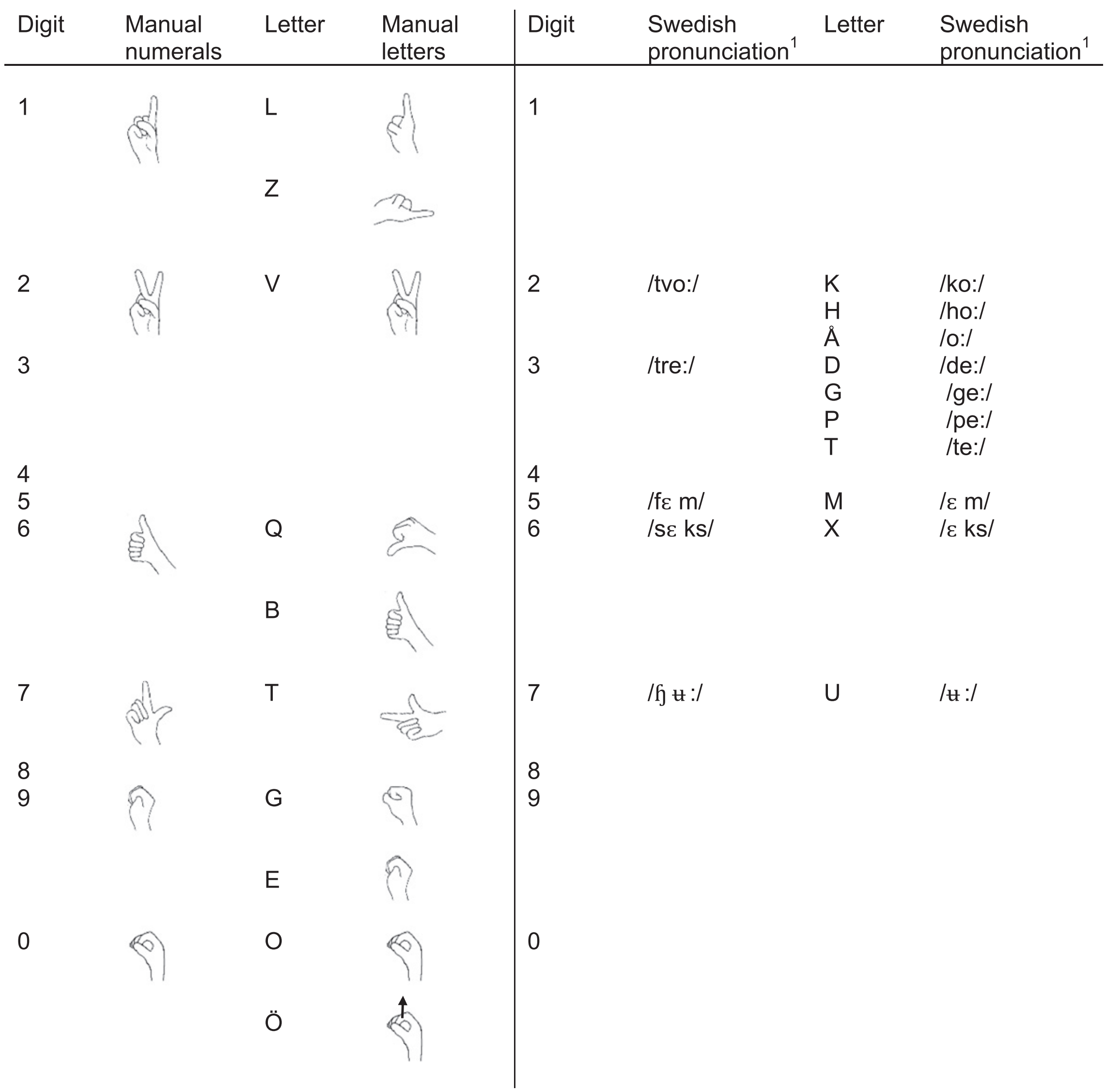

Fig. 2. Digits and letters of the phonological similarity task. Overview of the ten phonologically similar digit-letter pairs used in the phonological similarity task. [1]Swedish pronunciation as expressed by the International Phonetic Alphabet.

sets to guard against material effects. Within a set, each of the six conditions appeared in two blocks with five trials in each block. During each trial the stimulus was presented for 4 s and was preceded by a task prompt indicating which task was to be performed. The subjects were asked to respond to each stimulus by pressing "yes" or "no" keys on the keyboard as fast as they could, without compromising accuracy. They were instructed to use one hand for each key. This may have conflicted with task-related overt or covert manual articulation for the signing group. Indeed, many of the signing participants used overt manual articulation, especially in the phonological task. A separate analysis was conducted to identify any such effect. The maximum response time allowed was 4 s. Inverse efficiency score (IE), response time divided by percentage correct, was calculated for each condition (Austen & Enns, 2003). This means that a lower IE score reflects a better performance. The stimuli were presented on a computer screen using Presentation software (Presentation version 10.2, Neurobehavioral systems Inc., Albany, CA).

2.2.3. Picture phonology judgement

Phonological awareness was tested in a picture phonology judgment task. All participants were presented with a series of 36 pairs of pictures, one pair at a time, on a computer screen. The hearing participants were asked to determine if the Swedish lexical labels for the two pictures rhymed. The signing participants were asked to determine if the SSL lexical labels for the two pictures had the same handshape. Thus, the deaf signers were instructed to concentrate only on the handshape of the signs for the presented pictures. The deaf signers were not informed about the rhyming task given to the hearing participants. Participants gave their answers by saying, signing or gesturing "yes" or "no" to the experimenter who then proceeded to the next pair of pictures. In contrast to the phonological task in the complex symbol processing subtest, the participants did not answer by key press, freeing both hands of the signing participants for articulation. Twelve out of the 36 pairs either rhymed or had the same hand-shape. The 24 non-matching trials were identical for both groups while the 12 matching trails were mutually exclusive. In Swedish, the mean number of syllables was 1.75 for the rhyming words and 1.73 for the non-rhyming words. All signs and words are commonly used in SSL and Swedish, respectively (http://www.ling.su.se, http://www.spraakbanken.gu.se).

2.2.4. Operation span

Working memory was tested using an operation span task based on Turner and Engle (1989). Apart from using operation span to measure working memory we also used the results from the processing step of the operation span as a measure of mathematical processing. Forty-two equations, each consisting of two operations, were used as stimuli. The first operation in each equation required multiplicative reasoning (multiplication or division) and the second required additive reasoning (addition or subtraction; e.g. $3 \times 3 - 1 = 8$). The task was to determine if the stated answer was correct or not. Single digit numbers 1–9 were used for all operands, sub-products and answers. Half of the equations were true and half were false. Answers were given within a 5 second limit by key press using two keys labelled "yes" and "no" on the computer numpad keyboard. After each sequence the participants were instructed to recall all the stated answers in the correct order using the same set of keys. During recall no visual feedback was presented on the computer screen. Each type of operation (multiplication, division, addition and subtraction) appeared an equal number of times in combination with each of the others. Twelve sequences of operations were created (2–5 operations in a row, 3 sequences of each length). Both the process operation (math process component) and the recall operation (operation span component; previously reported in Andin et al. (2013)) were assessed in this study. The math process component was further analysed in relation to each of the four operations.

2.3. Statistics

Data analysis was performed using PASW statistics 18 (Predictive Analytics Software, version 18, SPSS Inc., Chicago, USA). The simple and complex symbol processing tasks were analysed by separate repeated measures factorial analyses of variance and independent *t*-tests. For simple comparisons of picture phonology and operation span, independent *t*-test was used. Finally, regression analysis was used to investigate predictor factors for performance on subtraction and multiplication. In the regression analysis, IE scores for multiplication and subtraction, respectively, were entered as outcome measures in stepwise backward regression analyses. Predictor variables included in the analysis were picture phonology, basic alphabetical and numerical processing from the simple symbol processing test, and Raven's SPM. Entry criterion was set to .04 and removal criterion to .05. Stein's formula was used for estimating adjusted R^2 when generalizing the results to the whole population.

Effect sizes, *r*, were estimated to describe focused effects for both main and simple effects. Effect sizes were interpreted in accordance with Cohen (1988), i.e. $r = 0.1$ indicates small effect, $r = 0.3$ medium effect and $r = 0.5$ large effect.

3. Results

3.1. Simple symbol processing

Both groups showed high performance (Table 2) and there were no differences between groups on basic alphabetical knowledge and basic numerical knowledge ($F(1,34) = .394$, $p = .534$, $r = .11$). For both groups performance on numerical knowledge was higher than on alphabetical knowledge ($F(1,34) = 32.6$, $p < 0.001$, $r = .70$). No interactions were found.

3.2. Complex symbol processing

3.2.1. Low level phonological and arithmetic knowledge

Both groups showed high performance (Table 2) and there were no differences between groups on basic alphabetical knowledge and basic numerical knowledge in the complex symbol processing test ($F(1,34) = .726$, $p = .400$, $r = .15$). For both groups, performance on numerical knowledge was higher than on alphabetical knowledge ($F(1,34) = 86.9$, $p < .001$, $r = .85$). No interactions were found neither was there any difference between the two groups on the visual control task ($t(34) = 1.76$, $p = .087$, $r = .29$). Thus, deaf signers and hearing non-signers did not differ in basic arithmetic or phonological knowledge.

3.2.2. High level phonological and arithmetic processing

There were no group differences for subtraction ($t(34) = .956$, $p = .346$, $r = .16$). However, in multiplication, hearing non-signers performed better than deaf signers ($t(34) = 2.06$, $p = .047$, $r = .33$). See Table 2.

On phonology no group difference was found ($t(34) = .897$, $p = .376$, $r = .15$). Results are shown in Table 2. The deaf signers sometimes used manual articulation which may have slowed their responses, obscuring better performance in this group than in the hearing group. To control for this, we analysed the accuracy and the response time components independently and found no between group differences in either of the two (accuracy: $t(34) = .779$, $p = .442$, $r = .13$, response time: $t(34) = 1.10$, $p = .280$, $r = .19$). This suggests that manual articulation did not appreciably interfere with performance.

3.3. Picture phonology judgment

Hearing non-signers performed better than deaf signers ($t(34) = 4.45$, $p < .001$, $r = .61$). Results are shown in Table 2. There was no

Table 2
Mean performance and standard deviation on all tests.

Test	Deaf participants		Hearing participants	
	M	SD	M	SD
Test 1 Simple symbol processing				
Basic letter processing	15.4	1.50	15.4	1.25
Basic digit processing	16.3	0.84	16.7	0.49
Test 2 Complex symbol processing[a]				
Digit order	2.14	0.49	1.84	0.39
Letter order	2.96	0.56	3.01	0.70
Multiplication*	2.96	0.88	2.45	0.56
Subtraction	2.72	0.77	2.49	0.60
Phonology	4.23	1.07	3.90	1.13
Control task	1.03	0.30	0.88	0.18
Test 3 Picture phonology*	32.8	1.86	35.1	1.13
Test 4 Operation span				
Operation span component[b]	3.56	1.62	3.94	1.26
Math process component[c]	33.0	7.96	35.8	1.62
Addition	15.8	3.78	17.3	2.57
Subtraction	17.2	4.41	18.5	3.49
Multiplication*	17.4	3.90	19.4	1.72
Division	15.6	4.35	16.4	4.17

$n = 18 + 18$.
* p < 0.05 between deaf signers and hearing non-signers.
[a] Note that results on this task are presented in inverse efficiency scores where a lower score indicates better performance.
[b] Results separately reported in Andin et al. (2013).
[c] *t*-Score from Raven's progressive matrices.

significant correlation between picture phonology judgement and the phonological task from the complex symbol processing test (deaf signers $r = .306$, $p = .217$; hearing non-signers $r = .108$, $p = .671$; whole group $r = .081$, $p = .640$).

3.4. Operation span

There was no overall difference between groups on either the operation span component or the math process component when all operations were included. However, when each equation type was extracted and analysed separately, hearing non-signers performed significantly better than deaf signers on equations including multiplication ($t(34) = 2.05$, $p = .049$, $r = .33$) but not on equations including the other operations (addition $t(34) = 1.44$, $p = .158$, $r = .24$; subtraction $t(34) = .964$, $p = .342$, $r = .16$; division $t(34) = .547$, $p = .588$, $r = .09$). In short, as expected, deaf signers were disadvantaged only in multiplication.

3.5. Regression analysis

To explore which variables could predict performance on multiplication and subtraction as measured by the complex symbol processing task, separate multiple linear regression analyses (with backward elimination of non-significant predictors) were performed for each group. In multiplication, performance on Raven's SPM explained 33% of the variance (adj. $R^2 = .330$, $F(1,17) = 9.37$, $p = .007$; Table 3) for HN. For deaf signers, a model with the basic alphabetical subtest, picture phonology judgment and Raven's SPM explained 60% of the variance in multiplication performance (adj. $R^2 = .595$, $F(3,17) = 9.34$, $p = .001$; Table 3). For subtraction no model that explained a significant amount of the variation was found for either group. Thus, non-verbal logical reasoning contributed to multiplication in both groups, but in deaf signers, basic letter processing and phonological awareness explained variance over and above non-verbal logic.

Table 3
Regression analysis of multiplication performance.

	Deaf signers			Hearing non-signers		
	B	*SE* B	β	B	*SE* B	β
Constant	4.91	2.51		5.00	.837	
Raven's SPM	−.074	.019	−.643**	−.046	.015	−.609*
Basic alphabetical processing	−.341	.096	−.581*			
Picture rhyme judgment	.215	.080	.453*			

Adj $R^2 = .595$ for deaf signers. Adj $R^2 = .330$ for hearing non-signers.
* p < .05.
** p < .001.

3.6. Age of exposure to sign language

Even though all deaf participants in the present study were early signers with native or native-like language development, language skills may be related to age of exposure to sign language (Mayberry & Eichen, 1991; Mayberry & Fischer, 1989). For example, age of sign language modulates the response of cortical language processing areas during grammatical judgement (Mayberry et al., 2011). To investigate if age of exposure to sign language had an impact on task performance, two additional sets of *t*-tests were performed. In the first of these, the deaf group was divided into native (signed with from birth, $n = 5$) versus non-native ($n = 13$) SSL users and in the second the group was divided according to age of exposure before ($n = 12$) or after ($n = 6$) eighteen months of age. There were no significant differences in performance between the subgroups of deaf signers on any of the tests (all ps > .05).

4. Discussion

In the present study deaf signers and hearing non-signers took part in an experiment in which the format of the visually presented stimuli was held constant across conditions while processing demands were manipulated. Processing demands were either low level arithmetic and phonological knowledge (letter and number order and visual perception) or high level arithmetic and phonological processing (subtraction, multiplication and phonological judgment of digit-letter pairs). The participants also completed a cognitive test battery including a picture-based phonology task and an operation span task. The results of the experiment show that deaf signers perform worse than hearing non-signers on multiplication but not on phonological judgment of digit-letter pairs in their native language (Swedish phonology for the hearing non-signers and SSL phonology for the deaf signers). As expected, no differences were found for subtraction, digit or letter processing. The lack of difference between the deaf signers and hearing non-signers groups on low level digit processing tallies the findings of Bull et al. (2006, 2005) who have shown that basic numerical knowledge, including magnitude representation, does not differ between deaf and hearing adults and college students.

In the cognitive test battery, deaf signers performed worse than hearing non-signers on the picture phonology task in their native language (Swedish phonology for the hearing non-signers and SSL phonology for the deaf signers). It is, however, possible that this reflects differences in cognitive task demands between the tests and not an actual difference in awareness of native language phonology. In the operation span task, although span performance did not differ between groups, deaf signers performed worse than hearing non-signers on the equations including multiplication.

The lower performance for deaf signers than hearing non-signers on the picture phonology test and on the multiplication tasks, together with the lack of difference between the two groups on the subtraction tasks, supports the hypothesis suggested by Bull et al. (2005) that deaf signers have poorer access to the speech based phonology, which is needed for multiplication processing, but equally good access to the visuo-analogue magnitude code, which is used in subtraction processing (Lee & Kang, 2002). This hypothesis is further supported by the results from the regression analysis, in the present study, where the two phonology-dependent measures, basic alphabetical processing and picture phonology judgment, were significant predictors of multiplication performance for deaf signers, but not for hearing non-signers. Hence, for deaf signers to perform well on multiplication they need to master sign language phonology, indicating the importance of phonological skills for successful development of multiplicative reasoning for deaf signers. Notwithstanding any potential difference in cognitive task demands between groups on the picture phonology task, it is interesting that performance plays out differently for the two groups in the regression analysis. Whereas phonological skill predicted multiplication skill in the deaf signing group, no such association was found in the hearing group.

It has been shown that there is a close correlation between phonological awareness and arithmetic problem solving for hearing individuals, especially for small sized problems that primarily require retrieval of information (De Smedt et al., 2010). For deaf individuals, associations between sign phonology skills and reading (Mayberry et al., 2011; Rudner et al., 2012) as well as between reading and arithmetic have been reported (Davis & Kelly, 2003). However, hitherto, little was known about the relation between sign-related phonological skill and arithmetic success. In the present study we tested phonological skills in the participants' respective first language and were able to draw conclusions on the importance of first language phonological skills for arithmetic processing. We show for the first time that arithmetic skills, especially multiplication skills, in deaf signers are associated with the ability to process sign language phonology relating to the lexical labels of pictures although not with the ability to process representations of manual numerals and fingerspelled letters. This may indicate that the phonological skills relating to processing the concrete objects that can be easily depicted are more relevant to arithmetic processing than phonological skills relating to the processing of abstract concepts such as letters and numbers. Further studies will show if there is a causal connection such that arithmetic skills can be enhanced not only by training speech phonology in hearing children but also by training sign language phonology in deaf children.

Previous literature on deaf individuals' mathematical achievement has suggested that there is a general lag in all kinds of arithmetic operations. In this study, the group difference was restricted to multiplication operations and not found in either subtraction (measured in the complex symbol processing experiment and in the operation span task), addition or division (measured in the operation span task). This indicates that the simple arithmetic skills of the bilingually educated group of Swedish deaf signers who took part in the present study are better than previously shown for other groups of deaf signers. In order to capture processes related to differences in the language modality used, we carefully matched the two groups on aspects of non-verbal intelligence, education and age, making conditions as equal as possible across groups. This, together with early sign language exposure in the deaf group, might explain why the results of the deaf signers were on a par with the hearing non-signers on most of the arithmetic tasks tested.

In hearing individuals, multiplication is automatized with training (Delazer et al., 2003; Ischebeck et al., 2006). This automatization leads to a shift such that areas in the parietal lobe, especially angular gyrus, becomes more active during arithmetic processing, while activation in inferior parietal areas, supplementary motor area and left inferior frontal gyrus (i.e. Broca's area) is reduced with training (Delazer et al., 2003; Ischebeck et al., 2006) and increased mathematical competence (Grabner et al., 2007). For subtraction the same parietal and frontal areas were found to be activated for untrained problems, while trained subtraction problems did not increase activation in angular gyrus (Ischebeck et al., 2006). This suggests that when multiplication is well established, less explicit language involvement is needed and instead a retrieval process supported by automatic circuits in the parietal lobe is recruited. For subtraction, even trained problems are solved by calculation rather than retrieval. Children in Swedish deaf schools are trained in reciting multiplication tables in both Swedish (written) and in SSL which should result in the same overlearning of the tables as found for hearing children. However, there has been no research on whether this leads to automatization of the multiplication process in this group. It is possible that the poorer performance in multiplication among the deaf signers in this study at least partly stems from incomplete automatization of simple arithmetic, where simple arithmetic is never shifted to the parietal areas but instead continues to rely on slower language dependent, calculation circuits. In an on-going fMRI-study we are investigating the neuronal networks involved in multiplication and subtraction in deaf signers and hearing non-signers to determine if the behavioural differences reported here depend on differences in recruitment of neuronal circuits used for calculation.

In the present work we show that deaf signers are better at arithmetic than previously shown. Indeed, only multiplication skills were lower in the deaf signing group than in the hearing non-signing group. Further, for the deaf signers, multiplication was dependent on sign language phonology. These results invite development of new teaching strategies with higher emphasis on sign language phonology for deaf signers. Further, studies investigating brain networks in deaf signers can facilitate the understanding of the connection between phonology and arithmetic.

5. Funding

The work was supported by funding from the Swedish Research Council [grant number 2005-1353]. The funding source had no role in study design, collection of data, analysis, interpretation of data, writing of the report or in the decision to submit the article for publication.

Acknowledgement

We would like to thank all the participants and Lena Davidsson for sign language interpreting and assistance in testing deaf participants.

References

Andin, J., Orfanidou, E., Cardin, V., Holmer, E., Capek, C. M., Woll, B., et al. (2013). Similar digit-based working memory in deaf signers and hearing non-signers despite digit span differences. *Frontiers in Psychology*, *4*, 942. http://dx.doi.org/10.3389/fpsyg.2013.00942.

Austen, E. L., & Enns, J. T. (2003). Change detection in an attended face depends on the expectation of the observer. *Journal of Vision*, *3*(1), 64–74. http://dx.doi.org/10.1167/3.1.7.

Bavelier, D., Dye, M. W., & Hauser, P. C. (2006). Do deaf individuals see better? *Trends in Cognitive Science*, *10*(11), 512–518. http://dx.doi.org/10.1016/j.tics.2006.09.006.

Bergman, B. (2012). Barns tidiga teckenspråksutveckling [Children's early sign language development]. In B. Bergman, & J. Mesch (Eds.), *Forskning om teckenspråk [Research on sign language], 22*, Stockholm: Department of linguistics, Stockholm university.
Writers. Bergman, B., & Wikström, L.-Å. (1981). *Supplement till Forskning om teckenspråk, videogram I: Svenska handalfabetet och bokstaverade tecken [Supplement to Research on sign language, videogram I; Swedish manual alphabet and fingerspelled signs].* (Stockholm).
Blondel, M., & Miller, C. (2001). Movement and rhythm in nursery rhymes in LSF. *Sign Language Studies*, *2*(1), 24–61. http://dx.doi.org/10.1353/sls.2001.0022.
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*(3), 289–302. http://dx.doi.org/10.1093/deafed/enj038.
Bull, R., Marschark, M., & Blatto-Vallee, G. (2005). SNARC hunting: Examining number representation in deaf students. *Learning and Individual Differences*, *15*(3), 223–236. http://dx.doi.org/10.1016/j.lindif.2005.01.004.
Bull, R., Marschark, M., Sapere, P., Davidson, W. A., Murphy, D., & Nordmann, E. (2011). Numerical estimation in deaf and hearing adults. *Learning and Individual Differences*, *21*(4), 453–457. http://dx.doi.org/10.1016/j.lindif.2011.02.001.
Campbell, J. I. D., & Xue, Q. (2001). Cognitive arithmetic across cultures. *Journal of Experimental Psychology: General*, *130*(2), 299–315. http://dx.doi.org/10.1037//0096-3445.130.2.299.
Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.
Davis, S., & Kelly, R. (2003). Comparing deaf and hearing college students' mental arithmetic calculations under two interference conditions. *American Annals of the Deaf*, *148*(3), 213–221. http://dx.doi.org/10.1353/aad.2003.0018.
De Smedt, B., Taylor, J., Archibald, L., & Ansari, D. (2010). How is phonological processing related to individual differences in children's arithmetic skills? *Developmental Science*, *13*(3), 508–520. http://dx.doi.org/10.1111/j.1467-7687.2009.00897.x.
Delazer, M., Domahs, F., Bartha, L., Brenneis, C., Lochy, A., Trieb, T., et al. (2003). Learning complex arithmetic — An fMRI study. *Cognitive Brain Research*, *18*(1), 76–88. http://dx.doi.org/10.1016/j.cogbrainres.2003.09.005.
Emmorey (2002). *Language, cognition & the brain — Insights from sign language research.* Mahwah, NJ: Lawrence Erlbaum Associates.
Foisack, E. (2003). *Döva barns begreppsbildning i matematik [Deaf children's conceptualization in mathematics].* PhD. Malmö: Malmö University College, 7.
Grabner, R. H., Ansari, D., Reishofer, G., Stern, E., Ebner, F., & Neuper, C. (2007). Individual differences in mathematical competence predict parietal brain activation during mental calculation. *NeuroImage*, *38*(2), 346–356. http://dx.doi.org/10.1016/j.neuroimage.2007.07.041.
Hyde, M., Zevenbergen, R., & Power, D. (2003). Deaf and hard of hearing students' performance on arithmetic word problems. *American Annals of the Deaf*, *148*(1), 56–64 (doi: 0002-726X).
Ischebeck, A., Zamarian, L., Siedentopf, C., Koppelstätter, F., Benke, T., Felber, S., et al. (2006). How specifically do we learn? Imaging the learning of multiplication and subtraction. *NeuroImage*, *30*(4), 1365–1375. http://dx.doi.org/10.1016/j.neuroimage.2005.11.016.
Kelly, R. R., Lang, H. G., Mousley, K., & Davis, S. M. (2003). Deaf college students' comprehension of relational language in arithmetic compare problems. *Journal of Deaf Studies and Deaf Education*, *8*(2), 120–132. http://dx.doi.org/10.1093/deafed/eng006.
Klima, E. S., & Bellugi, U. (1976). Poetry and song in a language without sound. *Cognition*, *4*(1), 45–97. http://dx.doi.org/10.1016/0010-0277(76)90010-x.
Kritzer, K. I. (2009). Barely started and already left behind: A descriptive analysis of the mathematics ability demonstrated by young deaf children. *Journal of Deaf Studies and Deaf Education*, *14*(4), 409–421. http://dx.doi.org/10.1093/deafed/enp015.
Lee, K. M., & Kang, S. Y. (2002). Arithmetic operation and working memory: Differential suppression in dual tasks. *Cognition*, *83*(3), B63–B68. http://dx.doi.org/10.1016/S0010-0277(02)00010-0.
MacSweeney, M., Waters, D., Brammer, M. J., Woll, B., & Goswami, U. (2008). Phonological processing in deaf signers and the impact of age of first language acquisition. *NeuroImage*, *40*(3), 1369–1379. http://dx.doi.org/10.1016/j.neuroimage.2007.12.047.
Marschark, M. (2003). *Cognitive functioning in deaf adults and children.* New York: Oxford University Press.
Marschark, M. (2006). Intellectual functioning of deaf adults and children: Answers and questions. *European Journal of Cognitive Psychology*, *18*(1), 70–89. http://dx.doi.org/10.1080/09541440500216028.
Marschark, M., Convertino, C., McEvoy, C., & Masteller, A. (2004). Organization and use of the mental lexicon by deaf and hearing individuals. *American Annals of the Deaf*, *149*(1), 51–61. http://dx.doi.org/10.1353/aad.2004.0013.
Marshall, C., Rowley, K., & Atkinsson, J. (2013). Modality-dependent and -independent factors in the organisation of the signed language lexicon: Insights from semantic and phonological fluency tasks in BSL. *Journal of Psycholinguistic Research*. http://dx.doi.org/10.1007/s10936-013-9271-5 (Epub ahead of print).
Mayberry, R. I., & Eichen, E. B. (1991). The long-lasting advantage of learning sign language in childhood: Another look at the critical period for language acquisition. *Journal of Memory and Language*, *30*, 486–512.
Mayberry, R. I., & Fischer, S. D. (1989). Looking through phonological shape to sentence meaning: The bottleneck of non-native sign language processing. *Memory and Cognition*, *17*, 740–754.
Mayberry, R. I., Chen, J. K., Witcher, P., & Klein, D. (2011). Age of acquisition effects on the functional organization of language in the adult brain. *Brain and Language*, *119*(1), 16–29. http://dx.doi.org/10.1016/j.bandl.2011.05.007.
Mayberry, R. I., del Giudice, A. A., & Lieberman, A.M. (2011). Reading achievement in relation to phonological coding and awareness in deaf readers: A meta-analysis. *Journal of Deaf Studies and Deaf Education*, *16*(2), 164–188. http://dx.doi.org/10.1093/deafed/enq049.
Mayberry, R. I., & Lock, E. (2003). Age constraints on first versus second language acquisition: Evidence for linguistic plasticity and epigenesis. *Brain and Language*, *87*(3), 369–384. http://dx.doi.org/10.1016/S0093-934X(03)00137-8.
Morere, D. A., & Roberts, R. (2012). Fingerspelling. In D. A. Morere, & T. Allen (Eds.), *Assessing literacy in deaf individuals: Neurocognitive measurement and predictors* (pp. 179–198). New York: Springer Science + Business Media.
Norell, K. (1998). *Döva elevers starka och svaga områden i matematik. En studie av matematikuppgifters innehåll i relation till elevers prestationsnivån (Vol. 3).* Stockholm, Sweden: Lärarhögskolan.
Nunes, T., Bryant, P., Burman, D., Bell, D., Evans, D., & Hallett, D. (2009). Deaf children's informal knowledge of multiplicative reasoning. *Journal of Deaf Studies and Deaf Education*, *14*(2), 260–277. http://dx.doi.org/10.1093/deafed/enn040.
Padden, C., & Gunsauls, D. C. (2003). How the alphabet came to be used in a sign language. *Sign Language Studies*, *4*(1), 10–33. http://dx.doi.org/10.1353/sls.2003.0026.
Robinson, K. M., & LeFevre, J. A. (2012). The inverse relation between multiplication and division: Concepts, procedures, and a cognitive framework. *Educational Studies in Mathematics*, *79*(3), 409–428. http://dx.doi.org/10.1007/s10649-011-9330-5.
Rudner, M., Karlsson, T., Gunnarsson, J., & Rönnberg, J. (2013). Levels of processing and language modality specificity in working memory. *Neuropsychologia*, *51*(4), 656–666. http://dx.doi.org/10.1016/j.neuropsychologia.2012.12.011.
Rudner, M., Orfanidou, E., Cardin, V., Capek, C., Woll, B., & Rönnberg, J. (2012, October). *Reading ability in adult deaf native signers is positively associated with their ability to judge the grammatically of their native sign language.* San Sebastian, Spain: Paper presented at the Neurobiology of Language. Abstract can be found at: http://www.neurolang.org/programs/NLC2012_Abstracts.pdf
Sandler, W., & Lillo-Martin, D. (2006). *Sign language and linguistic universals.* Cambridge, NY: Cambridge University Press.
Serrano Pau, C. (1995). The deaf child and solving problems of arithmetic. The importance of comprehensive reading. *American Annals of the Deaf*, *140*(3), 287–290. http://dx.doi.org/10.1353/aad.2012.0599.
Sutton-Spence, R. (2001). Phonological “deviance” in British sign language poetry. *Sign Language Studies*, *2*(1), 62–83. http://dx.doi.org/10.1353/sls.2001.0029.
Titus, J. C. (1995). The concept of fractional number among deaf and hard of hearing students. *American Annals of the Deaf*, *140*(3), 255–262. http://dx.doi.org/10.1353/aad.2012.0582.
Traxler, C. B. (2000). The Stanford Achievement Test, 9th Edition: National norming and performance standards for deaf and hard-of-hearing students. *Journal of Deaf Studies and Deaf Education*, *5*(4), 337–348. http://dx.doi.org/10.1093/deafed/5.4.337.
Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28*(2), 127–154. http://dx.doi.org/10.1016/0749-596X(89)90040-5.
Venneri, A., & Semenza, C. (2011). On the dependency of division on multiplication: Selective loss for conceptual knowledge of multiplication. *Neuropsychologia*, *49*(13), 3629–3635. http://dx.doi.org/10.1016/j.neuropsychologia.2011.09.017.
Vigliocco, G., Vinson, D. P., Woolfe, T., Dye, M. W. G., & Woll, B. (2005). Language and imagery: Effects of language modality. *Proceedings of the Royal Society B: Biological Sciences*, *272*(1574), 1859–1863. http://dx.doi.org/10.1098/rspb.2005.3169.
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*(3), 315–326. http://dx.doi.org/10.1093/deafed/enh034.