Modality and Interrelations among Language, Reading, Spoken Phonological Awareness, and Fingerspelling

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Abstract

Better understanding of the mechanisms underlying early reading skills can lead to improved interventions. Hence, the purpose of this study was to examine multivariate associations among reading, language, spoken phonological awareness, and fingerspelling abilities for three groups of deaf and hard-of-hearing (DHH) beginning readers: those who were acquiring only spoken English (*n*=101), those who were visual learners and acquiring sign (*n*=131), and those who were acquiring both (*n* =104). Children were enrolled in kindergarten, first, or second grade. Within-group and between-group confirmatory factor analysis showed that there were both similarities and differences in the abilities that underlie reading in these three groups. For all groups, reading abilities related to both language and the ability to manipulate the sublexical features of words. However, the groups differed on whether these constructs were based on visual or spoken language. Our results suggest that there are alternative means to learning to read. Whereas all DHH children learning to read rely on the same fundamental abilities of language and phonological processing, the modality, levels, and relations among these abilities differ.

Many deaf and hard-of-hearing (DHH) children struggle to learn to read, while others develop age-appropriate skills (Lederberg, Schick, & Spencer, 2013). Understanding the factors that relate to individual differences in reading is critical to designing better interventions and improving reading for all DHH children. One fiercely-debated but unanswered question is how much reading relies on children's knowledge of spoken language (Paul & Lee, 2010; Petitto et al., 2016). Because written language encodes spoken language, many claim that DHH children need to acquire spoken language through auditory or visual means. For example, Paul and colleagues (Paul & Lee, 2010; Wang, Trezek, Luckner, & Paul, 2008) posited that all DHH children must use qualitatively-similar processes to learn to read as hearing children. If this is true, reading interventions for DHH children should resemble those for hearing readers with an additional emphasis on increasing children's knowledge of the phonological, semantic, and syntactical features of spoken language. Others propose that DHH children use different processes to read (Hoffmeister & Caldwell-Harris, 2014; Petitto et al., 2016). This view implies that interventions should differ in substantial ways from those developed for hearing children. There is a third possibility: Both hypotheses may be true, but for different DHH children, depending on their acquisition of spoken and signed language (Lederberg et al., 2013; Miller, 2002). Indeed, research suggests that reading processes differ depending on deaf adults' primary mode of communication (spoken vs. signed language) (Hirshorn, Dye, Hauser, Supalla, & Bavelier, 2015; Miller, 2002).

We do not know which of these three hypotheses best explains how young DHH children learn to read. Based on both reading theory and previous research, we hypothesized that DHH children's early reading abilities would be closely related to phonological awareness and language abilities, but the nature of this relation might differ for children acquiring signed and/or

spoken language. We tested this hypothesis by examining the structure of language and literacy skills for 336 young DHH children using confirmatory factor analyses. We hypothesized that, for children who were unimodal visual learners and acquiring sign, reading would relate to children's *fingerspelling* phonological awareness and bilingual (American Sign Language and English) language abilities. On the other hand, for children who were only acquiring spoken language, we expected reading would be related to *spoken* phonological awareness and spoken language abilities. We also included a third group of children: bimodal bilingual DHH children (acquiring both spoken and signed language) who have not been extensively studied (Davidson, Lillo-Martin, & Pichler, 2014; Marschark, Tang, & Knoors, 2014). We hypothesized that reading for these children would be related to their spoken and fingerspelling phonological abilities, as well as their bilingual (ASL and English) language abilities. How these abilities relate to one another for the three groups of DHH children needs to be better understood and was the main goal of this study. A secondary goal was to show if tests that measured the four constructs (i.e., reading, language, spoken PA, and fingerspelling) were equally good indicators of their hypothesized constructs for children in the three language groups.

Reading Theory

There is widespread consensus on how hearing children learn to read (Lonigan & Burgess, 2017; Seidenberg, 2013). The Simple View of Reading and other more complex theories posit that reading comprehension depends on both word identification and language. Word identification in an alphabetic language requires the acquisition of the alphabetic principle: the knowledge of how to translate letters and printed words into the phonemes of the language. This knowledge is fundamental to phonologically recoding of letters into phonemes and blending them into words, a critical strategy when reading words that are not recognized. Even for sight

word recognition, the ability to remember or recognize printed words is facilitated by the storage of sublexical connections between letters and their corresponding phonemes (Ehri, 2014). Acquisition of the alphabetic principle depends on children's phonological awareness ability (Anthony et al., 2002; Seidenberg, 2013). Phonological awareness (PA) is the ability to attend to and manipulate the sublexical structure of words (e.g., syllables, rimes, and phonemes). Research clearly documents that many hearing children who struggle to learn to read have poor phonological awareness skills (Seidenberg, 2013).

Early reading skills also relate to children's language abilities. Children's understanding of the words and sentences they decode depends on their knowledge of vocabulary and syntax (Connor, 2016). The quality of the children's vocabulary knowledge, defined by both the breadth and depth of vocabulary, influences the development of sight word recognition (Perfetti & Stafura, 2014). Children's PA, especially their ability to manipulate phonemes, is also influenced by lexical quality (Braze et al., 2016).

DHH Children's Reading

There is extensive research on the underlying processes of reading of DHH children (see Lederberg et al., 2013; Petitto et al., 2016 for reviews) but most of this research examines DHH children as a single group, regardless of the children's language modality. We hypothesize this type of research is likely to miss important differences in the fundamental skills among DHH children. The goal of the present study is to compare the structure of reading and language skills for children who differ in language modality (spoken, sign, or both).

Language Modality

DHH children differ on the modality of their language as a function of their language input and their speech perception abilities (Lederberg et al., 2013). DHH children who are

exposed to sign in school and/or at home will acquire sign language because there are no sensory barriers to visual language. In contrast, DHH children's speech perception abilities will influence the acquisition of spoken language. Because of cochlear implants and digital hearing aids, many, but by no means all, DHH children have sufficient speech perception abilities to access spoken language. Children who are not exposed to sign language will only acquire spoken language. On the other hand, DHH children who are in signing environments and can perceive spoken language may acquire both spoken and signed language. We follow the example of those who refer to these children as bimodal bilingual children because they are acquiring two languages in two modes (Davidson et al., 2014). DHH children who are unimodal visual learners (i.e., those who have limited or no auditory abilities) only acquire spoken language to the extent that it can be learned through visual means (e.g., through speechreading or print). To emphasize their visual acquisition of spoken language, Woll and MacSweeney (2016) also referred to the latter group as bimodal. In this paper, we restrict the term bimodal for those who are able to use both modalities in communication in order to test our assumption that children who sign may differ in how they read depending if they have auditory access to speech. We next review research about these three groups of DHH children.

Children acquiring spoken language. DHH children who are acquiring spoken language are learning to read the language that they can hear. Researchers have found that, as with hearing children, early reading skills of DHH children are correlated with their phonological awareness (PA) and language skills (Cupples, Ching, Crowe, Day, & Seeto, 2014; Webb, Lederberg, Branum-Martin, & Connor, 2015). Overall, correlations among these three constructs tend to be similar and in the moderate to high range (i.e., r = .60 to .80). A number of studies have examined the relative importance of the two skills for reading with conflicting results.

Some researchers have found that PA predicted more variance in reading than language (Cupples et al., 2014). Others have found that language predicted more variance in early reading than PA (Nittrouer, Caldwell, Lowenstein, Tarr, & Holloman, 2012). Finally, others have found that both vocabulary and PA play a strong and equal role in reading (Dillon, de Jong, & Pisoni, 2012).

These conflicting results may be due to the high intercorrelations among the three constructs. In fact, using confirmatory factor analyses of DHH children's early literacy skills, Webb et al. (2015) found that relations among three constructs (i.e., vocabulary, reading, and phonological awareness) were high and homogenous (r = .58 to .67), suggesting that PA and vocabulary play complementary and perhaps equal roles in young DHH preschoolers' performance on reading tasks. In a study of elementary school children with cochlear implants (CI), Dillon et al. (2012) reached the same conclusion. The present study will be the first to use confirmatory factor analyses to examine the relations among PA, reading, and language in early elementary school.

Children who are unimodal visual learners and acquiring sign language. Some DHH children do not have auditory access to spoken language, and acquire language only through vision. These children are learning to read a language that differs on every dimension—phonological, semantic, and syntactical—from their first language (Chamberlain & Mayberry, 2008; Hoffmeister & Caldwell-Harris, 2014; Petitto et al., 2016). However, some researchers posit that even these DHH children use some knowledge of spoken English to read. This is supported by research that shows correlations between reading and non-auditory assessments of spoken phonological awareness (Harris, Terlektsi, & Kyle, 2017; Kyle & Harris, 2010). For these children, reading abilities may relate to how well they can use visual means to acquire the phonological structure of spoken language (Kyle, Campbell, & MacSweeney, 2016). They may

use mouth movements that provide visual cues to spoken phonology and are a natural part of some sign languages (Petitto et al., 2016; Woll & MacSweeney, 2016). Indeed, reading correlates with DHH children's speech-reading abilities (Kyle et al., 2016). Other researchers have shown that DHH children can develop knowledge and awareness of spoken phonology when teachers use visual-manual systems such as Visual Phonics and Cued Speech to represent spoken phonemes (see Lederberg et al., 2013 for a review). Thus, reading abilities may relate to the ability to develop spoken PA visually.

Other researchers suggest that reading does not require translation into spoken language (Hoffmeister & Caldwell-Harris, 2014; Petitto et al., 2016). DHH readers may directly map the printed word, learned as a sight word, to a sign through an orthographic-semantic pathway (Morford, Kroll, Piñar, & Wilkinson, 2014), prompting many teachers of DHH children to focus on building a large sight word vocabulary. While some DHH readers may be able to use this strategy to learn to read, research with hearing and DHH children suggests that a sight word reading strategy is an ineffective way to read, especially during the early stages of learning to read (Ehri, 2014). In fact, Reitsma (2009) showed that learning to recognize new words through repeated direct associations with sign is a very slow process for DHH children.

Consistent with others, our own theoretical stance is that good reading requires awareness of the sublexical structure of words, and this awareness is fundamental to reading for all children (Lederberg et al., 2013; Petitto et al., 2016). While "phonology" is most frequently used in reference to spoken phonology, linguists studying sign language define phonology more broadly. For example, Brentari (1998) defines phonology as the "sub-lexical structure that is systematically organized and constrained." Fingerspelling is one visual phonological system that may support reading. Fingerspelling, which consists of a manual alphabet representing the

English print alphabet, is a natural part of ASL and many other sign languages. The phonology of fingerspelling and of signs is related because they use the same articulators (Keane & Brentari, 2016). Importantly, linguists have concluded that fingerspelling can be used as a visual-manual phonological representation of English words when produced fluently as a word (Keane & Brentari, 2016). Fluently fingerspelled words contain some syllable structure depicted by sign-like movement or envelope, while chunking or coarticulation of frequently co-occurring letter sequences aids comprehension (Brentari, 1998). For example, consonantal clusters (bl, sl, cl, str) or common affixes (-tion, -ness, pre-) are produced as smooth, coarticulated sequences, not distinct letters. Researchers suggests fingerspelling a word can facilitate learning how to connect a new printed word to a sign. It may also act as aid in recognizing known print words (Haptonstall-Nykaza & Schick, 2007; Hirsh-Pasek, 1987).

While researchers have identified fingerspelling as a possible important link to reading for deaf students, surprisingly few studies have examined its role in learning to read. Researchers (Emmorey & Petrich, 2012; Stone, Kartheiser, Hauser, Petitto, & Allen, 2015) have found that fingerspelling and reading correlate in deaf adults. Some small scale ($n < 30$) studies have found that deaf children's fingerspelling abilities correlate with reading (Padden & Ramsey, 2000; Puente, Alvarado, & Herrera, 2006), while others have not (Chamberlain & Mayberry, 2008; Haptonstall-Nykaza & Schick, 2007). These studies have included DHH students who range widely in age and reading abilities. Therefore, they cannot isolate the contribution of fingerspelling to early literacy—the age when phonological awareness is hypothesized to be particularly important. In addition, these studies often measured fingerspelling very narrowly. For some studies, children matched fingerspelled words to written words, thus confounding fingerspelling with literacy (Padden & Ramsey, 2000). Other studies defined fingerspelling as

the ability to imitate fingerspelled words correctly (Emmorey, McCullough, & Weisberg, 2015; Stone et al., 2015). We know of only one study that measured children's ability to manipulate the sublexical structure of fingerspelled words (Hirsh-Pasek, 1987). In the present study, we assessed fingerspelling abilities through three tasks: imitation, blending and elision. The latter two were designed to be analogous to spoken PA tasks.

Research also suggests that reading is related to sign language abilities. Research has consistently shown that reading correlates with signed vocabulary. Given that readers connect printed words to signs (Morford et al., 2014), it is not surprising that reading abilities correlate with signed vocabulary abilities (Kyle et al., 2016). More controversial is the role of the syntax of sign language. Proponents of bilingual education, especially in the US, argue that a strong foundation in a natural sign language supports reading skills and that DHH children can learn the syntax of the written language through print (Hoffmeister & Caldwell-Harris, 2014). Others suggest that sign language does not support reading in another language (Paul & Lee, 2010). A third perspective is that deaf children are developing both a natural sign language and contact sign (i.e., signing that resembles written language) and both are mutually supportive of reading (Hermans, Ormel, & Knoors, 2010).

There are a number of reports that sign language syntax skills correlate with reading skills (see Lederberg et al., 2013 for a review). In the present study, we hypothesized that DHH signing children are developing unimodal bilingual abilities (i.e. bilingual abilities in a single [visual] modality). Specifically, we hypothesized that DHH children who are acquiring sign learn both a natural sign language (e.g., ASL) and English-like sign, and that these languages will be integrated and related to reading.

Bimodal-bilingual children. Some DHH children are acquiring both spoken and signed languages. These DHH children have sufficient auditory access to acquire spoken language and are in environments where adults use both sign and spoken languages (not necessarily at the same time). These children's language is considered bimodal-bilingual because they learn two languages and these languages differ in modality (Davidson et al., 2014). There is surprisingly little research on bimodal-bilingual DHH children, and this research is almost exclusively focused on whether signing interferes with spoken language development. Indeed, Hermans and colleagues (2010) call for more research that assesses both sign and spoken language abilities. We hypothesized that bimodal-bilingual children develop spoken phonological awareness, fingerspelling, and bilingual language abilities (American Sign Language/spoken English) and that these abilities would relate to reading.

The Present Study

While a fair amount is known about reading, language, spoken phonological awareness, and fingerspelling in subgroups of DHH children, less is known about the specific relations among these four constructs for young DHH children who are learning to read. Even more importantly, few studies have examined how language modality might change the relations among these important constructs. For example, it is possible that spoken phonology may have diminished importance and fingerspelling may take on a crucial relation to reading for unimodal signers. The primary purpose of this paper was to examine these four constructs in a sample of children who differ in their access and acquisition of signed and spoken language.

We examined literacy and language skills in 336 DHH children in kindergarten, first, or second grade. The participants included three groups of children who differed in their language

modality: (1) children acquiring only spoken language, (2) children who were unimodal visual learners acquiring sign, and (3) children acquiring both spoken and signed language (bimodal).

We used both within-group and multigroup confirmatory factor analyses (CFA) to address the following questions.

1. What skills relate to reading abilities in young DHH children in three language groups?
2. Is there measurement equivalence across groups? In other words, do the tests measure the four constructs in the same way for each language group?
3. Do children in the three groups differ in terms of relations between abilities (correlations), proficiency (means), and individual differences (variances) of their reading, language, spoken PA, and fingerspelling abilities?

Method

Participants

Three hundred and thirty-six DHH children (47% boys) participated in the study. Criteria for participants were (a) enrollment in kindergarten through second grade, (b) hearing loss (better ear-pure tone average or BE-PTA) greater than 25 dB, and (c) and no severe disabilities (e.g., autism or cognitive impairment). We excluded children when their teachers reported the presence of a severe disability or if they scored more than two standard deviations below the mean on the Differential Ability Scales-II (DAS-II) Matrices subtest (Elliot, 2007; see below).

One hundred and nineteen (35.4%) children had cochlear implants (CI). Among the 217 DHH children who did not have a CI, 15 children (7.7%) had mild hearing loss (unaided Better Ear-Pure Tone Average between 25 and 40 dB), 42 (21.4%) had moderate hearing loss (41 to 55 dB), 38 (19.4%) had moderately severe hearing loss (56 to 70 dB), 34 (17.4%) had severe

hearing loss (71 to 90 dB), and 67 (34.2%) had profound hearing loss (91 dB or greater). Audiological information was missing for 21 children. Approximately 57% of children were identified with hearing loss before six months of age, 19% between 6 and 23 months, and 12% between age of 24 and 35 months.

Language groups. Children were divided into three language groups based on their auditory access to spoken language and availability of sign language. We determined that children had some auditory access to spoken language if they were able to identify referents of spoken words presented through audition alone on the *Early Speech Perception Test* (ESP; Moog & Geers, 1990, see below). Sign language was available for those children whose teachers signed. Because these two dimensions were orthogonal to each other, there were four possible language groups. The current sample only contained three groups because there were no children who were in spoken only environments without auditory access. The three groups were:

1. **Unimodal Sign group**. Children who did not have auditory access to spoken language and whose teachers signed (with or without spoken language) (*n* = 131). While these children may have received spoken language input, they were visual learners because they had little or no speech perception even with their typical amplification.

2. **Spoken-only group**. Children whose teacher and parents only used spoken language (*n* = 101). All children had auditory access to spoken language.

3. **Bimodal group.** Children who had auditory access to spoken language and whose teachers signed (with or without spoken language) (*n* = 104).

Teachers and examiners (i.e., those who administered study assessments) completed ratings about children's language abilities that indicated our categorization accurately divided our sample. They confirmed that almost all children in the unimodal sign and spoken only groups

used only one language modality. In the sign group, five of the 131 children knew some spoken language but teachers rated these abilities as severely limited. In the spoken language group, there was one child who knew some sign language but teachers' ratings indicated sign was severely limited. Bimodal children showed a range of language use, with 74% using both spoken and signed language, 14% preferred to only use spoken language and 14% preferred to only use sign. While the bimodal children varied in their preferred language modality, they had access to both languages (as evidenced by their speech perception and language environment) and thus were judged to be acquiring both signed and spoken language (to some extent).

INSERT TABLE 1

Demographic characteristics. Table 1 provides demographic and audiological characteristics of the three groups. Comparisons across language groups showed no significant differences in grade, gender, age of diagnosis of hearing loss or presence of an additional disability. The groups differed in their ethnicity and race, χ^2 (2) = 6.8, p = .03 and χ^2 (8) = 28.9, p < .001, respectively. The unimodal sign group had more white and fewer black children compared to the other groups, and the spoken-only group had more black and fewer Hispanic children than the other groups. Other group differences were expected. The three groups differed on parental hearing status, $\chi 2$ (2) = 50.9, p < .001. Children in the spoken only group were more likely to have a cochlear implant than the other groups, χ^2 (2) = 30.3, p < .001. According to teacher report, 100% of children in the spoken-only group, 97% of children in the bimodal group, and only 65% of children in the unimodal sign group *almost always* used their CI at school; 27% of children with CI in the unimodal sign group *never* used their CI. For those using hearing aids, 96% of children in the spoken-only group, 94% of children in the bimodal group

and only 51% of children in the unimodal sign group *almost always* used their hearing aid(s) at school. Instead, 45% of the latter group *only occasionally* used their hearing aids.

Classes and teachers. Data were collected from children in 103 classes located in 40 schools in nine states and one Canadian Province. These programs were located in a variety of educational programs including 18 schools that served only DHH children (2 charter schools, 1 federally-funded school, 6 private schools, and 9 state-funded schools) or in 22 public elementary schools that served DHH and hearing children. There were many more children in the schools for the deaf than in the public elementary school programs. Thus, while the sample was almost evenly split between schools for the deaf and local elementary school programs, 87.5% of the children were in self-contained classes that served only DHH children; 12.5% were educated in settings that included hearing children. Eighty-five percent of the children had teachers who had a master's degree; the rest had teachers with bachelor degrees. They had, on average, 11.26 (S.D. = 9) years of teaching DHH children. Teachers of children who signed (i.e., unimodal sign and bimodal groups) reported using ASL alone (62%), using both ASL and Signed English (27%), and only signed English (11%).

Measures

Speech perception. On the ESP (Moog & Geers, 1990), examiners asked children to select referents of spoken words using an acoustic hoop to prevent speechreading. Performance was classified into four categories: 1 = no pattern perception, 2 = pattern perception, 3 = some word identification, and 4 = consistent word identification.

Speech articulation. On the *Arizona Articulation Proficiency Scale–3* (Fudala, 2000), children were asked to supply a spoken word for a series of pictures. Speech pathology graduate

students scored responses from videos. Raw scores were converted to degree of speech articulation impairment based on age norms provided in the manual.

Nonverbal IQ. Examiners administered the DAS-II Matrices subtest (Elliott, 2007). Children were asked to select a picture that fits the pattern of a matrix. Raw scores were converted to T-scores. The norming population has a mean of 50 and a standard deviation of 10.

Reading. We used three measures to assess the Reading construct. The *Woodcock-Johnson Tests of Achievement-III* (WJ-III, Mather & Woodcock, 2001) Letter-Word Identification (Letter-Word Id) requires children to identify letters and single words. On the WJ-III Passage Comprehension (Passage Comp), initial items require a child to match a rebus with a picture, the next set of items require a child to match short phrases to the appropriate picture among three pictures, and the final set requires a child to provide a missing word in sentences and paragraphs (i.e., cloze technique). Standard ceiling and basal rules were used. For both tests, spoken and/or signed words were acceptable.

The third test measured reading fluency (Fluency). Examiners presented three passages in order of difficulty. The first passage came from the primer (kindergarten) level of the *Reading Mastery Rainbow Edition* (Englemann & Bruner, 1995). The next two passages (one first grade, the other second grade) came from the Florida Center for Reading Research (www.fcrr.org). Examiners only gave the next passage if children met the reading fluency criteria for the previous passage. All passages were followed by one comprehension question. Because it takes longer to sign than to speak, we set different reading fluency criteria depending on children's language use. Children who used spoken language had to read at least five sentences in 60 seconds, while children who signed had to read at least four sentences in 90 seconds to go on to the next passage. We scored the number of passages read fluently.

Spoken phonological awareness. We used three subtests from the *Comprehensive Test of Phonological Processing* (CTOPP; Wagner, Torgesen, & Rashotte, 1999) to assess children's phonological awareness abilities. Examiners delivered directions in the child's preferred modality, but used only spoken language for test items. Because they required spoken language abilities, Elision and Blending were administered only to the spoken-only and bimodal groups. Elision required children to say the remainder of a word when a sound was dropped (e.g., "farm without saying /f/"). Blending required children to combine spoken sounds to form words (e.g., "s-ŭn"). Sound Matching required children to select the picture that matched the initial or final sound of the target picture (e.g., "Which word starts with the /n/ sound like *neck*? Nut, bed, or cake?"). Not surprisingly, given Sound Matching was designed to test early phonological awareness, all initial sound and all but two final sound-matching words also started or ended with the same written or fingerspelled letters. With the addition of signing the directions when appropriate, assessors used standard administration as described in the manual. Following the manual, examiners stopped administration of a subtest when a child was incorrect on all practice items and a score was not given for that subtest.

Fingerspelling phonological awareness. The *Fingerspelling Ability and Phonological Awareness Test* (FS-PAT; Schick, 2012) was used to assess fingerspelling skills and phonological awareness in fingerspelling. The FS-PAT was administered only to the sign-only and bimodal groups. Items on the FS-PAT were presented via a laptop with stimuli signed by a native Deaf signer. For each subtest, the examiner gave directions using an ASL script. Each subtests had two practice items. Fingerspelling Imitation (F. Imitation) required children to imitate a series of fingerspelled real words of increasing length and difficulty (first item = car, last item = caterpillar). Fingerspelling Blending (F. Blend) and Elision (F. Elision) subtests were

modeled after items on the CTOPP blending and elision subtests. For F. Blend, children were required to blend handshapes into a real word; it included eight items of increasing difficulty (first item = t-oy, last item = g-r-a-ss-h-o-pp-e-r, with hyphens showing the segmentation). The Deaf signer paused slightly between the segments as well as spatially separated the segments. F. Elision required children to fingerspell a new word after removing a fingerspelled chunk from a fingerspelled model. The Deaf signer fingerspelled a word and instructed the child to delete a specific fingerspelled segment or letter. It included eight items of increasing difficulty (first item = popcorn without –corn, last item = strain without –r).

Language. We used the *Expressive One-Word Picture Vocabulary Test-4* (EOWPVT; Martin & Brownell, 2011) to measure children's expressive vocabulary ability. EOWPVT required a child to name (using either speech or sign or both) pictures of increasingly unfamiliar items. Examiners used standard basal and ceiling rules; however, the examiners used a list of acceptable signs to score children's signed responses. We used the Elaborated Phrases and Sentences subtest of the *Test of Auditory Comprehension of Language-3* (TACL; Carrow-Woolfolk, 1999) to assess children's abilities in receptive English grammar and word order at the sentence level. Assessors administered items in spoken English, voice-off English-like signing, or simultaneous spoken and signed communication (SimCom), depending on child's preferred communication method. Assessors signed the sentences in English word order but did not sign English morphemes (e.g., -ed, -s). Children had to select the correct picture from three choices. We administered the Word Structure of the *Clinical Evaluation of Language Fundamentals-4* (CELF; Semel, Wiig, & Secord, 2003) to assess children's abilities in expressive spoken English inflectional morphology. The test used cloze-set items to elicit expressive morphology. Standard administration procedures were used for the children in the spoken-only group. Examiners

administered stimuli to children who sign using SimCom. Children had to produce the word with the correct morphology, using either speech, English signed morphemes, or fingerspelling. We used the *ASL Receptive Skills Test-Revised* (Schick, 2013) to measure DHH children's ability to understand ASL syntax and classifiers at the sentence level. Examiners administered this test only to the sign-only and bimodal groups. Children watched a video of a model signing ASL sentences and selected a picture from a closed set of three, four, or six pictures.

Procedures

Our test battery included tests developed for hearing children. We adapted these tests for use with signing children by having a team of experts that included native Deaf and hearing signers create videos of standardized directions, items (e.g., sentences on the TACL), and a list of acceptable signed responses (all available from first author). Examiners were teachers or speech-language-pathologists and had expertise in the children's language. The examiners were extensively trained in administration procedures and the accommodations based on children's language knowledge (e.g., acceptable sign in vocabulary assessments) during a two-day training workshop. Examiners who administered the tests to signing children were provided videos of a deaf examiner and administered the tests to the fourth author, a native signer, for approval.

We recruited schools primarily from the home or neighboring states of the research team. We targeted schools that had a concentration of DHH children. We obtained appropriate Institutional Review Board approval to use parent notification for this study. This meant that we were able to assess all children who met eligibility criteria in these schools. During the fall, examiners administered tests individually in a quiet, familiar room in the school building.

We maintained data integrity in four ways. Examiners doublechecked their live scoring by watching videorecordings. Graduate students rescored expressive items on language and

reading assessments for 20% of children randomly chosen (blocked by modality). Interrater agreement between examiners and students was excellent: EOWPVT $r = .99$, LetterWordID $r = .86$; PassComp $r = .99$; CTOPP blending $r = .91$; CTOPP Elision $r = 1.0$. Graduate students independently calculated test scores twice and conferenced with a third researcher to resolve discrepancies. Finally, graduate students independently entered scores twice into the database and discrepancies were resolved by the third author.

Statistical Analysis

Whereas the three groups were administered many of the same measures, some measures were not administered based on the group's spoken or sign language knowledge, following a known-missing design (Widaman, Grimm, Early, Robins, & Conger, 2013). Examiners did not administer the fingerspelling and ASL tests to children who did not know sign (the spoken-only group) or the tests that required spoken responses to children in the unimodal sign group. Expressive English Syntax was administered to all children but excluded from the analyses for children in the signing groups because children, on average, performed at floor. Figure 1 shows a schematic form of the a-priori confirmatory factor model to be fit, including factors for Reading, Fingerspelling, Spoken PA, and Language. The four latent factors are shown as circles and the 13 tests are shown as rectangles, present or absent for their respective groups. Each test is intended to measure the respective factor (or construct) as shown by the arrows, and all factors have correlations which are freely estimated. These latent correlations represent relations between factors after removing measurement error due to the separate tests.

INSERT FIGURE 1

We used CFA to test the model fit for a structure with four factors: Reading, Fingerspelling, Spoken PA, and Language. Models were initially fit in SAS PROC CALIS (SAS

Institute Inc., 2014), which allows for unequal numbers of measures, and then fit in Mplus (Muthén & Muthén, 2012), with constraints to force non-administered measures to be effectively missing in the appropriate groups (Widaman et al., 2013). This model is a planned-missing design, in which a joint model is fit across groups without all groups having the same measures. Tests each represent a sample of all possible measures of a factor (standard CFA) in each group. The current planned-missing design allows us to evaluate a joint model across groups, estimating factor scores using only the tested measures. The basis for such estimation is standard full-information maximum likelihood. Preliminary models were tested with complete measures across both software programs to ensure comparable solutions, and estimated via full information maximum likelihood.

Because our goal is to understand the functioning of these tests within as well as across groups, we present two sets of analyses: within-group CFA and a multiple-group CFA. Fitting models separately can highlight distinctions missed in a joint model, while a joint model can highlight commonalities that otherwise might be missed. In fitting a multiple-group model, the emphasis is on distinguishing measurement differences due to tests (e.g., bias) from genuine differences due to students (e.g., in the means or variances of the factors).

Within-group CFA. We fit the four-factor model shown in Figure 1 to each group to evaluate its fit and validity to describe the structure of language and literacy abilities among these tests with the fingerspelling factor not modeled for the spoken language group.

Multiple-group CFA (measurement invariance). We tested this model for across-group equality of measurement parameters so that factor scores and their relations could be compared across groups. For testing measurement equivalence across groups, we used a standard sequential process (Vandenberg & Lance, 2000). Specifically, we tested to see if the groups were

equivalent for five nested models: Model 1—configural (factor structure) invariance, Model 2—metric (loading) invariance, Model 3—scalar (intercept) invariance, Model 4—equality of factor covariances, and Model 5—equality of factor means. This sequence of five models evaluates the following respective hypotheses of equality across the three groups: 1) Tests aligned with their factors in the proposed, theory-based configuration. 2) Tests measured their factors on an equivalent metric (i.e., in the same units). 3) Tests had the same model-implied means. 4) Factors had the same variance and covariance, and 5) Factors had the same group means.

Model fit. Evaluating CFA is a complex issue with many guidelines, but no single, objective criterion for model fit (Marsh, Hau, & Grayson, 2005; Marsh, Hau, & Wen, 2004). There are several indices to evaluate, and these must be considered relative to comparable models in this particular field. Multiple-group testing is complex, with several common indices being overly stringent (Chen, 2007; Cheung & Rensvold, 2002) and little guidance beyond the two-group case—we are testing across three groups. There are multiple criteria recommended and we will report those in our evaluations of fit (see Chen, 2007). While there are few, if any, reported CFA models for DHH children (Webb et al., 2015), we follow guidelines of comparative fit index (CFI) near 0.90 and the root mean square of error of approximation (RMSEA) and the standardized root mean square residual (SRMR) near 0.10.

Results

Description of the Three Language Groups

Cognitive and speech abilities. The three groups scored in the average range on the DAS-II Matrices subtest (see Table 1), with no group differences. As expected, the groups differed on their speech perception and speech articulation abilities (see Table 1).

Language and literacy abilities. Table S1 (available online) displays descriptive statistics and internal consistency reliability (Cronbach's alpha) for the 13 measures in each of the three groups. (See Authors, 2019, for descriptive statistics of standard scores for tests that have norms). Dashes indicate that the measure was not administered for that group. Estimates using full-information maximum likelihood for the missing tests were at floor (or slightly negative), suggesting our choice not to administer these tasks was an ethical decision to minimize children's frustration. Model-based reliability (R^2) is presented in Table S6. Reliabilities for our assessments were moderate to high.

Table S2 (available online) presents correlation matrices for each of the three groups among the 13 measures. Correlations within constructs were high and homogeneous, conforming to the four blocks of variables designed to measure reading, fingerspelling, spoken PA, and language. The correlations were somewhat mixed and heterogeneous across constructs.

We organize our results in the order of our three research questions.

Research question 1. *What skills relate to reading abilities in young DHH children in three language groups?* We answered this question with within-group and multi-group CFA.

Within-group CFA

We examined the degree to which the hypothesized four-factor model for unimodal sign and bimodal groups and three-factor model for spoken-only group fit the data. Figure 2 shows fit indices for each model for the three groups. Model Fit for the spoken-only group (for three factors) and for the unimodal sign group (for four factors) was good with CFI > .95, SRMR < .05, and RMSEA close to 0.10. The fit for the bimodal group was marginal (CFI = .91; SRMR = .08; RMSEA = .13). We judged the global fit to be reasonable.

INSERT FIGURE 2 HERE

The fully standardized estimates from the four-factor model fit to each group are shown in Figure 2. The standardized loadings on the straight arrows represent the correlation between measures (rectangles) and factor (circles). Figure 2 shows that these loadings are all generally high, suggesting that the measures are good indicators of the underlying factors for all three groups. The loadings were particularly high for the reading measures with loadings above .89. The loadings for the language factors were also high with all but one measure above .82. ASL and English receptive syntax had high loadings on the language factor for both the bimodal and unimodal sign groups. Measures for fingerspelling and for spoken PA loaded well on their respective factors.

The curved arrows between factors in Figure 2 represent the correlations between factors. For the spoken-only group, reading was highly correlated with spoken PA (.92), and moderately correlated with language (.66). For the bimodal group, reading was highly correlated with both fingerspelling (.92) and spoken PA (.84), and moderately correlated with language (.78). For the unimodal sign group, reading was highly correlated with fingerspelling (.99) and language (.87), and only moderately correlated with spoken PA (.66). In the latter two groups, fingerspelling was moderately correlated with spoken PA (.78 and .73, respectively).

Multiple-group CFA

Research question 2. *Is there measurement equivalence across groups? In other words, do the tests measure constructs in the same way for each language group?*

Based on these initial four-factor within-group models, a joint, multiple-group four-factor model was fit, but had serious estimation problems because of the high correlation between fingerspelling and reading. We therefore modified the model to three factors, placing the fingerspelling and reading measures as indicators of a single broader factor that we call literacy.

INSERT TABLE 2 HERE

Table 2 presents the tests of measurement invariance using this three-factor structure. As the table shows we tested measurement invariance for four nested models. The fifth model tests for full equality of latent means across groups. The columns of Table 2 show fit indices, along with differences (Δ) comparing each model to the less restricted model above it (Chen, 2007).

The first line of Table 2 shows that this modified three-factor model fit reasonably well, with some degree of misfit (CFI = .94; RMSEA = .11; SRMR = .17). While the fit of this model was not ideal, the substantive interpretation matches theoretical expectation with good loadings and interpretable latent correlations. We, therefore, retained the three-factor model of literacy (that included both reading and fingerspelling), spoken PA, and language as the most reasonable across the groups.

In the second row of Table 2, we show the tests of equivalence of factor loadings to identify group differences in the scales or variances of the latent factors. In the third row, we tested equivalence of regression intercepts. Based on changes in CFI, RMSEA and SRMR (Chen, 2007), we suggest that Model 3, which imposes equality across groups for intercepts and loadings, fit reasonably. Model 3 suggests that the factor structure, loadings (i.e., correlations between measure and factor) and intercepts (i.e., the model-implied means) of the 13 measures were similar across the three groups.

In the bottom two rows of Table 2, we present tests of across-group equality for the latent variance-covariance matrix (Model 4) and latent means (Model 5). Chen (2007) does not provide explicit alternative criteria for testing across-group factor structure, but recommends that SRMR can be informative. Model 4 had a large change in CFI, SRMR, and BIC. Model 5 resulted in a large change in CFI but little else. Because Model 4 had several indices of poor fit, we retain

Model 3 of intercept invariance as the final model for examination of group differences in factor scores (both correlations between factors and latent means of those factors).

INSERT FIGURE 3 AND TABLE 3 HERE

The results of this Model 3 of intercept invariance are presented in Figure 3. The groups are shown as before, left to right: spoken-only, bimodal, and unimodal sign. For each group, fully standardized results are shown. Table 3 shows the latent factor correlation matrix, the latent means, and latent standard deviation for each group (relative to the spoken-only group, SD = 1).

Because Model 4 of full equality of latent covariance was rejected, we next tested group differences in the individual bivariate relations between the constructs to address the third research question.

Research question 3. *Do children in the three groups differ in terms of relations between abilities (correlations), proficiency (means), and individual differences (variances)?*

We next tested each factor for differences across groups: correlations via Fisher's Z-test and latent means by a t-test, reported in Table 3 (each calculated within Model 3, using MODEL CONSTRAINT in Mplus to test for statistical significance of the differences). The correlation between Literacy and Spoken PA did not differ between the spoken-only and bimodal groups (r = 0.92 and 0.88, respectively), but was significantly lower for unimodal sign group (r = 0.69). The correlation between Language and Spoken PA was also lower for unimodal sign than for the spoken-only group. On the other hand, the correlation between Language and Literacy was significantly higher (.89) for the unimodal sign than for the spoken-only group (.67). As shown in Table 3 and Figure 4, the three groups did not significantly differ in their means for Language. In contrast, all three groups differed significantly from each other in spoken PA. For Literacy, the unimodal sign group differed from the spoken-only group. Figure S1 (available online)

combines the mean information from Table 3 with the correlations from Figure 3 in a compact layout.

INSERT FIGURE 4 HERE

Figure 4 allows for visual comparison of the three groups' performance, using estimated factor scores for each student. The Language boxplots in the top panel show the high degree of similarity across groups, both in their level and spread of scores. The middle panel shows the strong differences in Spoken PA: the unimodal sign group in particular has lower scores and is highly homogeneous. However, some extreme scores in this group overlap with high-scoring children in the Bimodal and Spoken-only groups. Finally, the lower panel shows boxplots for Literacy, showing the high degree of overlap across groups, though the Spoken-only group has a larger spread of scores, especially above average.

Tables S3-S6 are available online to provide additional statistical information. The estimates of loadings and intercepts from the final Model 3 are shown with standard errors in Table S3. The estimates in Table S4 in this three-factor model of measurement equivalence are reasonably close to those in Table S3, based on the four-factor model not imposing measurement equivalence. Table S5 reports residual variances. Table S6 reports R^2 values.

Discussion

The goal of this study was to describe the multivariate relations among language and literacy skills for three groups of DHH children who differed in their language modality. While other researchers have contrasted the reading processes of oral deaf adults and those who sign (Hirshorn et al., 2015; Miller, 2002), this is the first study to examine differences in young children who are learning to read. It is also the first of its kind to compare these groups with bimodal DHH children. Our results confirmed our hypothesis that all DHH children learning to

read rely on the same fundamental abilities of language and phonological processing but the modality, levels, and relations among these abilities differ.

Multivariate relations for three language groups

Our first analysis examined children's language and literacy skills *within* each of our language groups. The results were consistent with our theoretically-driven models of three factors for the unimodal spoken group and four factors for the bimodal and unimodal sign group. We describe the constructs, the implications of the models for the constructs' indicators (i.e., tests), and relations between reading the other constructs in the following section.

Language. We assessed expressive vocabulary and receptive grammatical knowledge. While these assessments required children to answer using different modes (expressive vs receptive) and different domains of language, they all formed one integrated language construct, with high factor loadings for all measures. This was true for all three language groups despite differences in the language or modality assessed (ASL vs. English; sign vs. spoken). For the spoken-only group, all three measures reflected children's knowledge of the English language. For the other two groups, we included measures of both English and ASL grammar. These measures had high and equal loadings on the language construct. This suggests that both groups of signing children were bilingual. This was not surprising for the bimodal group; they were in signing environments but had some auditory access to spoken English. Importantly, the same pattern of loadings was found for the unimodal sign group, indicating that these children may also be bilingual, even when they were not bimodal. Some researchers have posited that unimodal sign DHH children become bilingual by acquiring English knowledge from print (Hoffmeister & Caldwell-Harris, 2014). However, the DHH children in this study were beginning readers so it is unlikely that they learned English grammar from print. Instead, we

hypothesize that they are acquiring English from adults in their community who use contact sign as well as ASL (Lucas & Valli, 1991). Our English receptive syntax test required children to understand English word order, including complex grammar. The language on this task was more complex than that on the passage comprehension reading test. While we did not test their English grammatical system fully, our results suggest high consistency in the way DHH children performed on these seemingly disparate language tasks. It may be that this knowledge can be leveraged to assist children in their acquisition of literacy (Hermans et al., 2010). Because we had only one indicator of the signing children's English language abilities (i.e., English receptive syntax), our findings should be considered suggestive and in need of further research.

Research with young hearing children has also found that language is unidimensional (Language and Reading Research Consortium, 2015). The Consortium concluded that, despite the fact that vocabulary and grammar are separate aspects of language, they measure a unitary, integrated language ability during early elementary school. This is consistent with theories of language development that posit the interconnection between lexical and grammatical development. Our results suggest this is also the case for DHH children.

Spoken PA. The three tests that measure children's ability to blend, segment, and identify phonemes in spoken words formed an integrated construct for both spoken-only and bimodal groups. Our results are similar to research with both DHH and hearing children that show that different phonological awareness tasks (e.g., rhyming, blending) measure one underlying PA ability (Anthony et al., 2002; Webb & Lederberg, 2014).

The blending and elision PA tasks required spoken language abilities; the sound matching task asked children to select pictures of words that share a phoneme. The latter could be completed without spoken language and resembles how other researchers have assessed PA with

DHH children (Kyle & Harris, 2010). The high loadings for all three tests on the spoken PA construct for the spoken-only and bimodal group suggests the matching task is a good measure of PA, and thus, may be a valid test to assess spoken PA in unimodal signing children.

Fingerspelling phonological processing. Fingerspelling was measured in both signing groups. We used three novel tasks to measure fingerspelling. We included a measure of phonological memory, the ability to imitate fingerspelled words that increased in length. We also included two measures of fingerspelling PA that required children to blend spaced fingerspelled words, or remove a fingerspelled letter to create a new word. Our results confirmed that these tasks measure one underlying construct that we define as fingerspelling phonological processing. Past researchers have only included one measure of fingerspelling ability and that measure is frequently one of phonological memory. Our study confirms that fingerspelling abilities include the ability to manipulate fingerspelled words through blending and elision. By including three tests, we were able to measure how it related to measures of language and reading.

Reading. Reading ability was measured by tests of word reading, reading comprehension, and fluency. These three tests had similarly strong associations (i.e., all more than $\geq .89$) with the Reading factor for all three groups. Most theories, including the Simple View of Reading, posit that word recognition and reading comprehension are separate constructs, with language comprehension more important for the latter than the former. However, in a test of this hypothesis with a large sample of hearing children, Lonigan and Burgess (2017) found that measures of children's ability to recognize words and to understand sentences and passages formed one factor (reading) for students in kindergarten to second grade. They found that children's word reading skills and reading comprehension formed two distinct constructs only with older children (third to fifth grade), suggesting that this represents a developmental process,

where comprehension only becomes separate from word reading when word decoding is no longer the roadblock to reading. In our study, we found that reading fluency also loaded essentially equally with word recognition and reading comprehension on the reading factor.

Despite the fact that these tests were created for hearing children, they measured reading in all three groups of DHH children, regardless of spoken or signed response. This is somewhat surprising given that the act of reading is different for children who use spoken vs. signed language. Indeed, using a large data set of 950 DHH children, Authors (2017) found that WJ Letter-Word ID and WJ Passage Comp had similar psychometric properties for the three language groups (including item difficulty and sensitivity). Factor loadings also suggest that our accommodation allowing longer response time on the reading fluency test for children who signed, still yielded equivalent tests across language groups.

Relations between constructs. The within-group models also estimated relations among the constructs. For the spoken-only group, reading abilities had a strong (r = .92) relation with spoken PA but only a moderate relation with (r = .67) language. This is consistent with research with both hearing (Lonigan & Burgess, 2017) and DHH beginning readers (Cupples et al., 2014; Webb et al., 2015) that shows that the ability to manipulate the sublexical structure of words is critical for learning to read an alphabetic script like English. This finding disputes the work of researchers who argue that language is more important than PA for DHH readers (Harris et al., 2017; Nittrouer et al., 2012). The latter researchers have included older children and differences may reflect the decreasing role of PA after children have learned the alphabetic principle.

For the bimodal group, reading was also strongly related to abilities to manipulate the sublexical structure of words, as reflected by both fingerspelling PA (r = .94) and Spoken PA (r = .84) abilities. These two phonological skills were also correlated with each other (r = .78) for

children acquiring both spoken and signed languages. Although we have posited that fingerspelling phonological processing may serve as a functional alternative to spoken PA, the two skills also may support each other, at least for bimodal children (Petitto et al., 2016).

For the unimodal sign group, reading was almost perfectly correlated with fingerspelling (r = .99). Unimodal sign children's reading abilities were also highly related ($r = .87$) to their language abilities, but less so, but still significantly, with spoken PA ($r = .66$).

Across-group comparison

The second analysis, using multi-group CFA, examined the extent to which all the features of the model shown in Figure 2 were the same across the three language groups. Specifically, we tested the equivalence of overall structure, relations of tests to constructs (loadings), model-implied means of those tests (intercepts), and differences among the latent factors across groups (factor means, variances, and correlations).

Configural invariance. A four-factor model was supported within each group, but the model could not be fit in a joint, multiple-group model. Instead, the high correlation between Fingerspelling and Reading ($r > .93$) suggested that a simpler three-factor model was necessary for comparison across groups. For children who sign (i.e., unimodal sign and bimodal), fingerspelling and reading appear to be integrated into a single construct. The model suggests that the same ability is responsible for reading and fingerspelling among signing children; this ability may represent the knowledge of how to represent words in print and with the hand. This is similar to studies where young elementary-school age hearing children also show an integration of seemingly diverse skills (e.g., spoken PA, alphabetic knowledge, word reading) into one construct that represents a higher-order ability (Mehta et al., 2005; Storch & Whitehurst, 2002).

Measurement equivalence. This three-factor model was tested for measurement equivalence across groups. We evaluated the relations (loadings) of the tests to their intended constructs, as well as whether the tests differed in mean levels for a construct across groups (intercepts). No strong evidence of measurement bias was found, suggesting that these tests give essentially equivalent information about children's latent abilities for the three subgroups.

This equivalence has two important implications. First, these tests can yield comparable scores across groups with the adaptations that we made. Given the heterogeneity of DHH children, being able to use one test for all children is critical for educators and researchers. In order for that to happen, a careful process of accommodation and standardization is required to make sure the test can be applied to all DHH children, as occurred in the current study. Establishing equivalence of loadings and intercepts for total scores across the three groups is an important first step. Future research that documents the psychometric properties of test items and indicates whether there is item bias is an important next step.

Second, our results suggest it may be appropriate to use individual tests as indicators of the underlying construct in consideration of cost, time, and burden on students. For example, to measure language, many researchers use vocabulary as a proxy for DHH children's language ability (Kyle et al., 2016; Webb et al., 2015). The advantage of vocabulary is that it can be adapted across signed and spoken languages. In the current study, we used expressive vocabulary because it allowed the children to answer with a spoken and/or signed word; assessors did not have to determine the children's preferred language, as would be the case for a receptive test. Our results suggest that vocabulary is likely to be a valid assessment of overall language in DHH children and is equally valid to measure spoken and signed language abilities.

Language modality group differences. Finding measurement equivalence allowed us to compare groups on their latent scores (i.e., their estimated true scores on the factors), as well as variances and relations among factors. The groups had equivalent mean language abilities. Other research has found that the variables that influence children's spoken and signed language abilities include those that are the same regardless of modality (e.g., age of identification) and those that are different (e.g., access to spoken or signed language; see Lederberg et al., 2013 for a review). Despite these differences, this study indicates that DHH children who use different language modalities are similar to each other in language ability or proficiency, at least for those who are attending special classrooms for DHH children in the U.S. Typically, researchers measure DHH children's spoken or signed language and thus, do not measure children's overall language ability. Because of our novel approach of creating a language factor that allowed the tests to vary for the groups, the language factor reflected the language of the group (i.e., ASL for two groups, English for all three). Thus, we were able to show that modality did not affect the language proficiency of DHH children. The inability to hear spoken language did not impact the ability to acquire language when given access to visual language.

Not surprisingly, the three groups differed in their ability to perceive and manipulate phonemes in spoken words (spoken PA). The unimodal sign group performed much lower than the spoken-only and bimodal groups. In fact, 75% of the unimodal sign group scored below the lower quartile of the other two groups. Intriguingly, 5% of children in the unimodal sign group performed above the mean of the spoken group. These exceptional children seemed able to develop sensitivity to spoken phonemes, even when they have little or no auditory access to spoken language. They likely used visual skills (speechreading) to build representations of spoken words. For example, they might complete the sound matching task by matching words

that look the same on the mouth (Kyle et al., 2016). They also could be using orthographic or fingerspelling knowledge. Although these few children may use spoken phonology in their reading, the majority of DHH children in the unimodal sign group did not develop spoken PA.

In contrast, while bimodal children scored a half standard deviation lower on spoken PA than spoken-only children, there was considerable overlap in these two groups' abilities. Despite the fact that the bimodal children differed considerably in their spoken language abilities compared to the spoken-only group, they were able to use their auditory access to speech to develop spoken PA almost to the same extent as the children with much better speech skills. This is consistent with Lederberg, et al.'s (2013) hypothesis that print serves as a visual support for DHH children's ability to perceive the sublexical phonological structure of words but only for those who have some auditory access to spoken phonemes.

The spoken-only and bimodal groups did not differ significantly in their reading abilities, notwithstanding their differences in speech abilities and spoken PA. On the other hand, the unimodal sign group had significantly weaker reading skills than the spoken-only children did. These results suggest that the use of sign language does not impede learning to read, but the lack of auditory access to spoken sublexical structure likely makes learning to read more difficult.

With respect to correlations among the constructs, the unimodal sign group had substantially different correlations than the speech-only group. The correlations between Language and Spoken PA, as well as between Literacy and Spoken PA were lower than those in the spoken-only group. This suggests that while Literacy and Spoken PA were related in all groups, Spoken PA plays a much less important role in reading for young children who do not have access to spoken language. Interestingly, the correlation between Language and Literacy was higher in the unimodal sign group than it was in the spoken-only group. Our findings

suggest that when researchers do not separate bimodal from unimodal sign children they may get conflicting results because these groups may learn to read through different pathways.

Educational Implications

Our results suggest that the overall learning objectives of reading interventions should be the same for all DHH children. All children need language and the ability to manipulate the sublexical structure of words to learn to read. For hearing children and for children who use spoken language (with or without sign), learning to read an alphabetic language depends on the ability to manipulate the sublexical structure of spoken words. For these children, instruction that includes phonics and support for the development of phonological awareness is important. For children who do not have auditory access to spoken language, manipulation of spoken words plays a less important role. Indeed, fewer than 5% of the unimodal sign children appear to be developing spoken PA, yet they were developing literacy skills at almost the same level as the other two groups. The strong relation between fingerspelling phonological processing and reading suggests that these children may use fingerspelling as an alternative pathway to manipulate the sublexical structure of printed words, and therefore to learn to read. Using fingerspelling to teach these children will probably facilitate their reading abilities.

The challenge in signing programs is that classrooms typically include both bimodal and unimodal sign children. Given that spoken PA appears to be differentially helpful for these two groups of children, optimal instruction will probably require appropriate differentiation of instruction. Future researchers may benefit from examining the potentially differential effects of spoken and fingerspelled phonics instruction on bimodal and unimodal signing children.

While instruction in PA is important, it should not replace intensive language instruction. Our results show that reading was related to children’s language abilities for all groups. Thus,

instruction that focuses on improving language in the modality that children can access should be an important part of all DHH children's educational environment. In addition to modality, the quality and type of instruction is likely to impact DHH children's language growth. For example, research suggests DHH children's language learning relates to the amount teachers explicitly teach the meaning of new words and expand on children's utterances (Duncan & Lederberg, 2018). As with hearing children, meaning-based instruction is as important for code-based instruction. A balance between the two is probably critical for successful reading.

Limitations

One major challenge of conducting research with low incidence populations is to obtain a sample size sufficient to examine differences within DHH children. We chose to examine differences among groups that differed in language modality but ignored other important variables. We included children from 5 to 8 years of age, but we did not include age in our models. While age may impact the structure of language and literacy skills, our groups did not differ by age. We also did not examine other potentially important variables such as audiological technology (e.g., CI), maternal education, and hearing status of parents. Additionally, the current model uses only a small, selected number of tests per factor.

The children in this study were part of classrooms, but our models did not account for classroom differences because of the complexity of the across-group tests we wanted to evaluate. Bimodal children shared classrooms with unimodal sign children, but spoken-only children were in different classes. Some group differences could be attributable to classroom differences.

While our models showed excellent fit for the spoken and unimodal sign groups, model fit for the bimodal group was substantially lower. This lack of fit may reflect the mixed nature of the bimodal group, which included children who were acquiring spoken language to varying

degrees. Children with only mild speech impairment might resemble the factor structure of the spoken-only group, while children with more severe speech impairment may resemble the unimodal sign model. A larger study could evaluate the complexities of group assignment for language modality with a factor mixture model.

Conclusion

A long-running debate in the field is whether DHH children learn to read through qualitatively-different processes than hearing children. In our paper, we ask a slightly different question: Do DHH children who differ on their language modality learn to read through qualitatively-different processes? The answer is yes and no. On the one hand, for all three groups, reading abilities were related to children's language and their ability to manipulate the sublexical structure of words. On the other hand, the role of spoken language differed for those without auditory access to language. For the unimodal sign children, reading relied less on spoken PA and more on fingerspelling and visual language compared to the other two groups. This suggests that there are qualitative differences in the way unimodal sign children learn to read and indicates that these children may need different instructional practices from that used with hearing children.

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Conflict of interest

The authors have no conflicts of interest to disclose.

References

Anthony, J. L., Lonigan, C. J., Burgess, S. R., Driscoll, K., Phillips, B. M., & Cantor, B. G. (2002). Structure of preschool phonological sensitivity: Overlapping sensitivity to rhyme, words, syllables, and phonemes. *Journal of Experimental Child Psychology, 82*(1), 65-92. doi:10.1006/jecp.2002.2677

Braze, D., Katz, L., Magnuson, J. S., Mencl, W. E., Tabor, W., Van Dyke, J. A., . . . Shankweiler, D. P. (2016). Vocabulary does not complicate the simple view of reading. *Reading and Writing, 29*(3), 435-451. doi:10.1007/s11145-015-9608-6

Brentari, D. (1998). *A Prosodic Model of Sign Language Phonology*. Cambridge, MA: MIT Press.

Carrow-Woolfolk, E. (1999). *Test for Auditory Comprehension of Language-Third Edition*. Austin, TX: Pro-Ed.

Chamberlain, C., & Mayberry, R. I. (2008). American Sign Language syntactic and narrative comprehension in skilled and less skilled readers: Bilingual and bimodal evidence for the linguistic basis of reading. *Applied Psycholinguistics, 29*(3), 367-388. doi:10.1017/S014271640808017X

Chen, F. F. (2007). Sensitivity of goodness of fit indexes to lack of measurement invariance. *Structural Equation Modeling, 14*(3), 464-504. doi:10.1080/10705510701301834

Cheung, G. W., & Rensvold, R. B. (2002). Evaluating goodness-of-fit indexes for testing measurement invariance. *Structural Equation Modeling: A Multidisciplinary Journal, 9*(2), 233 - 255. doi:10.1207/S15328007SEM0902_5

Connor, C. M. (2016). A lattice model of the development of reading comprehension. *Child Development Perspectives, 10*(4), 269-274. doi:10.1111/cdep.12200

Cupples, L., Ching, T. Y. C., Crowe, K., Day, J., & Seeto, M. (2014). Predictors of early reading skill in 5-year-old children with hearing loss who use spoken language. *Reading Research Quarterly, 49*(1), 85-104. doi:10.1002/rrq.60

Davidson, K., Lillo-Martin, D., & Pichler, D. C. (2014). Spoken English language development among native signing children with cochlear implants. *Journal of Deaf Studies and Deaf Education, 19*(2), 238-250. doi:10.1093/deafed/ent045

Dillon, C. M., de Jong, K., & Pisoni, D. B. (2012). Phonological awareness, reading skills, and vocabulary knowledge in children who use cochlear implants. *Journal of Deaf Studies and Deaf Education, 17*(2), 205-226. doi:10.1093/deafed/enr043

Duncan, M. K., & Lederberg, A. R. (2018). Relations between teacher talk characteristics and child language in spoken-language deaf and hard-of-hearing classrooms. *Journal of Speech, Language, and Hearing Research, 61*(12), 2977-2995. doi:10.1044/2018_JSLHR-L-17-0475

Ehri, L. C. (2014). Orthographic mapping in the acquisition of sight word reading, spelling memory, and vocabulary learning. *Scientific Studies of Reading, 18*(1), 5-21. doi:10.1080/10888438.2013.819356

Elliott, C. D. (2007). *Differential Ability Scales-II* (2nd ed.). San Antonio, TX: The Psychological Corporation.

Emmorey, K., McCullough, S., & Weisberg, J. (2015). Neural correlates of fingerspelling, text, and sign processing in deaf American Sign Language-English bilinguals. *Language, Cognition & Neuroscience, 30*(6), 749-767. doi:10.1080/23273798.2015.1014924

Emmorey, K., & Petrich, J. A. F. (2012). Processing orthographic structure: Associations between print and fingerspelling. *Journal of Deaf Studies and Deaf Education, 17*(2), 194-204. doi:10.1093/deafed/enr051

Englemann, S., & Bruner, E. (1995). SRA Reading Mastery Rainbow Edition. *Chicago, IL: SRA: McGraw-Hill*.

Fudala, J. B. (2000). *Arizona Articulation Proficiency Scale (3rd ed.)*. Los Angeles, CA.: Western Psychological Services.

Haptonstall-Nykaza, T. S., & Schick, B. (2007). The transition from fingerspelling to English print: Facilitating English decoding. *Journal of Deaf Studies and Deaf Education, 12*(2), 172-183. doi:10.1093/deafed/enm003

Harris, M., Terlektsi, E., & Kyle, F. E. (2017). Literacy outcomes for primary school children who are deaf and hard of hearing: A cohort comparison study. *Journal of Speech, Language, and Hearing Research, 60*(3), 701-711. doi:10.1044/2016_JSLHR-H-15-0403

Hermans, D., Ormel, E., & Knoors, H. (2010). On the relation between the signing and reading skills of deaf bilinguals. *International Journal of Bilingual Education and Bilingualism, 13*(2), 187-199. doi:10.1080/13670050903474093

Hirsh-Pasek, K. (1987). The metalinguistics of fingerspelling: An alternate way to increase reading vocabulary in congenitally deaf readers. *Reading Research Quarterly, 22*(4), 455-474. doi:10.2307/747702

Hirshorn, E. A., Dye, M. W. G., Hauser, P., Supalla, T. R., & Bavelier, D. (2015). The contribution of phonological knowledge, memory, and language background to reading comprehension in deaf populations. *Frontiers in Psychology, 6*. doi:10.3389/fpsyg.2015.01153

Hoffmeister, R. J., & Caldwell-Harris, C. L. (2014). Acquiring English as a second language via print: The task for deaf children. *Cognition, 132*(2), 229-242. doi:10.1016/j.cognition.2014.03.014

Keane, J., & Brentari, D. (2016). Fingerspelling: Beyond handshape sequences. In M. Marschark, P. E. Spencer, M. Marschark, & P. E. Spencer (Eds.), *The Oxford handbook of deaf studies in language.* (pp. 146-160). New York, NY, US: Oxford University Press.

Kyle, F. E., Campbell, R., & MacSweeney, M. (2016). The relative contributions of speechreading and vocabulary to deaf and hearing children's reading ability. *Research in Developmental Disabilities, 48*, 13-24. doi:10.1016/j.ridd.2015.10.004

Kyle, F. E., & Harris, M. (2010). Predictors of reading development in deaf children: A 3-year longitudinal study. *Journal of Experimental Child Psychology, 107*(3), 229-243. doi:10.1016/j.jecp.2010.04.011

Language and Reading Research Consortium (2015). The dimensionality of language ability in young children. *Child Development, 86*(6), 1948-1965. doi:10.1111/cdev.12450

Lederberg, A. R., Schick, B., & Spencer, P. E. (2013). Language and literacy development of deaf and hard-of-hearing children: Successes and challenges. *Developmental Psychology, 49*(1), 15-30. doi:10.1037/a0029558

Lonigan, C. J., & Burgess, S. R. (2017). Dimensionality of reading skills with elementary-school-age children. *Scientific Studies of Reading, 21*(3), 239-253. doi:10.1080/10888438.2017.1285918

Lucas, C., & Valli, C. (1991). ASL or contact signing: Issues of judgment. *Language in Society, 20*(2), 201-216.

Marschark, M., Tang, G., & Knoors, H. (2014). *Bilingualism and bilingual deaf education*. New York, NY: Oxford University Press.

Marsh, H. W., Hau, K.-T., & Grayson, D. (2005). Goodness of fit in structural equation models. In A. Maydeu-Olivares & J. J. McArdle (Eds.), *Contemporary psychometrics: A festschrift for Roderick P. McDonald* (pp. 275-340). Mahwah, NJ: Lawrence Erlbaum.

Marsh, H. W., Hau, K.-T., & Wen, Z. (2004). In search of golden rules: Comment on hypothesis-testing approaches to setting cutoff values for fit indexes and dangers in overgeneralizing Hu and Bentler's (1999) findings. *Structural Equation Modeling: A Multidisciplinary Journal, 11*(3), 320-341. doi:10.1207/s15328007sem1103_2

Martin, N. A., & Brownell, R. (2011). *Expressive One-Word Picture Vocabulary Test - Fourth Edition*. Novato, CA: Academic Therapy

Mather, N., & Woodcock, R. W. (2001). *Woodcock-Johnson III Tests of Achievement*. Itasca, IL: Riverside.

Miller, P. (2002). Communication mode and the processing of printed words: Evidence from readers with prelingually acquired deafness. *Journal of Deaf Studies and Deaf Education, 7*(4), 312-329. doi:10.1093/deafed/7.4.312

Moog, J. S., & Geers, A. E. (1990). *Early speech perception test*. St. Louis, MO: Central Institute for the Deaf.

Morford, J. P., Kroll, J. F., Piñar, P., & Wilkinson, E. (2014). Bilingual word recognition in deaf and hearing signers: Effects of proficiency and language dominance on cross-language activation. *Second Language Research, 30*(2), 251-271. doi:10.1177/0267658313503467

Muthén, L. K., & Muthén, B. O. (2012). *Mplus user's guide. Seventh edition.* Los Angeles, CA: Muthén & Muthén.

Nittrouer, S., Caldwell, A., Lowenstein, J. H., Tarr, E., & Holloman, C. (2012). Emergent literacy in kindergartners with cochlear implants. *Ear And Hearing, 33*(6), 683-697. doi:10.1097/AUD.0b013e318258c98e

Padden, C., & Ramsey, C. (2000). American Sign Language and reading ability in deaf children. In C. Chamberlain, J. P. Morford, R. I. Mayberry, C. Chamberlain, J. P. Morford, & R. I. Mayberry (Eds.), *Language acquisition by eye.* (pp. 165-189). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.

Paul, P. V., & Lee, C. (2010). The qualitative similarity hypothesis. *American Annals of the Deaf, 154*(5), 456-462. doi:10.1353/aad.0.0125

Perfetti, C. A., & Stafura, J. (2014). Word knowledge in a theory of reading comprehension. *Scientific Studies of Reading, 18*(1), 22-37. doi:10.1080/10888438.2013.827687

Petitto, L. A., Langdon, C., Stone, A., Andriola, D., Kartheiser, G., & Cochran, C. (2016). Visual sign phonology: Insights into human reading and language from a natural soundless phonology. *WIREs Cognitive Science, 7*(6), 366-381. doi:10.1002/wcs.1404

Puente, A., Alvarado, J. M., & Herrera, V. (2006). Fingerspelling and sign language as alternative codes for reading and writing words for Chilean deaf signers. *American Annals of the Deaf, 151*(3), 299-310. doi:10.1353/aad.2006.0039

Reitsma, P. (2009). Computer-based exercises for learning to read and spell by deaf children. *Journal of Deaf Studies and Deaf Education, 14*(2), 178-189. doi:10.1093/deafed/enn031

SAS Institute Inc. (2014). SAS Release 9.4. Cary, NC: SAS Institute Inc.

Schick, B. (2012). *Fingerspelling Ability and Phonological Awareness Test*. Boulder, CO: University of Colorado.

Schick, B. (2013). *American Sign Language Receptive Skills Test - Revised*. Boulder, CO: University of Colorado.

Seidenberg, M. S. (2013). The science of reading and its educational implications. *Language Learning and Development, 9*(4), 331-360. doi:10.1080/15475441.2013.812017

Semel, E., Wiig, E. H., & Secord, W. (2003). *Clinical Evaluation of Language Fundamentals (4th ed) [CELF-4]*. San Antonio, TX: Pearson.

Stone, A., Kartheiser, G., Hauser, P. C., Petitto, L.-A., & Allen, T. E. (2015). Fingerspelling as a novel gateway into reading fluency in deaf bilinguals. *PLoS ONE, 10*(10). doi:10.1371/journal.pone.0139610

Vandenberg, R. J., & Lance, C. E. (2000). A review and synthesis of the measurement invariance literature: Suggestions, practices, and recommendations for organizational research. *Organizational Research Methods, 3*(1), 4-69. doi:10.1177/109442810031002

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1999). *Comprehensive Test of Phonological Processing* Austin, TX: Pro-ed.

Wang, Y., Trezek, B. J., Luckner, J. L., & Paul, P. V. (2008). The role of phonology and phonologically related skills in reading instruction for students who are deaf or hard of hearing. *American Annals of the Deaf, 153*(4), 396-407. doi:10.1353/aad.0.0061

Webb, M. L., & Lederberg, A. R. (2014). Measuring phonological awareness in deaf and hard-of-hearing children. *Journal of Speech, Language, and Hearing Research, 57*(1), 131-142. doi:10.1044/1092-4388(2013/12-0106)

Webb, M. L., Lederberg, A. R., Branum-Martin, L., & Connor, C. M. (2015). Evaluating the structure of early English literacy skills in deaf and hard-of-hearing children. *Journal of Deaf Studies and Deaf Education, 20*(4), 343-355. doi:10.1093/deafed/env024

Woll, B., & MacSweeney, M. (2016). Let's not forget the role of deafness in sign/speech bilingualism. *Bilingualism: Language and Cognition, 19*(2), 253-255. doi:10.1017/S1366728915000371

Table 1. Demographic and audiological characteristics of participants

Variable	Spoken	Bimodal	Sign	Sample Mean
Mean Age in years (SD)	6.6 (1.0)	6.6 (0.9)	6.8 (1.0)	6.7 (1.0)
Grade: Kindergarten (%)	50	38	34	40
First	28	36	34	33
Second	23	26	31	27
Ethnicity: Hispanic	23	39	30	31
Race: White	44	55	63	55
Black	26	17	11	17
Asian	7	3	8	6
Other	14	20	8	13
Home Language				
Spoken English only	69	30	14	36
ASL only	0	9	41	19
ASL + Spoken English	3	30	28	21
Spoken language only-not English	12	9	7	9
Bilingual Spoken	15	8	2	8
Deaf or hard-of-hearing parent	7	23	50	29
Timing of hearing loss				
Congenital	52	76	82	65
Acquired	11	4	5	6
Don't Know	35	21	27	28
Audiological technology				
Unilateral CI (with or without HA)	20	25	14	19
Bilateral CI	35	10	7	15
Hearing aid(s)only	45	56	47	51
None	1	3	30	13
Additional disability (any)	25	30	19	25
Disability (attention)	8	8	5	7
Disability (cognitive)	4	4	2	3
Disability (motor)	13	11	6	10
Disability (emotional/behavior)	2	5	4	4
Differential Ability Scale T score M (SD)	46.7(8.1)	46.7 (9.1)	45.9 (8.1)	
Early Speech Perception				
No pattern perception	0	0	93	39
Pattern perception	0	0	7	1
Some word identification	1	1	0	2
Consistent word identification	99	98	0	58
Level of speech articulation impairment				
None	53	25	-	37
Mild	24	13	-	18
Moderate	21	28	-	25
Severe	2	34	-	20

Note. All numbers are percentages within each language group and for the entire sample, except where noted otherwise. Percentages may not sum to 100 due to rounding.

Table 2. Tests of measurement invariance for the three-factor model across groups

Model	χ^2	*df*	CFI	RMSEA	SRMR	BIC	$\Delta\chi^2(\Delta df)$	ΔCFI	ΔRMSEA	ΔSRMR	Fit 1	Fit 2
1. Configural	271.8	116	0.944	0.110	0.166	15,704						
2. Metric (loadings)	319.7	128	0.931	0.116	0.173	15,682	47.8 (12)	-0.013	0.006	0.007	Yes	Yes
3. Scalar (intercepts)	413.8	140	0.902	0.132	0.174	15,706	94.2 (12)	-0.029	0.016	0.001	No	Yes
4. Latent Covariance	437.3	146	0.895	0.133	0.184	15,695	23.4 (6)	-0.007	0.001	0.010	n/a	n/a
5. Latent Means	495.6	152	0.876	0.142	0.191	15,718	58.4 (6)	-0.019	0.009	0.007	n/a	n/a

Note. CFI = Comparative Fit Index. RMSEA = Root Mean Squared Error of Approximation. SRMR = Standardized Root Mean Residual. BIC = Bayesian Information Criterion. "n/a" = not applicable. Each model is tested relative to the one above it. "Fit 1" and "Fit 2" refer to Chen's (2007) criteria for invariance testing. n/a = not applicable. All chi-square difference tests were statistically significant ($p < .01$), but are likely overpowered (Chen, 2007). The metric model (2) passed both criterion 1 and criterion 2 for loading invariance. Model 3, which tested for intercept invariance failed Chen's criterion 1 (CFI and RMSEA differences were both too high), but passed Chen's criterion 2 for SRMR.

Table 3. Latent correlations, SD, and means from the three factor, three-group model of scalar invariance.

Group	Factor	Literacy	Spoken PA	Language
Spoken	Literacy	*1*		
	Spoken PA	**0.92**	*1*	
	Language	**0.67**	**0.84**	*1*
Bimodal	Literacy	*0.83*		
	Spoken PA	**0.87**	*1.08*	
	Language	**0.80**	**0.75**	*0.96*
Sign	Literacy	*0.78*		
	Spoken PA	**0.69** [c]	*1.02*	
	Language	**0.89** [c]	**0.58** [c]	*1.20*
Means	Group	Literacy	Spoken PA	Language
	Spoken	0	0	0
	Bimodal	-0.19	-0.52[ab]	0.00
	Sign	-0.26[a]	-1.14[a]	-0.12

Note. Correlations appear in boldface, SD in italics on the diagonal, and means at bottom of the table. These estimates are from multi-group three factor Model 3 in Table 6 and Figure 3. The scales of the latent factors were set to those of the Spoken group (mean = 0; variance = 1).
[a] = mean statistically significantly different from the mean of the Spoken group ($p < .05$).
[b] = mean statistically significantly different from the mean of the Sign group ($p < .05$).
[c] = Correlation significantly different from that in the Spoken group ($p < 0.01$).

Figure 1: Schematic representation of the planned missing design for test administration and the intended four-factor model for each group

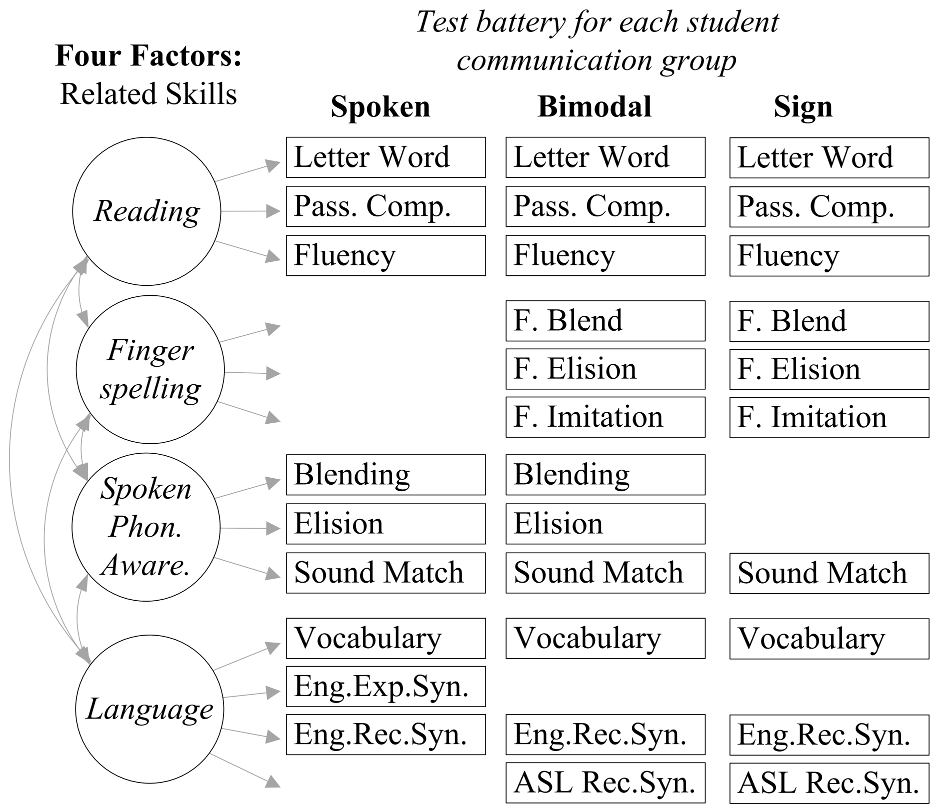
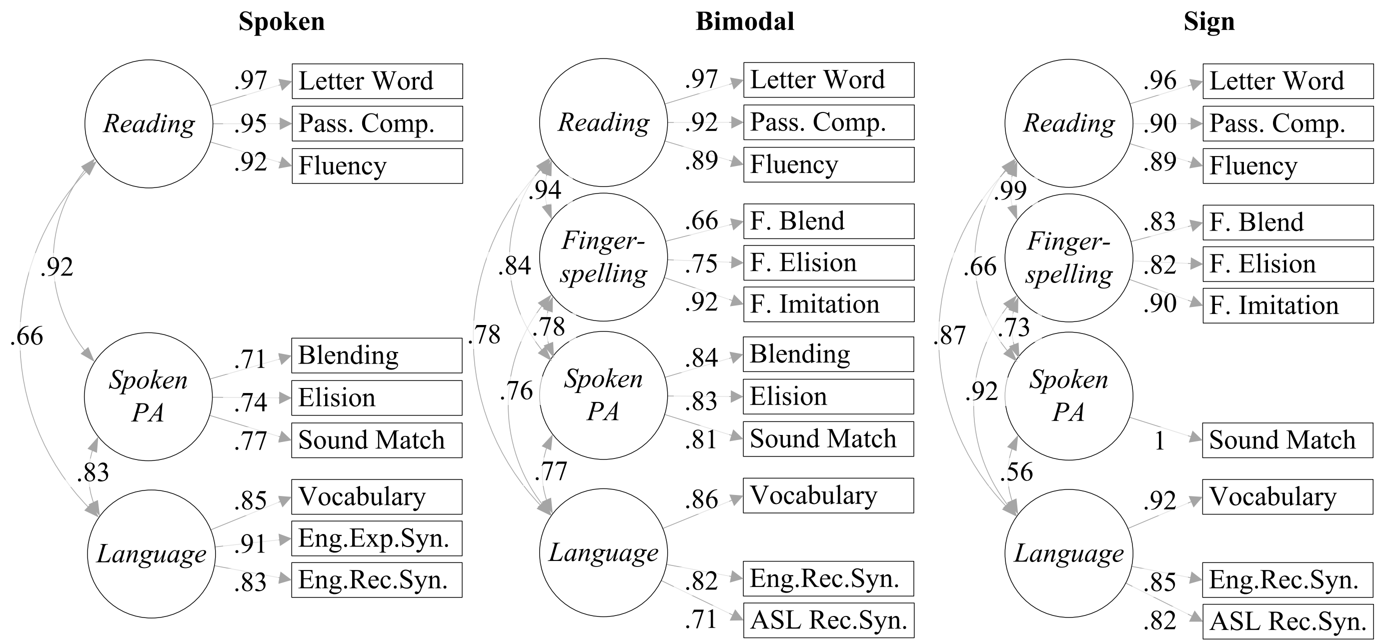


Figure 2. Four-factor results from each of the separate groups (fully standardized results; mean structure not shown)



Fit statistics for tests for models tested within groups

Model	Group	χ^2	*df*	CFI	RMSEA	(90% CI)	SRMR
Four Factor	Spoken[a]	57.3	24	.956	.117	(.078 - .157)	.045
	Bimodal	134.5	48	.907	.132	(.106 - .158)	.078
	Sign	63.1	30	.970	.092	(.060 - .123)	.037

Note. CFI = Comparative Fit Index. RMSEA = Root Mean Squared Error of Approximation, with 90% confidence interval in parentheses). SRMR = Standardized Root Mean Residual.

[a] The four-factor model for the Spoken group did not include a factor for Fingerspelling and is therefore equivalent to a three-factor model

Figure 3. Three-factor, three-group model with scalar invariance (fully standardized results; mean structure not shown)

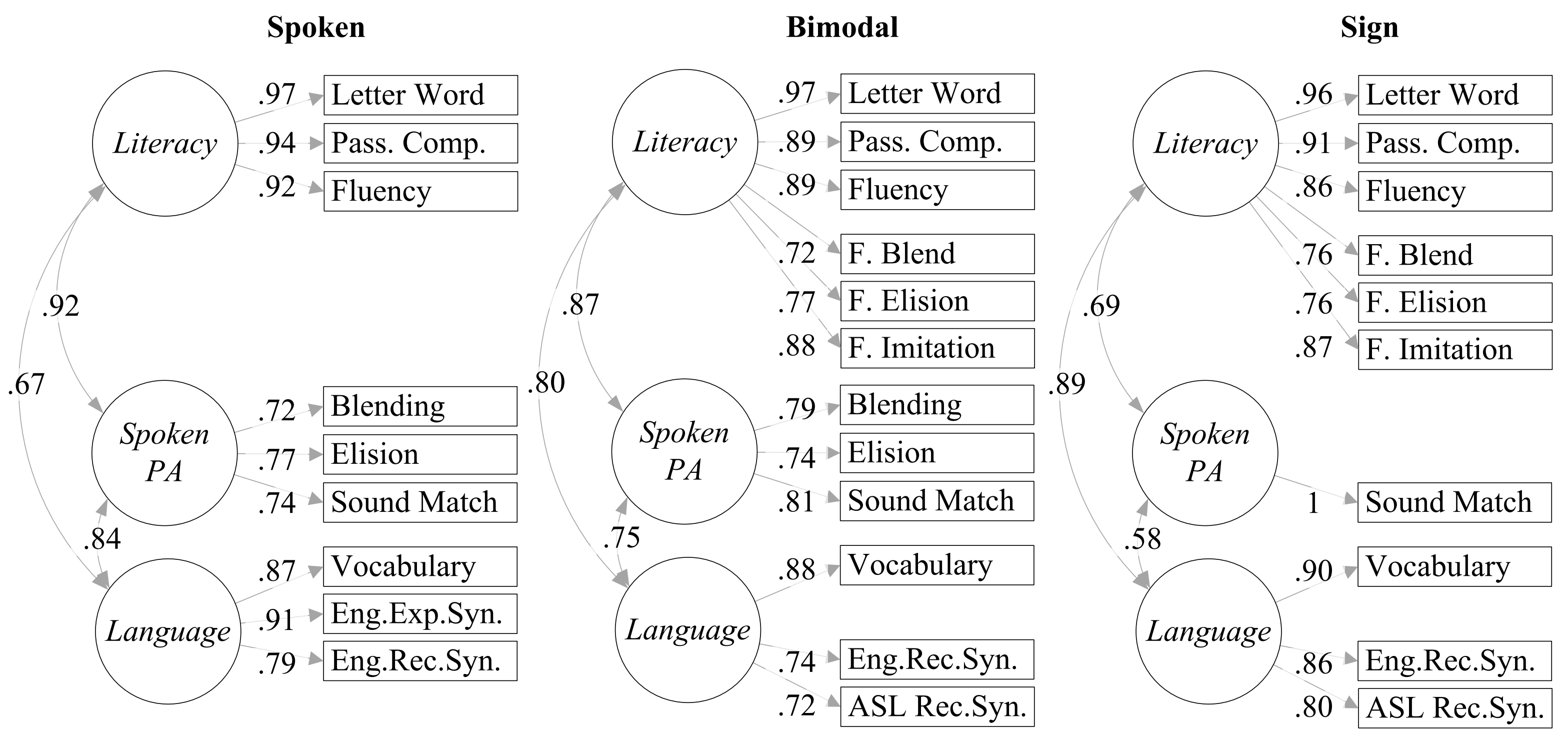
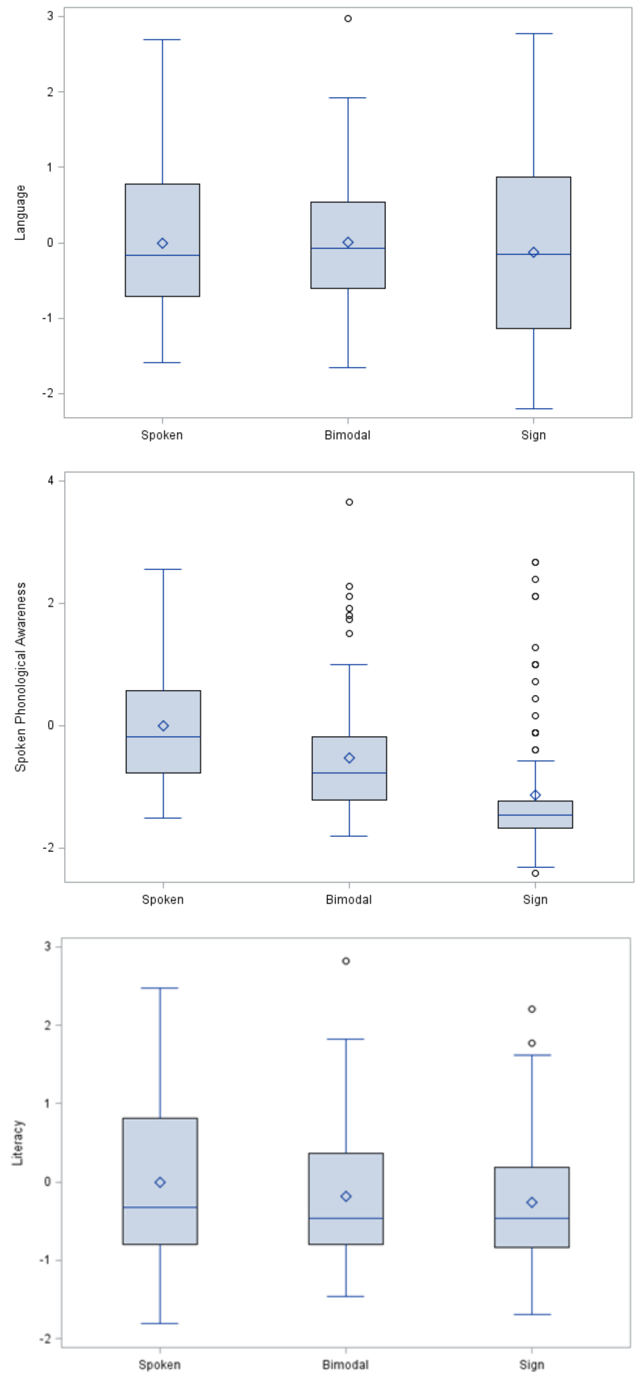


Figure 4. Factor scores for each group on each of the three factors



Note. These are descriptive boxplots for the summary statistics of factor scores reported in Table 3. The box is between the first and third quartile, the median is indicated by the middle line, the mean is the diamond, while the ends (whiskers) represent data within 1.5 times the interquartile range (circles represent scores outside this range).

Table S1. Descriptive statistics of measures

Group	Variable	N	Mean	SD	Min	Max	Skew	Kurt.	α
Spoken	Letter-Word Id.	100	21.06	10.57	1	49	.54	-.48	.96
	Passage Comp.	99	9.71	5.19	4	24	.78	-.47	.90
	Fluency	97	1.05	1.21	0	3	.65	-1.20	(a)
	F. Blending	0	—	—	—	—	—	—	—
	F. Elision	0	—	—	—	—	—	—	—
	F. Imitation	0	—	—	—	—	—	—	—
	Blending	71	6.79	3.94	0	17	.11	-.40	.87
	Elision	54	3.83	2.93	0	9	.13	-1.37	.82
	Sound Matching	97	6.94	5.04	0	20	.82	-.50	.91
	Exp. Vocabulary	96	54.79	17.88	18	102	.10	-.18	.97
	English Exp. Syntax	100	5.72	2.59	0	12	.79	-.47	.91
	English Rec. Syntax	99	16.85	8.70	1	40	.63	.09	.94
	ASL Rec. Syntax	0	—	—	—	—	—	—	—
Bimodal	Letter-Word Id.	102	19.98	9.27	1	54	.93	1.00	.95
	Passage Comp.	101	8.93	4.85	2	31	1.39	2.96	.89
	Fluency	70	1.00	1.17	0	3	.68	-1.11	(a)
	F. Blending	84	1.29	1.56	0	6	.94	-.12	.67
	F. Elision	89	0.78	1.59	0	7	2.45	5.48	.84
	F. Imitation	98	4.01	3.34	0	12	.63	-.82	.88
	Blending	55	3.98	4.13	0	18	1.34	1.56	.91
	Elision	43	2.86	3.99	0	16	1.78	2.92	.92
	Sound Matching	94	6.15	4.88	0	20	1.14	.54	.90
	Exp. Vocabulary	97	54.77	16.92	19	105	.07	-.10	.96
	English Exp. Syntax	0	—	—	—	—	—	—	—
	English Rec. Syntax	102	18.00	8.82	0	42	.18	-.29	.94
	ASL Rec. Syntax	102	19.32	5.36	9	31	-.09	-.71	.79
Sign	Letter-Word Id.	131	17.85	8.10	1	43	.66	.50	.94
	Passage Comp.	129	8.26	3.86	2	21	.92	.39	.85
	Fluency	66	1.32	1.10	0	3	.19	-1.28	(a)
	F. Blending	110	1.48	1.83	0	8	1.32	1.58	.76
	F. Elision	110	1.01	1.72	0	7	1.85	2.53	.83
	F. Imitation	122	4.75	3.42	0	13	.43	-1.06	.88
	Blending	0	—	—	—	—	—	—	—
	Elision	0	—	—	—	—	—	—	—
	Sound Matching	102	3.80	3.70	0	17	2.15	4.30	.87
	Exp. Vocabulary	108	54.79	22.13	11	109	.12	-.68	.97
	English Exp. Syntax	0	—	—	—	—	—	—	—
	English Rec. Syntax	128	14.30	8.56	1	37	.65	-.24	.94
	ASL Rec. Syntax	128	20.21	6.27	6	30	-.41	-1.04	.85

Note. Dashes indicate that the measure was not administered in that group. (a) indicates that Cronbach's alpha reliability is not appropriate for items of a speeded measure. F. = Fingerspelling. Exp. = Expressive. Rec. = Receptive. ASL = American Sign Languag

Table S2. Correlations among measures for each group

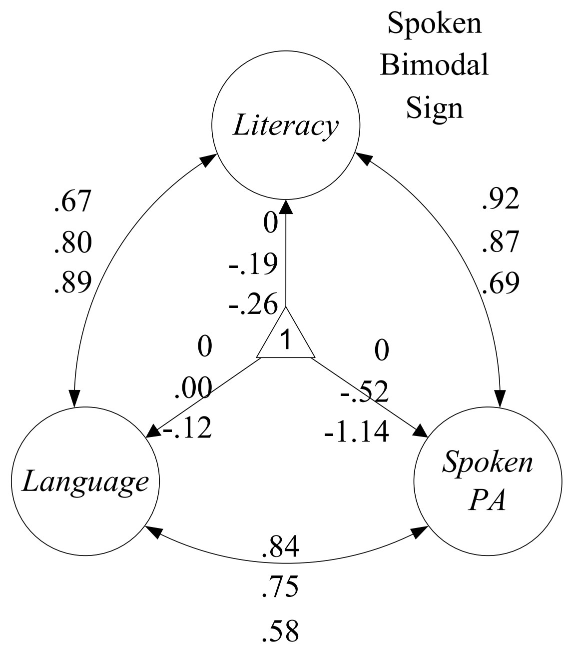
Group	Variable	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
Spoken														
	1. Letter-Word Id.	1.00												
	2. Passage Comp.	0.91	1.00											
	3. Fluency	0.89	0.87	1.00										
	4. F. Blending	—	—	—	—									
	5. F. Elision	—	—	—	—	—								
	6. F. Imitation	—	—	—	—	—	—							
	7. Blending	0.64	0.57	0.45	—	—	—	1.00						
	8. Elision	0.72	0.65	0.57	—	—	—	0.56	1.00					
	9. Sound Match	0.69	0.70	0.67	—	—	—	0.54	0.56	1.00				
	10. Vocabulary	0.70	0.66	0.58	—	—	—	0.54	0.58	0.55	1.00			
	11. Eng. Exp. Syntax	0.49	0.48	0.41	—	—	—	0.49	0.65	0.38	0.53	1.00		
	12. Eng. Rec. Syntax	0.54	0.59	0.44	—	—	—	0.53	0.61	0.56	0.68	0.59	1.00	
	13. ASL Rec. Syntax	—	—	—	—	—	—	—	—	—	—	—	—	—
Bimodal														
	1. Letter-Word Id.	1.00												
	2. Passage Comp.	0.90	1.00											
	3. Fluency	0.83	0.76	1.00										
	4. F. Blending	0.59	0.53	0.49	1.00									
	5. F. Elision	0.72	0.64	0.63	0.61	1.00								
	6. F. Imitation	0.85	0.79	0.84	0.65	0.67	1.00							
	7. Blending	0.64	0.71	0.68	0.37	0.47	0.58	1.00						
	8. Elision	0.66	0.71	0.58	0.50	0.62	0.62	0.88	1.00					
	9. Sound Match	0.74	0.76	0.65	0.49	0.59	0.66	0.65	0.70	1.00				
	10. Vocabulary	0.69	0.60	0.68	0.34	0.51	0.61	0.62	0.69	0.48	1.00			
	11. Eng. Exp. Syntax	—	—	—	—	—	—	—	—	—	—	—		
	12. Eng. Rec. Syntax	0.57	0.54	0.54	0.37	0.46	0.52	0.71	0.76	0.50	0.69	—	1.00	
	13. ASL Rec. Syntax	0.55	0.53	0.58	0.37	0.43	0.58	0.31	0.24	0.37	0.60	—	0.62	1.00

Table S2 (continued)

	Variable	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
Sign														
1.	Letter-Word Id.	1.00												
2.	Passage Comp.	0.86	1.00											
3.	Fluency	0.75	0.68	1.00										
4.	F. Blending	0.78	0.74	0.74	1.00									
5.	F. Elision	0.75	0.73	0.67	0.68	1.00								
6.	F. Imitation	0.85	0.79	0.73	0.75	0.70	1.00							
7.	Blending	—	—	—	—	—	—	—						
8.	Elision	—	—	—	—	—	—	—	—					
9.	Sound Match	0.66	0.59	0.48	0.61	0.78	0.55	—	—	1.00				
10.	Vocabulary	0.77	0.70	0.70	0.61	0.58	0.80	—	—	0.49	1.00			
11.	Eng. Exp. Syntax	—	—	—	—	—	—	—	—	—	—	—		
12.	Eng. Rec. Syntax	0.74	0.65	0.60	0.63	0.65	0.74	—	—	0.56	0.77	—	1.00	
13.	ASL Rec. Syntax	0.66	0.58	0.62	0.56	0.51	0.67	—	—	0.41	0.76	—	0.69	1.00

Note. Dashes indicate that the measure was not administered in that group. F. = Fingerspelling. Exp. = Expressive. Rec. = Receptive. ASL = American Sign Language.

Figure S1. Three-group factor means and correlations



Note. This is a compact representation of the final, three-group model presented in Table 7 and Figure 3. Factor means are inside the figure on the path from the central triangle. Correlations between factors are on the outside of the arcs connecting the factors. Parameters are presented vertically in the order of spoken, bimodal, and sign only groups.

Table S3: Freely estimated unstandardized parameters from the four-factor model, fit separately to each group.

		Loadings			Intercepts		
Factor	Test	Spoken	Bimodal	Sign	Spoken	Bimodal	Sign
Reading	Letter-Word Id.	10.21	8.95	7.76	21.07	19.90	17.85
	Passage Comp.	4.93	4.40	3.46	9.62	8.87	8.22
	Fluency	1.12	0.98	0.96	1.00	0.74	0.75
Fingerspelling	F. Blending	—	1.02	1.50	—	1.17	1.30
	F. Elision	—	1.17	1.41	—	0.66	0.85
	F. Imitation	—	3.04	3.11	—	3.91	4.54
Spoken PA	Blending	2.78	3.25	—	5.92	2.71	—
	Elision	2.06	2.96	—	3.06	1.51	—
	Sound Match	3.87	3.88	3.65	6.82	5.93	3.32
Language	Exp. Vocabulary	15.06	14.63	20.44	55.02	55.16	55.46
	Exp. Syntax	5.82	—	—	7.22	—	—
	Rec. Syntax	7.15	7.18	7.30	16.80	17.94	14.20
	ASL Syntax	—	3.77	5.16	—	19.29	20.06

Note. Dashes indicate the measure was not administered to that group.

Table S4: Unstandardized parameters from the final model: three-factor, three group model with scalar (intercept) invariance across groups

Factor	Test	Loading	SE	Intercept	SE
Literacy	Letter-Word Id.	10.21	0.75	21.05	1.04
	Passage Comp.	4.83	0.37	9.60	0.50
	Fluency	1.16	0.09	1.01	0.12
	F. Blending	1.60	0.17	1.64	0.19
	F. Elision	1.57	0.15	1.14	0.18
	F. Imitation	3.71	0.31	5.13	0.40
Spoken PA	Blending	2.94	0.35	5.11	0.43
	Elision	2.28	0.27	2.99	0.32
	Sound Match	3.59	0.42	7.40	0.47
Language	Exp. Vocabulary	15.90	1.38	55.79	1.78
	Exp. Syntax	5.80	0.52	7.22	0.64
	Rec. Syntax	6.57	0.62	16.25	0.77
	ASL Syntax	4.12	0.45	20.03	0.54

Note. SE = standard error. These estimates are from Model 3 in Table 5 and Figure 3.

Table S5: Residual variances from the final model: three-factor, three-group model with scalar invariance

Factor	Test	Spoken	SE	Bimodal	SE	Sign	SE
Literacy	Letter-Word Id.	5.73	2.05	7.63	2.04	6.04	1.34
	Passage Comp.	3.00	0.62	4.14	0.73	3.03	0.47
	Fluency	0.24	0.04	0.25	0.05	0.28	0.06
	F. Blending	—	—	1.66	0.28	1.14	0.17
	F. Elision	—	—	1.18	0.19	1.11	0.16
	F. Imitation	—	—	2.64	0.49	2.59	0.41
Spoken PA	Blending	8.17	1.64	6.11	1.87	—	—
	Elision	3.50	0.79	5.09	1.50	—	—
	Sound Match	10.99	1.90	7.93	1.81	0.00	—[a]
Language	Exp. Vocabulary	78.42	17.27	66.08	17.84	88.47	20.82
	Exp. Syntax	7.41	2.13	—	—	—	—
	Rec. Syntax	25.43	4.47	33.26	6.02	21.33	3.90
	ASL Syntax	—	—	14.59	2.51	13.72	2.13

Note. SE = standard error. Dashes indicate that the measure was not administered in that group.
[a]Parameter fixed to identify the factor in that group.

Table S6: R-square values from the final model: three-factor, three-group model with scalar invariance

Factor	Test	Spoken	Bimodal	Sign
Literacy	Letter-Word Id.	0.95	0.90	0.91
	Passage Comp.	0.89	0.80	0.82
	Fluency	0.85	0.79	0.75
Fingerspelling	F. Blending	—	0.52	0.58
	F. Elision	—	0.59	0.58
	F. Imitation	—	0.78	0.76
Spoken PA	Blending	0.52	0.62	—
	Elision	0.60	0.54	—
	Sound Match	0.54	0.65	1.00[a]
Language	Exp. Vocabulary	0.76	0.78	0.80
	Exp. Syntax	0.82	—	—
	Rec. Syntax	0.63	0.54	0.74
	ASL Syntax	—	0.52	0.64

Note. Dashes indicate that the measure was not administered in that group. [a]Parameter fixed to identify the factor in that group.