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Contribution of Lexical Quality and Sign Language Variables to Reading Comprehension

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Abstract

The lexical quality hypothesis proposes that the quality of phonological, orthographic, and semantic representations impacts reading comprehension. In Study 1, we evaluated the contributions of lexical quality to reading comprehension in 97 deaf and 98 hearing adults matched for reading ability. While phonological awareness was a strong predictor for hearing readers, for deaf readers, orthographic precision and semantic knowledge, not phonology, predicted reading comprehension (assessed by two different tests). For deaf readers, the architecture of the reading system adapts by shifting reliance from (coarse-grained) phonological representations to high-quality orthographic and semantic representations. In Study 2, we examined the contribution of American Sign Language (ASL) variables to reading comprehension in 83 deaf adults. Fingerspelling (FS) and ASL comprehension skills predicted reading comprehension. We suggest that FS might reinforce orthographic-to-semantic mappings and that sign language comprehension may serve as a linguistic basis for the development of skilled reading in deaf signers.

The lexical quality hypothesis (LQH) proposes that variation in the quality of word representations within an individual can account for much of the variation in reading comprehension (Perfetti & Hart, 2002; Perfetti, 2007). Skilled reading requires high-quality lexical representations that are fully specified and consist of orthographic, phonological, and semantic components. The LQH derives from the triangle model of word reading which assumes a cooperative division of labor among orthographic, phonological, and semantic components (Harm & Seidenberg, 2004; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg, 2005). When input to the phonological component is reduced or altered, as occurs with congenital deafness, phonological representations will be coarser and less consistent. Underspecified phonological representations (i.e., weaker phonological skills) have been linked to poor reading abilities in both hearing children (Wagner et al., 1997) and hearing adults (Macaruso & Shankweiler, 2010; Stothers & Klein, 2010). But for deaf readers, the role of phonological skills in becoming a skilled reader remains under debate (e.g., Mayer & Trezek, 2014; Miller & Clark, 2011). Some deaf readers achieve good reading levels by adulthood despite reduced access to speech and relatively weak phonological skills (Bélanger, Baum, & Mayberry, 2012; Hirshorn, Dye, Hauser, Supalla, & Bavelier, 2015). Such skilled deaf readers pose an interesting challenge for the LQH because weakness in any one of the three lexical components (phonology, orthography, or semantics) is hypothesized to lead to poor reading comprehension. To assess this hypothesis, in Study 1, we investigated the relative contribution of lexical quality variables to reading comprehension in a group of deaf and hearing adults who were all skilled readers.

An important characteristic of many deaf readers in the USA is that they are bilingual in American Sign Language (ASL) and English. Deaf children in bilingual contexts often learn to read with the assistance of techniques that incorporate both signing and fingerspelling (FS), referred to as “chaining” and “sandwiching” (Humphries & MacDougall, 2000). Such techniques are used by educators (and parents) to link printed English vocabulary with corresponding ASL signs and fingerspelled words. The FS—an inventory of ASL handshapes that represent the letters of the English alphabet—has been argued to play an important role in forming associations between print and meaning. Further, FS ability has been linked to reading proficiency in deaf adults (Stone, Kartheiser, Hauser, Petitto, & Allen, 2015) and vocabulary learning in deaf children (Haptonstall-Nykaza & Schick, 2007; Padden & Ramsey, 2000). In addition, strong ASL skills have been associated with better reading ability in deaf children (e.g., Chamberlain & Mayberry, 2008; Strong & Prinz, 1997). In Study 2, we investigated the relative contribution of ASL and FS skills to reading comprehension for deaf signing adults who

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were skilled readers (largely overlapping with the deaf participants in Study 1).

In both studies, we used a hierarchical regression model to assess the contribution of either lexical quality variables (Study 1) or sign language variables (Study 2) to reading comprehension, above and beyond other variables known to impact reading abilities, that is, nonverbal reasoning (NVIQ), age, and education.

Study 1: The Contribution of Lexical Quality Variables to Reading Comprehension in Adult Deaf and Hearing Readers

Reading outcomes have historically been poorer for deaf readers compared to hearing readers (Qi & Mitchell, 2012). Some researchers have hypothesized that the discrepancies in reading ability arise due to deaf readers' reduced access to speech and poorly specified phonological representations (Geers, 2003; Johnson & Goswami, 2010; Perfetti & Sandak, 2000; Wang, Trezek, Luckner, & Paul, 2008). Others propose that phonological precision is not necessary for reading success in deaf people (Bélanger & Rayner, 2015; Costello, Caffarra, Fariña, Duñabeitia, & Carreiras, 2021; Mayberry, del Giudice, & Lieberman, 2011). One issue that may have contributed to the disparate outcomes of previous studies is that many studies included deaf individuals who were not reading at age level, and thus it was not possible to identify whether reading difficulties arose due to poorer phonological processing or due to general reading or language proficiency deficits (Mayer & Trezek, 2014). To effectively characterize the extent to which poorer reading comprehension is indeed related to weaker phonological abilities, group comparisons should include deaf and hearing readers with similar reading levels.

The present study examined the unique contributions of lexical quality variables—phonological awareness, orthographic precision (spelling ability), and semantic knowledge (vocabulary size)—to reading comprehension in adult deaf and hearing readers who did not differ in reading level. We explored the hypothesis that, for deaf readers, the division of labor shifts among the three components in the triangle model (Seidenberg, 2005). Specifically, we hypothesized that more skilled deaf readers develop precise orthographic representations and robust connections between orthography and semantics, which can circumvent reliance on phonological coding for semantic access (Bélanger & Rayner, 2015). We also tested the prediction that precise phonological representations will be associated with better reading comprehension for hearing but not for deaf readers.

Few tests of phonological awareness are currently available to effectively measure phonological awareness or phonological skill in adult deaf readers. Hirshorn et al. (2015) specifically designed phonological awareness tests for use with profoundly deaf adults who do not require spoken responses and present picture stimuli rather than written words (see Materials and Procedure for details). We expected that hearing readers would outperform deaf readers on these phonological awareness tests regardless of whether phonological sensitivity predicted reading comprehension in either group.

Orthographic precision is typically assessed by spelling tasks (e.g., dictation) and has provided a reliable index of the stability of orthographic representations (see Andrews, Veldre, & Clarke, 2020, for review). Several studies have demonstrated that spelling ability accounts for unique variance in single word and sentence reading tasks in adult readers which are not explained by other variables associated with individual differences in reading skill (Andrews et al., 2020; Hersch & Andrews, 2012; Veldre & Andrews, 2015). To overcome the challenge of dictation for deaf people who cannot hear the words to be spelled, we assessed orthographic precision using the test of spelling recognition (i.e., receptive spelling skill) developed by Andrews and Hersch (2010). This test has been used successfully in many studies to characterize individual differences in the precision of orthographic representations (Andrews et al., 2020). Additionally, to obtain a well-rounded measure of orthographic skill, it is important to also assess productive spelling skills. Hanson, Shankweiler, and Fischer (1983) developed a sentence cloze task to examine the nature of spelling production errors in deaf adults, which avoids dictation (this test was expanded by Sehyr, Manriquez, & Emmorey, 2019; see Materials and Procedure for details). We hypothesized that if deaf readers develop more precise orthographic representations, they would exhibit better spelling ability compared to hearing readers. Regardless of possible group differences in spelling ability, we expected that orthographic precision would predict reading comprehension skill in both groups but more strongly for the deaf readers.

Vocabulary assessments are typically used to provide a measure of semantic lexical quality (e.g., Protopapas, Sideridis, Mouzaki, & Simos, 2007), and vocabulary knowledge is positively associated with reading abilities in hearing children (Tannenbaum, Torgesen, & Wagner, 2006), hearing adults (Braze, Tabor, Shankweiler, & Mencl, 2007), deaf children (Harris, Terlektsi, & Kyle, 2017), and deaf adults (Cates, Traxler, & Corina, 2021; Wauters, van Gelder, & Tijsseling, 2021). Typically, deaf readers of all ages tend to score lower than hearing readers on vocabulary tests, and this result may be related to the fact that many deaf people acquire a spoken/written language as their second language (Piñar, Dussias, & Morford, 2011). Interestingly, vocabulary tends to be a stronger predictor of reading comprehension for deaf compared to hearing individuals (Harris et al., 2017; Moreno-Pérez, Saldaña, & Rodríguez-Ortiz, 2015) as well as for (hearing) second language learners compared to first language learners (van den Bosch, Segers, & Verhoeven, 2020). A widely used test of lexical semantic knowledge in deaf readers is a version of the Peabody Picture Vocabulary Test (PPVT-IV; Dunn & Dunn, 2007) adapted for deaf individuals by Sarchet et al. (2014). We predicted that vocabulary would be positively associated with reading comprehension in both deaf and hearing readers but that it would be a stronger predictor for deaf people.

A recent study by Cates et al. (2021) compared reading predictors for native deaf signers (born into deaf signing families), non-native deaf signers (born into hearing families; most learned ASL after age 8), hearing Chinese-English bilinguals, and hearing monolingual English speakers. The groups did not differ in reading comprehension ability, except the non-native deaf signers who scored significantly below the hearing monolingual readers. Reading comprehension was measured by multiple choice questions that followed self-paced word-by-word reading of narrative and expository texts. For all groups, regression models indicated that vocabulary knowledge (the Nelson-Denny Test; Brown, 1981) was a significant contributor to reading comprehension. A measure of phonological awareness (decide which word sounds like an English word, e.g., KHAT or KLAT) predicted reading comprehension for hearing monolingual readers and for the non-native deaf signers but not for the native deaf signers or the Chinese-English bilinguals. Cates et al. (2021) speculated that early exposure to ASL may have reduced the relative importance of speech-based phonological skills on reading development for the native signers. In Study 1, we explored this hypothesis with deaf signers who were all exposed to ASL at an early age. In addition, we used more extensive tests of phonological awareness which involved phoneme manipulation and judgments.

In sum, the aim of Study 1 was to examine the relative contributions of lexical quality variables (phonological, orthographic, and semantic skill) to reading comprehension for skilled deaf readers who had early access to ASL compared to hearing readers with similar reading ability.

Method

Participants

Deaf participants were 97 adult ASL signers (*M* age 31.3 years, SD = 9.4; 52 female, 45 male). There were 51 signers who reported being exposed to ASL from birth and had at least one deaf parent, and there were 46 signers who had hearing parents and reported exposure to ASL before age 7 (mean age of exposure = 3.7 years; SD = 4.4). Eighty-eight participants reported severe or profound hearing level, and nine reported mild–to–moderate hearing level. All participants were born deaf or became deaf prior to age 3. Hearing participants were 98 monolingual English speakers (*M* age 26 years, SD = 8.8; 69 female, 29 male) and reported no experience with ASL beyond one university semester class. Deaf participants received on average 5.4 years of higher education (e.g., college), and hearing participants received 3.3 years of higher education. Deaf participants were recruited from the community via personal contacts or advertising, and hearing participants were recruited on the university campus and via personal contacts or advertising. All deaf participants were financially compensated for their time, and hearing participants either obtained course credit or financial compensation.

Materials and Procedure

Reading comprehension was the dependent variable and was assessed using the Reading Comprehension subtest of the Peabody Individual Achievement Test—Revised (PIAT-R): (Markwardt, 1989) in which participants were required to read (silently) and remember a sentence and then choose from four pictures the one that best matches the sentence they just read. Items increased in difficulty throughout the test. We administered the last 40 items from this subtest (or more if the test's basal rule was not achieved), and the maximum score was 100. The test was discontinued if a participant made five errors within seven consecutive responses. The score was calculated as the proportion of correct trials.

As another independent measure of reading comprehension, we administered the Woodcock Johnson IV Tests of Achievement Test 4 (WJ-IV): Passage Comprehension (Schrank, Mather, & McGrew, 2014) to a subgroup of 75 deaf and 75 hearing readers (demographic information for this subset of participants is provided in Supplementary Materials on OSF.[1] We included the WJ-IV in our assessment battery because it is a more recently developed test of reading comprehension with an extended grade equivalency and to assess whether the results hold regardless the format of the reading comprehension test. All deaf and hearing participants who completed the WJ-IV test and all other tests necessary for the regression analyses were included in these subgroups. In this test, participants read silently a short passage and provided a missing word to demonstrate their comprehension of the passage by writing it down on a response sheet. We administered the last 30 items from this subset (or more if the test's basal rule was not achieved), and the test was discontinued when a participant reached the ceiling (i.e., made six consecutive error responses). There was a total of 46 trials, and the score was the proportion of correct trials.

All participants also completed the following measures of lexical quality:

Phonological skill was assessed using the set of tests developed by Hirshorn et al. (2015). These tests present picture stimuli rather than written words to control for overt orthographic cues to phonological structure, and a subset of the test items require phonological decisions that cannot be made based on orthographic cues (i.e., decisions involving irregularly spelled words). The subtest administered in this study consists of two tasks, a phoneme judgment task, and a phonological manipulation task. In the former, participants see a triad of pictures on a computer screen and reject the one containing a different consonant or vowel sound from the

1 https://osf.io/spmc9/

other two ("odd–man–out"). For shallow phonology trials (regular spelling), similar sounding pairs overlapped in both phonology and orthography (e.g., doll, door, belt), and for deep phonology trials (irregular spelling), similar pairs share only phonology (e.g., compass, kettle, lemon). In the phonological manipulation task, participants were shown two pictures (e.g., "a ring" and "a hat") and were asked to combine the first sound of the word (onset) in the first picture with the rime of the word in the second picture to produce a new legal word in English (e.g., "rat") by typing the word on a keyboard. The manipulation task also included shallow trials (e.g., "ring" + "hat" = "rat") and deep trials (e.g., "bird" + "toe" = "bow"). Scores on both tasks were combined to calculate the average overall score as the proportion of correct trials across both tasks. We also computed the average score for shallow phonological awareness (i.e., correct answers can be derived on knowledge of orthography alone) and deep phonological awareness (i.e., phonology must be accessed to answer the trial correctly).

Orthographic skill was assessed using the test of spelling recognition developed by Andrews and Hersch (2010), and a test of spelling production (developed by Sehyr et al., 2019). The spelling recognition test consists of a list of 88 items, half of which are misspelled. Misspellings changed one to three letters of the word and preserved the pronunciation of the base word (e.g., *addmission and *seperate). Participants were instructed to circle items they thought were incorrectly spelled (incurring a penalty for false alarms). The score was calculated as the number of correctly identified items minus any incorrectly identified items. In the spelling production test, participants were asked to spell 30 words using a cloze procedure in which a written sentence context was provided for the target word and the first letter of the target word was presented. For example, "She carried a backpack on one s________." The target words were drawn from previous studies on spelling errors (Hanson et al., 1983; Olson & Caramazza, 2004). Trials where participants failed to retrieve the correct word were excluded. The final score for orthographic skill was the proportion of correct trials across both spelling tasks.

Semantic skill was assessed using a version of the PPVT–IV (Dunn & Dunn, 2007) adapted for deaf individuals by Sarchet et al. (2014). On each trial, participants saw four pictures and a visually presented target word in the middle of the display and were asked to point to the picture that corresponded to the word. Participants began at item 157 (set 14) out of a total of 228 items or lower if the basal rule was not reached. The test was discontinued when participants reached a ceiling (eight or more errors in a set). The score was the proportion of correct trials.

Finally, participants' NVIQ skill was assessed using the Matrices subtest of the Kaufman Brief Intelligence Test—2nd Edition (Kaufman & Kaufman, 2004). The Matrices subtest assesses nonverbal intelligence and is a multiple-choice test of NVIQ. The raw score was calculated as the ceiling item minus errors. Raw scores were standardized using age-adjusted norms. The maximum raw score was 46.

Instructions for all tests were presented in ASL or English as appropriate for each group. Participants completed all tests individually, either in a single session lasting ∼3 hr (with breaks) or across multiple sessions as part of a larger ongoing battery of language and cognitive tests. Test order was not systematically controlled.

Our hypotheses were tested using a hierarchical multiple regression analysis in which we investigated the extent to which lexical quality variables predict reading comprehension while controlling for other variables known to impact reading, such as age, education, and NVIQ. The analysis was conducted by entering the demographic variables in the first step, NVIQ in the second step, followed by lexical quality variables in the third step.

Results

We first compared the performance between the deaf native signers ($N = 51$) and deaf early signers ($N = 46$) on lexical quality variables, reading comprehension (PIAT-R), and demographic measures. The two groups did not differ on reading comprehension (PIAT-R scores), NVIQ, vocabulary, or orthographic skill (see Table 1). However, early signers outperformed native signers on the phonological awareness average test score and on the deep phonology (irregular spelling) trials, but the groups did not differ on the shallow phonology (regular spelling) trials.

In the native signer group, reading comprehension and lexical variables were all positively correlated (Table 2). Education was positively correlated with orthographic scores, average phonological test score, and deep (but not shallow) phonological test score. In the early signer group, reading comprehension was positively correlated with all lexical quality variables except spelling production. Somewhat surprisingly, orthographic and phonological skills were not correlated in the early signer group (Table 2).

We next examined the contribution of lexical quality variables to reading comprehension in these two groups using a multiple stepwise regression model with trait variables (age, education) in the first step, NVIQ scores in the second step, and lexical quality variables as predictors in the final step of the regression. For deaf native signers (Table 3, top panel), the full model (M3) with all six variables significantly predicted reading comprehension scores, $F\,(6, 50) = 11$, $p < .001$, adj. $R^2 = .539$, and explained 60% of variance in the scores; the lexical quality variables in the final step significantly explained additional 27% of variance after accounting for age, education, and NVIQ (R^2 change = .265, F (3, 44) = 10, $p < .001$). Further, orthography ($\beta = .334$; $p = .019$) and semantics ($\beta = .244$, $p = .036$), both contributed to

Table 1. Average age, years in higher education, performance (Proportion, SD, 95% CIs) on reading comprehension (PIAT-R), nonverbal reasoning (NVIQ), and lexical quality measures for deaf native signers (N = 51) and deaf early signers (N = 46)

Variable	Measures	Deaf native signers			Deaf early signers			*t*	*p*
		M	**SD**	**95% CI**	**M**	**SD**	**95% CI**		
Demographic	Age	30	8	[28; 32]	33	11	[30; 36]	−1.5	.144
	Education	5.5 years	2.2	[4.9; 6.1]	5.3 years	3.0	[4.4; 6.2]	.395	.694
NVIQ	Kaufman Brief Intelligence Test 4th Ed.	108	13	[104; 111]	107	11	[104; 110]	.385	.701
Reading	Comp. (PIAT-R)	.85	.10	[.82; .88]	.84	.11	[.81; .87]	.396	.693
Orthography	Avg.	.83	.11	[.80; .86]	.80	.15	[.75; .85]	1.11	.268
	Recognition	.86	.07	[.84; .88]	.86	.09	[.83; .88]	.372	.711
	Production	.80	.15	[.75; .84]	.74	.21	[.68; .81]	1.38	.173
Phonology	Avg.	.62	.12	[.58; .66]	.69	.14	[.64; .73]	−2.3	.024
	Deep	.44	.18	[.38; .49]	.55	.23	[.48; .63]	−2.7	.008
	Shallow	.80	.11	[.77; .83]	.82	.10	[.79; .85]	−.752	.454
Semantics	Vocabulary	.90	.10	[.83; .88]	.90	.10	[.85; .89]	−.795	.428

Table 2. Correlations among age, education, non-verbal reasoning (NVIQ), reading comprehension (PIAT-R), and lexical quality variables for deaf native signers and deaf early signers

	1 Age	2	3	4	5	6	7	8	9	10
					Deaf native signers					
2 Education	.104									
3 NVIQ	–.094	.275								
4 Reading (PIAT)	–.07	.303*	.541**							
5 Orthography	–.026	.372*	.445**	.735**						
6 Ortho(Recog.)	.010	.306*	.418**	.732**	.926**					
7 Ortho(Prod.)	–.047	.354*	.432**	.672**	.982**	.837**				
8 Phonology	.118	.346*	.327*	.524**	.659**	.690**	.615**			
9 Phon(Deep)	.168	.374*	.241	.361*	.514**	.512**	.494**	.909**		
10 Phon(Shallow)	–.010	.152	.344*	.573**	.611**	.692**	.547**	.735**	.385**	
11 Semantics	.025	.048	.340*	.657**	.475**	.518**	.422**	.349*	.285	.549**
					Deaf early signers					
2 Education	.198									
3 NVIQ	–.181	.207								
4 Reading (PIAT)	–.111	.304*	.668**							
5 Orthography	.109	.187	.112	.309*						
6 Ortho(Recog.)	.112	244	.184	.385**	.934**					
7 Ortho(Prod.)	.095	.152	.084	.259	.986**	.861**				
8 Phonology	.008	.064	.416**	.398*	.252	.219	.252			
9 Phon(Deep)	–.021	.017	.450**	.372*	.203	.165	.210	.971**		
10 Phon(Shallow)	.075	.157	.242	.363*	.309	.291	.293	.833**	.677**	
11 Semantics	.085	.183	.617**	.745**	.430**	.474**	.386*	.527**	.452**	.577**

**$p < .01$ *$p \leq .05$

the model's explanatory power, but phonology did not ($\beta = .139$, $p = .274$). Age and education alone in the first step (M1) did not explain a significant amount of variance in the data, $p = .136$. Adding NVIQ in the second step (M2) explained 33% of variance, F (3, 50) = 7.7, $p < .001$, adj. $R^2 = .287$.

For early signers (Table 3, bottom panel), the full model also predicted reading comprehension, explaining 64% of variance, F (6, 45) = 11, $p < .001$, adj. $R^2 = .581$. Lexical quality explained 17% in the third step (R^2 change = .162, F (3, 39) = 6, $p = .002$), and only semantic knowledge was a significant contributor in the model ($\beta = .504$, $p = .001$). Age and education did not predict reading comprehension in the early signers, $p = .059$, but adding NVIQ explained a total of 48% of variance in the scores, F (3, 45) = 13, $p < .001$, adj. $R^2 = .438$.

We next assessed the contribution of lexical quality variables to reading comprehension (PIAT-R) for all deaf ($n = 97$) and hearing ($n = 98$) readers using multiple regression. The descriptive statistics for all deaf and hearing participants are shown in Table 4. The deaf and hearing participants did not statistically differ on reading comprehension (PIAT-R), the composite orthography test score, and NVIQ. Deaf readers outperformed hearing readers on the spelling recognition test but scored worse on phonological awareness and semantic knowledge (vocabulary) than the hearing readers.

Table 3. Multiple regression model of reading comprehension (PIAT-R) with age, education, non-verbal reasoning (NVIQ), and lexical quality variables as predictors for deaf native signers and deaf early signers

Model	R^2 *(adj.)*	*F (p)*		*B*	*SE*	*β*	*t*	*sig.*	*95%CI*
				Deaf native signers					
M1	.08 (.04)	2.1 (.136)	(constant)	.82	.06		12.7	<.001	[.69; .95]
			Age	.00	.00	−.10	−.71	.484	[−.01; .00]
			Education	.01	.01	.28	1.98	.054	[.00; .03]
M2	.33 (.29)	7.3 (<.001)	(constant)	.38	.12		3.20	.002	[.14; .62]
			Age	.00	.00	−.03	−.28	.784	[−.00; .00]
			Education	.01	.01	.12	.99	.327	[−.01; .02]
			NVIQ	.00	.00	.52	4.19	<.001	[.00; .01]
M3	.60 (.54)	9 (<.001)	(constant)	−.01	.13		−.09	.927	[−.27; .25]
			Age	.00	.00	−.06	−.60	.552	[−.00; .00]
			Education	.00	.01	.02	.18	.856	[−.01; .01]
			NVIQ	.00	.00	.29	2.58	.013	[.00; .00]
			Orthography	.35	.15	.33	2.43	.019	[.06; .64]
			Phonology	.12	.11	.14	1.11	.274	[−.10; .34]
			Semantics	.31	.14	.24	2.17	.036	[.02; .60]
				Deaf early signers					
M1	.12 (.08)	3 (.059)	(constant)	.83	.05		16.3	<.001	[.73; .94]
			Age	.00	.00	−.18	−1.23	.227	[−.01; .00]
			Education	.01	.01	.34	2.33	.025	[.00; .02]
M2	.48 (.44)	13 (<.001)	(constant)	.16	.13		1.19	.239	[−.11; .43]
			Age	.00	.00	−.03	−.29	.774	[−.00; .00]
			Education	.01	.00	.18	1.53	.133	[−.00; .02]
			NVIQ	.01	.00	.62	5.31	<.001	[.00; .01]
M3	.64 (.58)	11 (<.001)	(constant)	−.18	.14		−1.25	.221	[−.46; .11]
			Age	.00	.00	−.13	−1.29	.205	[−.00; .00]
			Education	.01	.00	.17	1.62	.113	[−.01; .01]
			NVIQ	.00	.00	.32	2.39	.022	[.00; .01]
			Orthography	.03	.08	.04	.36	.724	[−.14; .20]
			Phonology	−.02	.09	−.03	−.24	.813	[−.19; .15]
			Semantics	.79	.23	.50	3.46	.001	[.33; 1.25]

Table 4. Average age, years in higher education, performance (Proportion, SD, 95% CIs) on reading comprehension (PIAT-R), nonverbal reasoning (NVIQ), and lexical quality measures for deaf (N = 97) and hearing (N = 98) participants

Variable	Measures	Deaf participants			Hearing participants				
		M	SD	95% CI	M	SD	95% CI	t	p
Demographic	Age	31	9	[29; 33]	26	9	[24; 28]	4.3	<.001
	Education	5.4 years	2.6	[4.9; 5.9]	3.3 years	1.61	[3.0; 3.6]	6.7	<.001
NVIQ	Kaufman Brief Intelligence Test 4th Ed.	107	12	[105; 110]	105	13	[103; 108]	.99	.280
Reading	Comp. (PIAT-R)	.84	.10	[.82; .87]	.87	.08	[.85; .89]	−1.9	.050
Orthography	Avg.	.81	.13	[.79; .84]	.82	.10	[.80; .84]	−.37	.712
	Recognition	.86	.08	[.84; .88]	.83	.09	[.81; .85]	2.3	.021
	Production	.77	.18	[.73; .81]	.81	.13	[.79; .84]	−1.8	.078
Phonology	Avg.	.65	.14	[.62; .68]	.88	.11	[.86; .90]	−13	<.001
	Deep	.49	.21	[.45; .54]	.85	.15	[.82; .88]	−13	<.001
	Shallow	.81	.11	[.79; .83]	.92	.08	[.90; .94]	−8	<.001
Semantics	Vocabulary	.86	.08	[.85; .88]	.90	.06	[.88; .91]	−3.6	<.001

Reading comprehension scores positively correlated with all lexical quality variables in both groups, suggesting that skilled readers possess higher quality lexical representations regardless of hearing status and language background (see Table 5). For deaf, but not hearing readers, education positively correlated with reading comprehension (PIAT-R), NVIQ, and orthographic skill.

For deaf readers (Table 6, top panel), the full regression model significantly predicted reading comprehension scores, F (6, 96) = 20.4, $p < .001$, adj. $R^2 = .548$, and explained 57.6% of variance in the scores. Lexical quality variables explained 18.7% of variance after controlling for age, education, and NVIQ, R^2 change = .187, F (3, 90) = 13, $p < .001$. Orthography ($\beta = .165$; $p = .038$) and

Table 5. Correlations among reading comprehension (PIAT-R), age, education, non-verbal reasoning (NVIQ), and lexical quality variables for deaf and hearing readers

	1 Age	2	3	4	5	6	7	8	9	10
Deaf participants										
2 Education	.155									
3 NVIQ	–.138	.237*								
4 PIAT	–.097	.288**	.607**							
5 Orthography	.037	.252*	.268*	.486**						
6 Ortho(Recog.)	.066	.270**	.303**	.548**	.929**					
7 Ortho(Prod.)	.015	.221*	.246*	.430**	.984**	.849**				
8 Phonology	.083	.153	.341**	.429**	.354**	.389**	.329**			
9 Phon(Deep)	.089	.132	.306**	.334**	.263*	.281**	.249*	.947**		
10 Phon(Shall.)	.044	.144	.299**	.474**	.420**	.474**	.379**	.766**	.519**	
11 Semantics	.066	.109	.436**	.693**	.420**	.482**	.368**	.438**	.375**	.562**
Hearing participants										
2 Education	.097									
3 NVIQ	–.05	.135								
4 PIAT	.095	.156	.489**							
5 Orthography	–.172	.075	.177	.286**						
6 Ortho(Recog.)	–.087	.094	.186	.267**	.900**					
7 Ortho(Prod.)	–.178	.082	.119	.232*	.953**	.726**				
8 Phonology	–.191	.017	.246*	.377**	.556**	.469**	.547**			
9 Phon(Deep)	–.205*	–.03	.237*	.360**	.513**	.439**	.495**	.961**		
10 Phon(Shall.)	–.142	.093	.217*	.328**	.519**	.425**	.530**	.862**	.690**	
11 Semantics	.206*	.126	.284**	.350**	.334**	.221*	.256*	.246*	.238*	.202*

** $p \leq .01$ * $p < .05$

semantics ($\beta = .347$, $p < .001$) significantly contributed to the model, but phonology did not ($\beta = .09$, $p = .259$). Age and education alone explained 10.2% of variance in the data, F (2, 96) = 5.3, $p < .006$; adj $R^2 = .083$, but only education significantly contributed to the model ($\beta = .307$, $p = .002$). Adding NVIQ ($\beta = .562$, $p < .001$) in the second step explained 38.9% of variance, F (3, 96) = 20, $p < .001$, adj. $R^2 = .370$.

For hearing readers (Table 6, bottom panel), the full model also predicted reading comprehension, F (6, 97) = 8.4, $p < .001$, adj. $R^2 = .315$, and explained 35.8% of variance in the data, lexical quality explained 10.8% of variance (R^2 change = .108, F (3, 91) = 5, $p = .003$). In contrast to deaf readers, phonology was the only significant contributor ($\beta = .251$, $p = .015$). Neither orthography ($\beta = .059$, $p = .558$) nor semantics ($\beta = .136$, $p = .153$) were significant. Age and education were not significant, $p = .227$, but adding NVIQ ($\beta = .48$, $p < .001$) improved the model's fit, F (3, 97) = 10.4, $p < .001$, adj. $R^2 = .225$, accounting for 24.9% of variance.

Finally, we conducted a secondary multiple regression analysis with the subgroup of 75 deaf and 75 hearing participants who completed the Woodcock-Johnson IV (WJ-IV) reading comprehension subtest in addition to all other assessment measures, as a replication using an unrelated reading comprehension measure. In this subgroup, deaf and hearing participants also did not differ on reading comprehension (WJ-IV) scores. The regression analysis is summarized in Table 7, and all descriptive statistics and correlations for these subgroups (and for deaf native and early signers, separately) are provided in Supplementary Analysis on OSF (Tables S1–S5, see footnote 1).

For deaf readers, the full model significantly predicted the WJ-IV scores after controlling for age, education, and NVIQ, F (6, 74) = 9.7, $p < .001$, adj. $R^2 = .413$, and explained 46% of variance in the data; lexical quality variables in the third step explained 13.1% of variance, R^2 change = .131, F (3, 68) = 5.5, $p = .002$. Like the results for PIAT-R, orthography ($\beta = .206$; $p = .041$) and semantics ($\beta = .269$, $p = .013$) significantly contributed to the model, but phonology did not ($\beta = .012$, $p = .905$). For hearing readers, the full model explained 52.2% of variance, F (6, 74) = 12.4, $p < .001$, adj. $R^2 = .480$, with lexical quality variables explaining 43.1% of variance in the data after accounting for the other variables, R^2 change = .431, F (3, 68) = 20, $p < .001$. Again, as for the PIAT-R scores, phonology was significant ($\beta = .361$, $p = .002$). Additionally, semantic knowledge was also a significant predictor ($\beta = .361$, $p < .001$). Thus, we replicated the main pattern of findings with an independent measure of reading comprehension.

Discussion

This study examined the contribution of lexical quality variables to reading comprehension in deaf and hearing adults with similar reading ability, assessed by the PIAT-R Reading Comprehension subtest and for a large subgroup of readers by the Woodcock-Johnson Passage Comprehension subtest (Test 4) (WJ-IV). For deaf readers as a whole group, the indicators of three different types of

Table 6. Multiple regression model of reading comprehension (PIAT-R) with age, education, NVIQ, and lexical quality variables as predictors for deaf and hearing readers

Model	R^2 (adj.)	F (p)		B	SE	β	t	sig.	95%CI
Deaf readers									
M1	.10 (.08)	5.3 (.006)	(constant)	.827	.039		21.4	<.001	[.75; .90]
			Age	−.002	.001	−.145	−1.46	.147	[−.00; .00]
			Education	.012	.004	.307	3.11	.002	[.00; .02]
M2	.39 (.37)	20 (<.001)	(constant)	.297	.086		3.45	<.001	[.13; .47]
			Age	.000	.001	−.044	−.53	.599	[−.00; .00]
			Education	.006	.003	.159	1.87	.065	[.00; .01]
			NVIQ	.005	.001	.562	6.62	<.001	[.00; .01]
M3	.58 (.55)	20 (<.001)	(constant)	−.046	.094		−.49	.624	[−.23; .14]
			Age	−.001	.001	−.106	−1.48	.141	[−.00; .00]
			Education	.005	.003	.130	1.77	.081	[−.00; .01]
			NVIQ	.003	.001	.340	4.20	<.001	[.00; .00]
			Orthography	.144	.068	.165	2.11	.038	[.01; .28]
			Phonology	.070	.062	.090	1.14	.259	[−.05; .19]
			Semantics	.484	.119	.347	4.08	<.001	[.25; .72]
Hearing readers									
M1	.03 (.01)	1.5 (.227)	(constant)	.825	0.030		27.3	<.001	[.77; .89]
			Age	.001	0.001	.081	.79	.429	[−.00; .00]
			Education	.008	0.005	.148	1.46	.148	[−.00; .02]
M2	.25 (.23)	10 (<.001)	(constant)	.493	0.069		7.17	<.001	[.36; .63]
			Age	.001	0.001	.110	1.23	.223	[−.00; .00]
			Education	.004	0.005	.082	.907	.367	[−.01; .01]
			NVIQ	.003	0.001	.473	5.23	<.001	[.00; .00]
M3	.36 (.32)	8.4 (< .001)	(constant)	.176	0.118		1.50	.138	[−.06; .41]
			Age	.001	0.001	.136	1.51	.134	[.00; .00]
			Education	.004	0.004	.068	.797	.428	[−.01; .01]
			NVIQ	.002	0.001	.370	4.12	<.001	[.00; .00]
			Orthography	.051	0.087	.059	.588	.558	[−.12; .22]
			Phonology	.195	0.079	.251	2.47	.015	[.04; .35]
			Semantics	.193	0.134	.136	1.44	.153	[−.07; .46]

lexical quality—phonological, orthographic, and semantic (vocabulary) knowledge, together with other variables known to predict reading skill—explained 57.6% of variance in PIAT-R and 46% in WJ-IV reading comprehension scores. Lexical variables in the third step significantly explained 18.7% in PIAT-R and 13.1% in WJ-IV scores. The model explained similar amount of variance separately for native signers (59.5% in PIAT-R scores, 39% in WJ-IV scores) and for early signers (63.7% in PIAT-R scores and 62% in WJ-IV scores). For hearing readers, the full model explained 35.8% variance in PIAT-R scores and 52.2% in WJ-IV scores. Lexical quality variables in the third step significantly explained 10.8% in PIAT-R scores and 43% in WJ-IV scores.

It is not clear why the full model was a worse fit for PIAT-R scores for hearing readers compared to deaf readers. One possibility is that the memory component of the PIAT-R reduced the sensitivity of the lexical variables for hearing readers; in this test, sentences had to be held in memory and then matched to one of four pictures on a separate page. Cates et al. (2021) found that working memory (reading span scores) contributed significantly to reading comprehension for hearing but not deaf readers. By contrast, the WJ-IV requires "fill in the blank" responses with lower memory demands. Further, the lexical quality variables alone explained more variance in WJ-IV scores in the hearing group (43%) than the deaf group (13%).

For hearing readers, phonological awareness significantly contributed to reading comprehension as measured by both the PIAT-R and the WJ-IV, and phonology was the only significant contributor for the PIAT-R model. It is possible that the ability to retain the phonological form of sentences in working memory for the PIAT-R subtest was particularly key for hearing readers. As expected, semantics (vocabulary knowledge) was a strong contributor to reading comprehension for hearing adults as measured by the WJ-IV, replicating previous studies (e.g., Braze et al., 2007; Cates et al., 2021).

In contrast to hearing readers, phonological awareness did not contribute significantly to reading comprehension in deaf readers when assessed either by the PIAT-R or the WJ-IV. Within the group of deaf readers, early signers with hearing parents performed better than native signers with deaf parents on tests of phonological awareness (the composite score and deep phonology test

Table 7. Multiple hierarchical regression model of WJ-IV reading comprehension with age, education, NVIQ and lexical quality variables as predictors for deaf and hearing readers

Model	R^2 (adj.)	F (p)		B	SE	β	t	sig.	95%CI
Deaf readers									
M1	.22 (.20)	1.1 (<.001)	(constant)	.915	.034		26.9	<.001	[.85; .98]
			Age	−.004	.001	−.467	−4.45	<.001	[−.01; −.00]
			Education	.004	.003	.127	1.21	.232	[−.00; .01]
M2	.33 (.30)	11.6 (<.001)	(constant)	.65	.084		7.75	<.001	[.48; .82]
			Age	−.004	.001	−.379	−3.74	<.001	[−.01; −.00]
			Education	.002	.003	.052	0.52	.606	[−.00; .01]
			NVIQ	.002	.001	.349	3.41	.001	[.00; .00]
M3	.46 (.41)	9.7 (<.001)	(constant)	.412	.098		4.19	<.001	[.22; .61]
			Age	−.004	.001	−.389	−4.16	<.001	[−.01; −.00]
			Education	.001	.003	.033	0.35	.731	[−.01; .01]
			NVIQ	.001	.001	.192	1.79	.077	[.00; .00]
			Orthography	.131	.063	.206	2.08	.041	[.01; .26]
			Phonology	.007	.061	.012	0.12	.905	[−.11; .13]
			Semantics	.282	.111	.269	2.54	.013	[.06; .50]
Hearing readers									
M1	.03 (.01)	1.1 (.331)	(constant)	.861	.027		31.9	<.001	[.81; .915]
			Age	−.001	.001	−.132	−1.13	.261	[−.00; .00]
			Education	−.004	.005	−.107	−.924	.358	[−.01; .01]
M2	.09 (.05)	2.4 (.076)	(constant)	.711	.074		9.67	<.001	[.57; .86]
			Age	−.001	.001	−.105	−.922	.360	[−.00; .00]
			Education	−.005	.005	−.134	−1.17	.245	[−.02; .00]
			NVIQ	.001	.001	.25	2.19	.032	[0; .00]
M3	.52 (.48)	12.1 (<.001)	(constant)	−.044	.126		−.351	.727	[−.30; .21]
			Age	−.001	.001	−.14	−1.41	.163	[−.00; .00]
			Education	−.007	.003	−.166	−1.96	.054	[−.01; .00]
			NVIQ	.001	.00	.098	1.12	.269	[.00; .00]
			Orthography	.028	.066	.043	.43	.671	[−.10; .16]
			Phonology	.227	.069	.361	3.29	.002	[.09; .37]
			Semantics	.70	.166	.437	4.23	<.001	[.37; 1.03]

scores). One speculative explanation for this result is that as children, deaf individuals with hearing parents may have had more exposure to speech and may have used speech more than those with deaf parents. Indeed, data on speech experience from a background questionnaire (used in a separate study) were available for 22 of the native and 32 of the early signers and indicated that early signers received more hours of speech training in school (~1.5 hr/weak) than native signers (~.4 hr/weak) and more early signers routinely used speech (53% vs. 5%). A greater reliance on speech may have enhanced phonological awareness for this group (Kyle, 2021). Regardless, phonological skill did not contribute significantly to reading comprehension ability for either the native or the early signers. This result replicates Cates et al.'s (2021) findings with native deaf signers and indicates that when sign language exposure occurs in early childhood, the lack of relationship between phonological skill and reading comprehension is quite robust, is not impacted by variation in phonological awareness, and is not specific to a particular test of reading comprehension.

Considering these findings, we revisit the LQH and argue that due to underspecified or coarser-grained phonological representations, skilled deaf readers develop more precise orthographic representations and rely more robustly on direct connections between orthography and semantics when reading. The triangle model of reading can be viewed as a computational instantiation of many aspects of the LQH, which highlights the role that poorly specified word representations play at every level of linguistic processing (e.g., lexical, grammatical, and semantic). The triangle model emphasizes the quality of the mapping between orthographic, phonological, and semantic levels (see e.g., Seidenberg & McClelland, 1989), while the LQH highlights that weak and imprecise bindings among these levels will have ramifications for higher-level comprehension processes (Perfetti, 2007; Perfetti & Hart, 2002). We suggest that due to weaker phonological pathways, the division of labor is shifted to orthographic and semantic representations that replace the systematic use of phonological mappings which is characteristic of both skilled and less-skilled hearing readers. For deaf readers, orthographic skill (assessed by both spelling recognition and production) was a significant contributor to reading comprehension, whether measured by the PIAT-R or the WJ-IV, whereas orthographic skill was not a significant contributor for hearing readers (using either reading measure). Although deaf and hearing readers did not differ on spelling skill overall, deaf readers exhibited better receptive but poorer productive spelling ability than hearing readers. While spelling recognition may be accomplished via a visual route (i.e., phonology might be less helpful), spelling production may be facilitated by activation of phonological representations. Therefore, the poorer performance on spelling production in deaf readers could be due to the weaker connections between phonology and orthography. Further, better performance on spelling recognition in deaf readers than hearing readers may imply an enhanced orthographic precision in deaf readers. Under this account, reading difficulties in deaf readers may arise due to poorly specified orthographic and/or semantic representations rather than deficits in phonological awareness and decoding skill.

Finally, deaf readers performed worse on the PPVT vocabulary test compared to hearing readers (86% vs. 90% correct). This difference in vocabulary knowledge could be attributed to the fact that deaf readers were all ASL-English bilinguals, while the hearing readers were all monolingual. For the deaf signers in this study, and most deaf signers were in the United States of America (USA), ASL is their dominant language and they like spoken language bilinguals, ASL-English bilinguals divide language use between their two languages. Thus, all bilinguals tend to have less exposure to vocabulary in each of their languages compared to monolingual users (e.g., Gollan, Montoya, Cera, & Sandoval, 2008). This situation may in turn result in smaller English vocabularies and worse performance on the PPVT for deaf bilinguals compared to hearing monolinguals (see also Gollan, Fennema-Notestine, Montoya, & Jernigan, 2007). We suggest that the bilingual status of deaf readers should be considered in educational practice and literacy development for deaf students (see also Cates et al., 2021). Further, the word items in the PPVT Test were chosen based on spoken word frequency and standardized for hearing populations. Thus, it is important to consider that deaf readers may have been less exposed to some vocabulary items, which may have contributed to worse performance on this test compared to their hearing peers.

Overall, the results of Study 1 support the hypothesis that lexical quality variables contribute differently to the reading comprehension ability for deaf compared to hearing readers. Phonological knowledge contributed to reading comprehension scores only for the hearing readers. Orthographic (spelling) skill was a stronger contributor for deaf readers (particularly for the early signers), with higher beta values and contributing to both the PIAT-R and WJ-IV models than for hearing readers. Semantic (vocabulary) knowledge was weaker for the deaf participants (possibly due to their status as bilinguals) but was nonetheless a significant contributor to reading comprehension skill (primarily for the native signers) as measured by both PIAT-R and WJ-IV models. This pattern of results supports the hypothesis that for deaf readers, the division of labor among lexical components shifts from reliance on phonological pathways to orthographic and semantic pathways. We next turn to our investigation of whether ASL and/or FS abilities are predictors of reading comprehension in adult deaf readers who are skilled readers.

Study 2. The Contribution of Sign Language Variables to Reading Comprehension

Sign language proficiency has been consistently linked with better reading comprehension and improved literacy outcomes in deaf readers (Allen & Morere, 2020; Andrew, Hoshooley, & Joanisse, 2014; Chamberlain & Mayberry, 2008; Freel et al., 2011; Hermans, Knoors, Ormel, & Verhoeven, 2008; Hoffmeister, 2000; Lederberg et al., 2019; Novogrodsky, Caldwell-Harris, Fish, & Hoffmeister, 2014; Padden & Ramsey, 2000; Padden & Hanson, 2000; Schönström, 2010; Stone et al., 2015; Strong & Prinz, 1997). Most studies have been conducted with children and/or adolescents, but a few have shown a positive relationship between signing skill/knowledge and reading comprehension in deaf adults (Chamberlain & Mayberry, 2008; Freel et al., 2011; Stone et al., 2015).

In Study 2, we investigated the relative contributions of ASL skill (assessed by an ASL comprehension task and an ASL sentence repetition task) and FS skill (assessed by a repetition task with fingerspelled words and pseudowords). The FS ability has been shown to be a strong predictor of reading abilities in signing children (Lederberg et al., 2019; Ormel, Giezen, Knoors, Verhoeven, & Gutierrez-Sigut, 2022) and in adults (Stone et al., 2015). We also explored whether ASL and FS abilities similarly predicted reading comprehension for deaf native signers and early signers after accounting for age, NVIQ, and education.

Method

Participants

Participants were 83 deaf ASL signers (*M* age 31, SD = 9.2; 46 female, 37 male) who also participated in Study 1. All were skilled readers and did not significantly differ from the hearing participants in Study 1 on PIAT-R reading comprehension, $t(179) = 1.7$, $p = .085$. The sample included 41 participants who were exposed to ASL from birth (native signers) and had at least one deaf parent, and 42 who were exposed to ASL prior to age 6 and had hearing parents (early signers). The participants reported hearing level that was profound ($n = 53$), severe ($n = 19$), or moderate to mild ($n = 7$). On average, the participants completed 5.7 years of higher education (SD = 2.5) and reported ASL as their preferred language of communication.

Table 8. Average age, years in higher education, performance (Proportion, SD, 95% CIs) on reading comprehension (PIAT-R), nonverbal reasoning (NVIQ), ASL measures for native signers ($N = 41$), early signers ($N = 42$), and all deaf signers ($N = 83$)

Measures	Native signers			Early signers			t	p	All deaf signers		
	M	SD	95% CI	M	SD	95% CI			M	SD	95% CI
Age	30	8	[27; 32]	33	11	[29; 36]	−1.39	.170	31	10	[29; 34]
Education	5.4	2.3	[4.7; 6.1]	5.4	3	[4.5; 6.3]	.016	.987	5.4	2.7	[4.8; 6]
NVIQ	107	14	[102; 111]	107	11	[104; 111]	−.230	.819	107	12	[104; 110]
Comp. (PIAT-R)	.85	.10	[.82; .88]	.84	.10	[.81; .88]	.335	.738	.85	.10	[.83; .87]
ASL-CT	.90	.07	[.87; .92]	.84	.09	[.81; .87]	2.98	.004	.87	.09	[.85; .89]
ASL-SRT	.75	.12	[.71; .79]	.61	.15	[.56; .65]	4.73	<.001	.68	.15	[.64; .71]
FS Avg.	.89	.08	[.86; .92]	.84	.11	[.81; .87]	2.35	.021	.86	.10	[84; .89]
FS real word	.88	.08	[.85; 90]	.83	.11	[.80; .87]	1.92	.058	.85	.10	[.83; .88]
FS pseudoword	.91	.09	[.89; .94]	.85	.12	[.81; .89]	2.58	.012	.88	.11	[.86; .91]

Materials and Procedure

In addition to NVIQ assessment and the PIAT-R reading comprehension subtest (see Methods, Study 1), participants completed the following.

FS reproduction

In the FS reproduction test (VL2 FS test; Morere & Allen, 2012), participants viewed video clips of fingerspelled words ($N = 45$) and pseudowords ($N = 25$). After each clip, the participant was required to repeat (i.e., fingerspell) the item they had just seen. The total score was the proportion of correctly fingerspelled items (out of 70), and we separately calculated the proportion of correctly spelled real words and pseudowords.

ASL Comprehension Test

This test (Hauser et al., 2016) is a computerized 30-item multiple-choice test that measures ASL receptive skills. Participants viewed prompts presented either as a static line drawing or picture (e.g., a dog laying in a corner) or a video of an event (e.g., water running out of a hose) and four signed descriptions as response choices. Participants used the computer mouse to select one of the four choices on the bottom of the screen that best matched the prompt video, picture, or line drawing at the top of the screen. The total score was the proportion of correctly selected items out of 30.

ASL Sentence Reproduction Test

This test (Supalla, Hauser, & Bavelier, 2014) is modeled after the Speaking Grammar subtest of the Test of Adolescent and Adult Language (Hammill, Brown, Larsen, & Wiederholt, 1994). Participants viewed a signer producing ASL sentences one at a time on a computer screen. The sentences were presented in the order of increasing difficulty—length, syntactic, thematic, and morphemic complexity. The participants were directed to first watch and then reproduce each sentence verbatim. A native deaf signer scored the sentence reproductions; correct reproductions were given a score of 1 and reproductions with errors or modifications of sign order were given a score of 0. Total score was calculated as the proportion of correctly reproduced sentences out of 35 (we used the extended version of the test; see Hauser, Paludneviciene, Supalla, & Bavelier, 2008, for a review of this earlier version).

Results

Table 8 summarizes performance on reading comprehension, NVIQ, and ASL assessments. Native and early signers did not differ on age, education, NVIQ, and reading comprehension, but native signers outperformed early signers on all of the ASL measures.

Table 9 shows that reading comprehension (PIAT-R) scores were positively correlated with all measures of ASL skill, and ASL skills correlated positively with each other in the early signers and in the whole group. In the native signer group, reading scores did not significantly correlate with the ASL Sentence Reproduction Test (ASL-SRT) or the pseudoword FS scores.

Table 10 presents the regression models separately for the native signers ($n = 41$), the early signers ($n = 42$), and the entire group ($n = 83$). For the native signers, the full model significantly predicted PIAT-R comprehension scores, $F\ (6, 40) = 6.4$, $p < .001$; adj. $R^2 = .447$, and explained 53% of variance. However, the ASL variables alone did not explain a significant amount of variance in the data, R^2 change = .096, $p = 095$, and none of the predictor variables were significant in the model, although both FS ($p = .093$) and the ASL Comprehension Test (ASL-CT; $p = .057$) approached significance. For the early signers, the full model also significantly predicted PIAT-R scores, $F\ (6, 41) = 10.7$, $p < .001$, adj. $R^2 = .588$, and explained 65% of variance in the data. The ASL variables alone explained 16% of variance in the scores, R^2 change = .156, $p = .005$; however, similar to the native signers, none of the ASL variables made a significant sole contribution to the model. Due to the low number of participants in the native and early signer groups, these analyses are relatively underpowered and must be interpreted with caution.

For the whole group of deaf signers, the full model significantly predicted PIAT-R scores, $F\ (6, 82) = 16$, $p < .001$,

Table 9. Correlations among reading comprehension (PIAT-R), age, education, non-verbal reasoning (NVIQ), and ASL variables for deaf native, early, and all signers

	1 Age	2	3	4	5	6	7	8
Deaf native signers								
2 Education	.035							
3 NVIQ	−.121	.266						
4 Comp (PIAT-R)	−.123	.386*	.613**					
5 ASL-CT	−.124	.121	.195	.395*				
6 ASL-SRT(35)	−.378*	.305	.138	.235	.409*			
7 FS	.010	.353*	.333*	.463**	.151	.377*		
8 FS real	.011	.381*	.430**	.533**	.156	.390*	.970**	
9 FS pseudo	.006	.256	.122	.279	.122	.301	.911**	.784**
Deaf early signers								
2 Education	.152							
3 NVIQ	−.169	.219						
4 Comp (PIAT-R)	−.034	.361*	.665**					
5 ASL-CT	−.311	.401*	.127	.410**				
6 ASL-SRT(35)	−.414**	.181	.121	.409**	.697**			
7 FS	.023	.107	.327*	.530**	.268	.408**		
8 FS real	.168	.148	.344*	.522**	.140	.257	.939**	
9 FS pseudo	−.230	.001	.193	.390*	.405*	.549**	.822**	.576**
All deaf signers								
2 Education	.108							
3 NVIQ	−.135	.234*						
4 Comp (PIAT-R)	−.076	.369**	.629**					
5 ASL-CT	−.294*	.287*	.125	.393**				
6 ASL-SRT(35)	−.429**	.193	.098	.299**	.652**			
7 FS	−.022	.181	.296**	.492**	.290*	.453**		
8 FS real	.078	.217	.350**	.517**	.198	.356**	.951**	
9 FS pseudo	−.187	.077	.136	.340**	.376**	.517**	.861**	.662**

**p ≤ .01, *p < .05

adj. $R^2 = .530$, and explained 56.4% of variance in the scores. In this case, the ASL variables alone in the third step explained 11.6%, R^2 change = .116, $p < .001$. The FS ($\beta = .276$, p = .005) and ASL-CT ($\beta = .262$, $p = .034$) significantly contributed to the model, but ASL-SRT scores did not ($\beta = -.016$; $p = .890$). Age and education alone were also significant, F (2, 82) = 7, $p = .002$, adj. $R^2 = .128$, accounting for 15% of variance. The NVIQ in the second step explained 45% of variance, F (3, 82) = 21, $p < .001$, adj. $R^2 = .428$.

We additionally entered the accuracy on FS pseudowords and real words separately in the whole group model instead of overall FS score. The model with real word FS significantly predicted 57% of variance in reading comprehension, $F = (6, 82) = 17$, $p < .001$; adj. $R^2 = .535$, The ASL variables alone accounted for 12% of variance, R^2 change = .121, $p < .001$. The FS accuracy for real words ($\beta = .272$, $p = .008$) as well as ASL-CT ($\beta = .232$, $p = .023$) made a unique contribution to the model. The full model with FS accuracy for pseudowords predicted 54% of variance in the scores, F (6, 82) = 15, $p < .001$, adj. $R^2 = .503$, with ASL variables alone explaining 9% of variance, R^2 change = .091. However, neither accuracy for FS pseudowords ($\beta = .175$, $p = .059$) nor ASL-CT scores ($\beta = .195$, $p = .063$) contributed significantly to model.

To sum up, FS and ASL-CT were the significant predictors of PIAT-R reading comprehension for the full group of deaf signers. Performance on FS of real words, not pseudowords, appeared to be driving the effect of FS on PIAT-R reading comprehension.

Discussion

An important first result from Study 2 is that native signers outperformed early signers on all ASL measures (Table 8). This result demonstrates the sensitivity of these tests to ASL proficiency and replicates previous studies comparing native and non-native signers (Hauser et al., 2008, 2016). As has been shown in numerous studies (see Mayberry (2010) and Hall (2017) for reviews), these results confirm that delayed access to ASL in childhood impacts signing (and FS) proficiency in adulthood.

The primary goal of Study 2 was to establish the relative contributions of ASL and FS skills to reading comprehension in adult deaf signers who were skilled readers.

Table 10. Multiple regression model of reading comprehension (PIAT-R) with age, education, non-verbal reasoning (NVIQ), and ASL vasriables as predictors for deaf signers

Model	R^2 (adj.)	F (p)		B	SE	β	t	sig.	95%CI
Deaf native signers									
M3	.53 (.45)	6.4 (<.001)	(constant)	−.084	.221		−.38	.705	[−.53; .37]
			Age	−.001	.002	−.090	−.68	.500	[−.00; .00]
			Education	.008	.006	.193	1.47	.151	[−.00; .02]
			NVIQ	.003	.001	.443	3.42	.002	[.00; .01]
			ASL-CT	.410	.208	.254	1.97	.057	[−.01; .83]
			ASL-SRT	−.089	.129	−.106	−.691	.494	[−.35; .17]
			FS	.316	.183	.238	1.73	.093	[−.06; .69]
Deaf early signers									
M3	.65 (.59)	11 (<.001)	(constant)	−.175	.169		−1.04	.307	[−.52; .17]
			Age	.001	.001	.158	1.30	.204	[−.00; .00]
			Education	.003	.004	.102	.851	.401	[−.01; .01]
			NVIQ	.005	.001	.557	4.94	<.001	[.00; .01]
			ASL-CT	.158	.170	.143	.933	.357	[−.19; .50]
			ASL-SRT	.128	.107	.186	1.19	.242	[−.09; .35]
			FS	.216	.117	.222	1.85	.073	[−.02; .45]
All deaf signers									
M1	.15 (.13)	7 (.002)	(constant)	.808	.039		20.7	<.001	[.73; .89]
			Age	−.001	.001	−.117	−1.13	.262	[−.00; .00]
			Education	.014	.004	.382	3.68	<.001	[.01; .02]
M2	.45 (.43)	21 (<.001)	(constant)	.312	.082		3.80	<.001	[.15; .48]
			Age	.000	.001	−.025	−.289	.773	[−.00; .00]
			Education	.009	.003	.238	2.74	.008	[.00; .02]
			NVIQ	.005	.001	.570	6.54	<.001	[.00; .01]
M3	.56 (.53)	16 (<.001)	(constant)	−.088	.123		−.711	.479	[−.33; .16]
			Age	.000	.001	.037	.412	.682	[−.00; .00]
			Education	.005	.003	.144	1.72	.089	[−.00; .01]
			NVIQ	.004	.001	.502	6.06	<.001	[.00; .01]
			ASL-CT	.262	.122	.215	2.15	.034	[.02; .50]
			ASL-SRT	−.010	.076	−.016	−.139	.890	[−.16; .14]
			FS	.276	.096	.259	2.87	.005	[.08; .47]

The correlation analyses (Table 9) revealed that all ASL measures positively correlated with reading comprehension (PIAT-R scores) for the full group of participants, and this pattern also held for the subgroup of early signers. For the native signer group, all measures except ASL-SRT and pseudoword FS correlated with PIAT-R scores. The regression models revealed that both the ASL-CT and overall FS scores were significant predictors of reading comprehension for the full group, with similar trends when the native and early signer groups were analyzed separately.

It was somewhat surprising that scores on the ASL-SRT did not contribute significantly to reading comprehension, given that Stone et al. (2015) found ASL-SRT scores to be a significant predictor of reading skill, as assessed by the WJ-III reading fluency subtest (and after accounting for NVIQ and working memory ability). Stone et al. (2015) utilized the standard 20-sentence version of the test rather than the longer 35-sentence version used here. However, when we entered scores for the shorter version into the model, the results did not change.[1] One possible explanation for the discrepancy between studies is that the deaf signers in the Stone et al. (2015) study were less-skilled readers than those in the current study. Scores on the WJ-IV reading fluency subtest were available for the participants in Study 2 and indicated that they scored higher and exhibited less variability than the deaf readers in the Stone et al.'s study: 82.3 (SD = 15) versus 7.3 (SD = 22.53). Thus, it is possible that performance on the ASL-SRT is not predictive of reading comprehension for more skilled deaf readers. This explanation is also consistent with previous findings that coactivation of ASL is strongest for less-skilled readers (Meade, Midgley, Sevcikova Sehyr, Holcomb, & Emmorey, 2017; Morford, Kroll, Piñar, & Wilkinson, 2014). That is, weaker deaf readers may rely more on ASL for support, leading to a stronger contribution of ASL ability to reading comprehension.

Nonetheless, ASL ability, as measured by the ASL-CT, was a significant predictor of reading comprehension for our large group of skilled deaf readers. The ASL-CT may have been more predictive of reading comprehension than the ASL-SRT because this test explicitly assesses sentence comprehension skill as does the PIAT-R, whereas the ASL-SRT taps the ability to remember and precisely reproduce an ASL sentence. The positive relationship between the ASL sentence and English sentence comprehension ability is consistent with robust evidence in the literature that general language ability predicts reading achievement in bilingual signers, above and beyond other factors, like phonological coding, nonverbal IQ, or memory span (e.g., Chamberlain & Mayberry, 2008; Piñar et al., 2011; Ormel, Hermans, Knoors, & Verhoeven, 2012; see also the meta-analysis by Mayberry et al., 2011).

Replicating Stone et al. (2015), we found that FS independently predicted a significant amount of variance in reading comprehension. However, the precise nature of the relationship between reading and FS, and how this relationship arises, remain unclear. It has been suggested that FS provides a nonauditory phonological system that can be used to represent the internal structure of written words (e.g., Haptonstall-Nykaza & Schick, 2007; Hirsh-Pasek, 1987) and can facilitate word decoding (Chamberlain & Mayberry, 2000; Haptonstall-Nykaza & Schick, 2007; Hirsh-Pasek, 1987; Padden & Ramsey, 2000). Deaf readers may utilize FS to (1) segment words into discrete units (Emmorey & Petrich, 2012), (2) reinforce orthographic skills (Dodd, 1980; Hanson, 1982), (3) read and spell out unfamiliar words (Maxwell, 1984), and (4) obtain some level of phonological awareness (Leybaert, 2000). Adult signers may also use FS as a means to help remember and encode new English vocabulary (Sehyr, Petrich, & Emmorey, 2017).

A novel finding was that FS of real words significantly predicted reading comprehension but FS of pseudowords did not. The associations between fingerspelled and written word forms can arise during early vocabulary acquisition in which written words are often paired with their fingerspelled form (Berke, 2013; Humphries & MacDougall, 2000). Signers may also acquire new English vocabulary words first via FS (during signed discussions, presentations, etc.), which are then linked to printed words (in textbooks, subtitles, etc.). For skilled readers, these associations might be tighter and more efficient, which would facilitate better retention of the fingerspelled word in memory, as required by the repetition test. But for pseudowords, associations between fingerspelled and written word forms do not exist—the mapping between FS and written orthography is only at the sublexical (letter) level. We suggest that lexical-level links between written and fingerspelled words may serve to stabilize and strengthen orthographic word representations which in turn supports skilled reading in deaf adults. To explore this hypothesis, we examined the correlations between FS scores and spelling skill (recognition and production) for the deaf readers in Study 2. The correlations were all significant ($ps < .001$), and of particular interest, the correlations were stronger for real word FS ($r = .604$ and .615 for spelling recognition and production, respectively) compared to pseudoword FS ($r = .374$ and .415 for recognition and production, respectively). This pattern of results lends support to the idea that the orthographic precision of written words (as indexed by spelling skill) is associated with robust lexical representations of fingerspelled words.

Summary and Conclusions

Together Studies 1 and 2 revealed how lexical quality variables (phonology, orthography, and semantics) and sign language variables (ASL comprehension, sentence reproduction, and FS) contributed to reading comprehension ability in a large group of skilled deaf readers in comparison to a matched group of hearing readers. Lexical quality variables contributed differently to reading comprehension for the two groups. Phonological awareness was a strong predictor of reading skill for hearing readers, indicating that the phonological quality of lexical representations continues to exert an influence on reading even into adulthood. But this result did not hold for the deaf readers—phonological ability did not predict reading comprehension, a result that is consistent with several recent studies showing that phonological skills do not modulate reading behavior for deaf adult signers (see Emmorey & Lee, 2021, for review). For deaf, but not hearing readers, the orthographic precision of lexical representations (assessed by spelling ability) was a significant contributor to reading ability. For deaf readers, semantic (vocabulary) knowledge also contributed to reading comprehension when measured either by the PIAT-R or by the WJ-III subtests, whereas for hearing readers, semantics was only a significant predictor for the WJ-III reading measure. This pattern of results provides evidence that the architecture of the reading system can be successfully and adaptively reorganized for deaf readers, shifting reliance from (coarse-grained) phonological representations to high-quality orthographic and semantic lexical representations. More skilled deaf readers appear to develop more robust orthographic-to-semantic mappings, reducing or bypassing phonological-to-semantic mappings.

The results from Study 2 suggest that orthographic-to-semantic mappings in deaf readers might be reinforced by FS, given that the ability to reproduce fingerspelled real words was a significant predictor of reading comprehension. The FS offers an additional way to encode printed words as well as providing a different type of link between orthography and word meaning. Further, neuroimaging studies indicate that the comprehension and production of fingerspelled words both engage the visual word form area (Emmorey, McCullough, & Weisberg, 2015; Emmorey, Mehta, McCullough, & Grabowski, 2016; Waters et al., 2007), implicating a neural link between fingerspelled and printed orthographic representations. Further research is needed to better characterize the nature of the relationship between FS experience and reading comprehension. For example, do high-quality orthographic representations support FS perception/production or does FS experience enhance the precision of orthographic representations? Or perhaps both?

Study 2 also revealed that better ASL comprehension was associated with better English reading comprehension, replicating studies with deaf signing children (Andrew et al., 2014; Hoffmeister, 2000; Novogrodsky et al., 2014; Strong & Prinz, 1997). This result provides additional support for the hypothesis that sign language comprehension can function as the linguistic basis for the development of skilled reading despite modality and grammatical differences between ASL and English (Chamberlain & Mayberry, 2008). In conclusion, by characterizing skilled reading in deaf versus hearing adults, we can better understand the deaf-specific adaptations of the architecture of the reading system. Understanding these patterns will be critical for developing and implementing effective educational and remediation programs for deaf adults, improving literacy instruction for deaf children, and advancing theories of reading development and plasticity.

Supplementary Data

Supplementary material is available at *Journal of Deaf Studies and Deaf Education*.

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Conflicts of Interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest.

Notes

[1]The prediction remained unchanged, F (6, 82) = 16, $p < .001$, adj. $R^2 = .530$, and ASL-SRT (20 sentences) remained non-significant in the model ($\beta = .019$, $p = .857$).

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