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Predictors of Word and Text Reading Fluency of Deaf Children in Bilingual Deaf Education Programmes

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Abstract: Reading continues to be a challenging task for most deaf children. Bimodal bilingual education creates a supportive environment that stimulates deaf children's learning through the use of sign language. However, it is still unclear how exposure to sign language might contribute to improving reading ability. Here, we investigate the relative contribution of several cognitive and linguistic variables to the development of word and text reading fluency in deaf children in bimodal bilingual education programmes. The participants of this study were 62 school-aged (8 to 10 years old at the start of the 3-year study) deaf children who took part in bilingual education (using Dutch and Sign Language of The Netherlands) and 40 age-matched hearing children. We assessed vocabulary knowledge in speech and sign, phonological awareness in speech and sign, receptive fingerspelling ability, and short-term memory at time 1 (T1). At times 2 (T2) and 3 (T3), we assessed word and text reading fluency. We found that (1) speech-based vocabulary strongly predicted word and text reading at T2 and T3, (2) fingerspelling ability was a strong predictor of word and text reading fluency at T2 and T3, (3) speech-based phonological awareness predicted word reading accuracy at T2 and T3 but did not predict text reading fluency, and (4) fingerspelling and STM predicted word reading latency at T2 while sign-based phonological awareness predicted this outcome measure at T3. These results suggest that fingerspelling may have an important function in facilitating the construction of orthographical/phonological representations of printed words for deaf children and strengthening word decoding and recognition abilities.

Keywords: deafness; reading development; bimodal bilingual education; word reading; text reading; sign language; phonological awareness; vocabulary; fingerspelling

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1. Introduction

Reading is a challenging task for most deaf children. It has been consistently observed that, at the group level, deaf children show lower reading levels than hearing children of the same age (e.g., Karchmer and Mitchell 2003; Marschark et al. 2007; Musselman 2000; Qi and Mitchell 2012; Wauters et al. 2006; Moreno-Pérez et al. 2015). Many deaf children experience difficulties with written word recognition and reading comprehension (e.g., Kelly 2003; Merrills et al. 1994; Wauters et al. 2006) that have been found to persist in adulthood (see, e.g., Bélanger and Rayner 2015; Wauters et al. 2021). Research with hearing children has established that vocabulary knowledge, phonological awareness (i.e., ability to recognize and manipulate the sub-lexical structure of words), fluent word recognition, and phonological short-term memory are strong predictors of reading skills in hearing children (e.g., Castles and Coltheart 2004; Dickinson et al. 2003; Verhoeven et al. 2011). However, relatively few studies have examined multiple predictors of reading development in deaf children (e.g., Easterbrooks and Huston 2008; Kyle and Harris 2010, 2011; Spencer and

Oleson 2008), and an even smaller number of studies have examined predictors of reading development in deaf children enrolled in bilingual education in both sign language (SL) and the surrounding spoken/written language (e.g., Scott and Hoffmeister 2016; Crume et al. 2021; Yiu et al. 2019).

Bilingual education has the potential to provide students, particularly those with little access to speech, with alternative routes to increase their reading skills. However, it is still unclear whether—and how—SL instruction effectively supports reading development. Some researchers have proposed that the development of sign-based phonological awareness can be generalized to written language (McQuarrie and Abbott 2013; McQuarrie and Parrila 2009, 2014). Other researchers have highlighted the beneficial role of fingerspelling, as a way to link SL vocabulary to printed words through chaining (Humphries and MacDougall 1999; Padden and Ramsey 2000), as a way to develop orthographic learning (Miller et al. 2021), or as an alternative way to manipulate the sub-lexical structure of words (see, e.g., Antia et al. 2020; Lederberg et al. 2019). Here, we investigated the contribution of different cognitive and linguistic variables to the development of word and text reading skills in a longitudinal study with 8–10-year-old deaf children participating in bilingual programmes. The children attended schools for the deaf where both spoken/written Dutch and Sign Language of the Netherlands (NGT) were part of the curriculum. In addition to speech-based vocabulary and phonological awareness, and short-term memory, we investigated whether sign-based vocabulary and phonological awareness, and fingerspelling ability, predict word and text reading fluency. In the rest of the introduction, we discuss relevant previous literature on each of these predictors.

2. Vocabulary

Knowledge of word meanings is one of the strongest predictors of word decoding and reading comprehension in hearing readers, including early readers, second-grade children, and adults (see, e.g., Verhoeven et al. 2011; Cates et al. 2021). Vocabulary knowledge is also one of the most important predictors of reading success in deaf readers (Aarnoutse and van Leeuwe 1998; Dillon et al. 2012; Geers and Moog 1989; Kyle and Harris 2006, 2010, 2011; Moores and Sweet 1990; Cates et al. 2021; Wauters et al. 2021), with some researchers suggesting that vocabulary might be a stronger predictor of reading for deaf than for hearing readers (for a recent discussion, see Wauters et al. 2021). Kyle et al. (2016) found that expressive vocabulary and speechreading ability were strong predictors of reading in deaf children aged 5 to 14 years. Furthermore, Moreno-Pérez et al. (2015) found that vocabulary was the strongest predictor of reading ability in deaf readers, followed by reading speed, speech phonological awareness, and speechreading ability. Similar results have been found for deaf children with cochlear implants (CIs; see, e.g., Connor and Zwolan 2004; Dillon et al. 2012; Kyle et al. 2016). For example, Connor and Zwolan (2004) found that vocabulary was a strong predictor of reading comprehension for children with CIs after controlling for age of implantation, amount of time using the implant, and socioeconomic status.

Many prior studies identifying vocabulary as a strong predictor of reading achievement in deaf children have focused on expressive vocabulary (e.g., Easterbrooks and Huston 2008; Kyle and Harris 2006; Kyle et al. 2016; Herman et al. 2019). Measuring expressive vocabulary allows researchers to deal with the variability in language background typically found in deaf children. Specifically, allowing the children to give an oral or signed response (or a mixture of both) to the test items allows for a fair measurement of children's global vocabulary knowledge. This global measure is independent of which is the child's preferred language, or how proficient they are in either the spoken or the sign language. However, measuring expressive vocabulary as a whole does not allow exploring the extent to which speech- and signed-based vocabularies contribute to reading skill. Due to the lack of sign-based vocabulary tests for many sign languages, most previous studies investigating receptive vocabulary only measured speech-based vocabulary (e.g., Moreno-Pérez et al. 2015). In contrast, in the current study, we examined receptive speech- and

SL-based vocabularies separately, which allowed us to explore the relationship between vocabulary knowledge in both modalities and their relative contribution to reading (for a similar approach, see Hermans et al. 2008a, 2008b; Hermans et al. 2010).

3. Phonological Awareness

The link between phonological awareness and reading in hearing children is well established: a higher ability to recognize and manipulate the sub-lexical structure of language is related to a higher reading ability (for a recent review, see Castles et al. 2018). Whether speech-based phonological awareness is a strong predictor of reading success in deaf readers is still a matter of intense debate. Some studies have found evidence for similar links between phonological awareness and reading ability in deaf readers as observed in hearing children (e.g., Dyer et al. 2003; Easterbrooks and Huston 2008; Harris and Beech 1998; Luetke-Stahlman and Nielsen 2003; Buchanan-Worster et al. 2020; Herman et al. 2019). For example, Buchanan-Worster et al. (2020) recently found moderate to strong correlations between phonological awareness and single-word reading in both deaf and hearing children. Herman et al. (2019) also found that several tasks measuring phonological awareness (i.e., phoneme deletion, spoonerism, and sequencing) were predictive of single-word reading in oral deaf children. However, other researchers have argued that having speech-based phonological awareness is of less or no importance in reading acquisition for deaf compared to hearing children (Hanson and Fowler 1987; Izzo 2002; Kyle and Harris 2006; Miller 1997; Mayberry et al. 2011). Similarly, many deaf children and adults do not seem to rely on phonological coding during visual word recognition (e.g., Bélanger et al. 2012; Ormel et al. 2010; Costello et al. 2021; but see, e.g., Bouton et al. 2015; MacSweeney et al. 2013; Transler and Reitsma 2005 for phonological effects). Consistent with this finding, recent research suggests that phonological coding may not be the driving force in determining reading ability in many deaf readers (for discussion, see Emmorey 2020; Emmorey and Lee 2021; Gutierrez-Sigut et al. 2017, 2019, 2022; Miller 2010). For example, a recent study with adult readers of Spanish showed that deaf readers activated phonological information from words during written word recognition. However, unlike for hearing readers, the use of phonology was not correlated with reading ability for deaf readers (Gutierrez-Sigut et al. 2017), suggesting that phonological processing might play a reduced role in deaf readers' reading comprehension.

Importantly, these studies only looked at speech-based phonological knowledge. Although deaf children generally have limited access to spoken language phonology, deaf children who sign (including those participating in bilingual programmes) also acquire phonological knowledge in a manual-visual language and develop sign-based phonological awareness. Sign-based phonological knowledge has been found to correlate with speech-based phonological awareness (Corina et al. 2014) and, importantly, with reading abilities in deaf students (McQuarrie and Abbott 2013). Specifically, McQuarrie and Abbott (2013) found low sensitivity to speech-based phonology in deaf children (see also McQuarrie and Parrila 2009) but moderate significant correlations between phonological awareness of American Sign Language and both word recognition and reading comprehension (cf. Holmer et al. 2017; Keck and Wolgemuth 2020). This pattern of results suggests that for deaf children whose first language is an SL, sign-based phonological awareness can be the foundation that supports reading (for further discussion, see (McQuarrie and Parrila 2014; Petitto et al. 2016)). In the current study, both speech-based and sign-based phonological awareness were therefore included as predictor variables.

4. Fingerspelling

Deaf signers have access to the manual representation of printed letters through fingerspelling. Teachers of deaf children have traditionally exploited this resource by explicitly linking written words, fingerspelling, and signs when teaching deaf children new printed vocabulary ('chaining'; Padden and Ramsey 2000). Some researchers noticed the utility of this practice early on (Humphries and MacDougall 1999; Padden and Ramsey 2000) and proposed that fingerspelling proficiency may contribute to deaf children's early reading development (Harris and Beech 1998; Treiman and Hirsh-Pasek 1983; Allen 2015). In a recent study with adult fluent signers, Stone et al. (2015) found that fingerspelling predicted word reading, above SL fluency. However, the mechanisms through which fingerspelling might support reading in deaf readers are not yet understood. A handful of recent studies offer divergent explanations for this seemingly beneficial role of fingerspelling. On the one hand, Miller et al. (2021) suggest that fingerspelling facilitates orthographic learning independently of speech phonology. The authors conducted an intervention study with four pre-school deaf children and observed that fingerspelling mediated the development of orthographic knowledge, independently of the children's phonological skills. On the other hand, it has been proposed that fingerspelling can carry some phonological information from printed words (for details, see Haptonstall-Nykaza and Schick 2007; Sehyr et al. 2016) and hence support the development of phonological representations of speech. Sehyr et al. (2016) found a phonological effect when adult signers recalled lists of fingerspelled words, indicating that fingerspelled words are coded using a speech-based phonological code. In the same line, Antia et al. (2020) and Lederberg et al. (2019) propose that fingerspelling offers an alternative way to manipulate the sub-lexical structure of words. Lederberg et al. (2019) studied the abilities underlying reading skill in oral deaf children and signers from pre-school to second grade. They found that the ability to manipulate the sub-lexical structure of words was strongly related to reading development for all deaf children. For the signers, fingerspelling supported visual access to phonology. In the current study, we further investigate the role of fingerspelling ability as a predictor of word and text reading fluency.

5. Short-Term Memory (STM)

Finally, several studies have found smaller short-term memory (STM) spans for deaf children compared to their hearing peers (e.g., Conrad 1970; Krakow and Hanson 1985; Marschark and Mayer 1998; Pisoni et al. 1999, 2011), which has been linked to differences in phonological access and processing. Specifically, hearing children may experience a facilitative effect of speech coding in phonological short-term memory performance (Perfetti and Sandak 2000; Marschark et al. 2002). It should be noted, however, that significant correlations between short-term memory capacity, phonological coding, and reading performance are not always observed for deaf readers (e.g., Waters and Doehring 1990; Bélanger and Rayner 2015; Kyle and Harris 2006, 2010, 2011; but see also Daneman et al. 1995; Harris and Moreno 2004). In a recent study, Sehyr et al. (2016) found a similar speech-based phonological similarity effect (i.e., recall of printed words was lower in lists with phonologically similar than phonologically dissimilar items) for printed words in adult deaf signers and hearing participants matched in reading skill. Moreover, the authors found positive correlations between accuracy recalling printed words and both reading skill and phonological awareness. Hirshorn et al. (2015) found correlations between serial recall performance and reading comprehension in oral adult deaf readers but not deaf signers, suggesting that phonological access may mediate the positive relation between auditory short-term memory and reading abilities in some studies. Consistent with this idea, recent studies have reported positive correlations between auditory short-term memory and reading comprehension in children and adolescents with CIs (e.g., Bharadwaj et al. 2015; Edwards et al. 2016; but see also Herman et al. 2019 for contrasting findings).

Given the mixed results for the contribution of short-term memory to reading development in deaf children, short-term memory was also included as a predictor in the current study.

6. Present Study

In the current study, we investigated the predictive value of several cognitive and linguistic variables (receptive vocabulary and phonological awareness in both modalities, fingerspelling recognition and short-term memory) for word and text reading fluency in a 2-year longitudinal study of deaf children in year 3 and year 5 of bilingual education programmes. Variables of interest included speech and sign phonological awareness, finger spelling, and short-term memory, in addition to vocabulary.

The predictor variables were measured when the deaf children were either in year 3 or year 5. Word and text reading fluency were assessed one year later (time 2) and two years later (time 3). At time 2 and time 3, word and text reading fluency were also assessed in a group of hearing children of the same age as the deaf children (the children were either in year 3 or year 5 at time 2), to examine performance gaps in word and/or text reading fluency between deaf children and their hearing peers.

7. Methods

7.1. Participants

Participants in the current study consisted of 62 severely or profoundly deaf children in year 3 (~8 years old) and year 5 (~10 years old) of a bilingual education programme in the Netherlands (hearing loss > 80 dB, 27 girls–35 boys; although 18 had a cochlear implant fitted at the time of the first testing session; 6 girls–12 boys). Sign Language of the Netherlands (Nederlandse Gebarentaal/NGT) or Sign supported Dutch (SSD) were used as the main language of instruction. Moreover, children received specific NGT instruction for approximately four hours a week from the age of four. Most deaf participants also attended a sign-oriented preschool from the age of 2–3 years.

At the start of the study, 30 children were 8 years old (mean age: 95 months, SD: 0.49 months) and 32 children 10 years old (mean age: 119 months, SD: 0.47 months). All children attended the school year expected for their chronological age (either year 3 or year 5). In total, 40 age-matched (t (81.6) = −5.01, $p > 0.05$) hearing children (23 boys; 17 girls; youngest group, mean age: 111 months, SD: 9.3 months; oldest group, mean age: 132 months, SD: 6.1 months, at year 2 of the study) with typical development were also tested on the word reading fluency and text reading fluency tasks in order to contextualize the performance of the deaf participants in comparison to a group of hearing peers of the same age and school year (details of the comparison between deaf and hearing children can be found in Appendix B). The participating school boards and Kentalis/Auris research boards approved the study.

7.2. Design and Procedure

The deaf children were tested once a year on three different occasions: Time 1 (T1), time 2 (T2), and time 3 (T3; see Figure 1). Word and text reading fluency were assessed (T2 and T3) for both deaf and hearing children. The children were individually tested in a quiet room at the child's school in 3 different sessions of approximately 15–20 min, 1 session a day across 3 consecutive days.

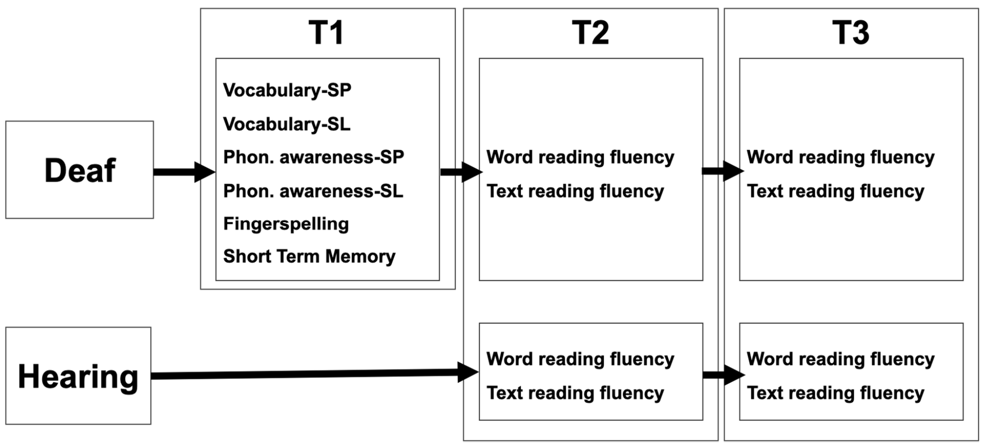

Figure 1. Detailed testing schedule across the years for deaf and hearing participants.

7.3. Materials

7.3.1. Predictors

Table 1 describes the various tests used in the present study. Both speech and sign vocabulary, short term memory, and the signed-based phonological awareness tests were part of standardized tests (for references, see Table 1). The speech phonological awareness and fingerspelling recognition tasks were developed specifically for this study and are described in more detail in the text below. The stimuli used in these tasks can be found in Appendix A. Table 2 shows an overview of the correlations between the predictor variables for deaf children at T1.

Table 1. Details of the study measures.

Predictor	Source	Dependent Variable	Method	Response Type	Task Description
Vocabulary-speech (VocSP)	Receptive vocabulary test from: Taaltest Alle Kinderen (TAK: Language Test for All Children; Verhoeven and Vermeer 2001)	Number of correct responses	In-person with test administrator	Multiple choice: printed words	The test administrator says aloud each of the 96 target words while the child, sitting opposite, looks at them. It is crucial that the mouth of the administrator is clearly visible. The child is asked to select one of four alternatives after being exposed to each item. Children responses are based on speechreading in addition to any residual hearing. The task is designed to simulate day-to-day speech-recognition.
Vocabulary-sign (VocSL)	Test-Nederlandse Gebarentaal (TNGT; Hermans et al. 2007)	Number of correct responses	Computerised	Multiple choice: pictures	After seeing each of the 60 NGT single sign video clips on a computer screen, the child selects one of 4 alternatives shown on the screen.
Phonological awareness-speech (PhoSP)	Custom designed	Number of correct responses	Computerised	Multiple choice: pictures	The child saw 1 picture at the top of the screen and 3 other pictures at the bottom. The child selected the picture from the bottom row that rhymed with the top one. There were 5 practice and 40 test items.
Sign-based phonological awareness (PhoSL)	Part of sign language assessment battery for elementary school-aged children (Hermans et al. 2007)	Number of correct responses	Computerised	YES or NO. Both spoken and signed responses were accepted	Two signs were presented simultaneously on a computer screen. The two signs are either identical or overlap phonologically but have a different hand shape, location, orientation, movement, or lip pattern. The children indicated whether the two signs were the same or not. The test contains 36 pairs of items, half of which were identical and half non-identical.

Table 1. *Cont.*

Predictor	Source	Dependent Variable	Method	Response Type	Task Description
Fingerspelling recognition (FSP)	Custom designed	Number of correct responses	Computerised and pen and paper	Multiple choice: printed words	After seeing each of the 26 test fingerspelling videos, the child selected one of four possible printed words on a piece of paper. The presentation order was fixed, and difficulty increased as the test progressed.
Short-term memory (STM)	Part of IQ assessment battery for elementary school-aged children, the RAKIT	Number of correct sequences recalled	In-person with test administrator	Arrangement of the objects on the table	After seeing a sequence of line-drawings depicting objects for 5 seconds, the child arranged the objects on the table in the same order. Difficulty increased from 2-item sequences to 7-item sequences.
Word reading fluency	Custom designed	Accuracy and RTs	Computerised	Word or Pseudoword decision in computer	Lexical decision over 72 letter strings (36 words) 3–6 letter long and familiar to children.
Text reading fluency	CITO (Krom 2001)	Number of items answered correctly relative to the total number of items responded to and corrected for guessing	Pen and paper	Multiple choice: printed words	Presents a story (approximately 1000 words long). Around every 10 words the child selects the correct word in that location out of 3 orthographically similar options.

Table 2. Overview of correlations between predictor variables for deaf children at time 1 with age partialled out.

		1		2		3		4		5		6
1	Vocabulary-Speech (VocSP)	—										
2	Vocabulary-Sign (VocSL)	0.404	**	—								
3	Phonological awareness Speech (PhoSP)	0.585	***	0.415	***	—						
4	Phonological awareness Sign (PhoSL)	0.185		0.287	*	0.413	***	—				
5	Fingerspelling (FSP)	0.219		0.383	**	0.499	***	0.265	*	—		
6	Short-term memory (STM)	0.241		0.216		0.351	**	0.142		0.459	***	—

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

For the speech phonological awareness (PhoSP) test, 5 practice and 40 target pictures were selected from the Dutch Leesladder (Reading Ladder; Irausquin and Mommers 2001). The words associated with the pictures were all 1-syllable words with 3 to 6 letters (mean = 3.88 letters). The mean log frequency for the words associated with the pictures was 1.63 (Baayen et al. 1993) and the mean number of orthographic neighbours was 17.88. The Cronbach's Alpha coefficient for the 40 test items was 0.91. In each trial, children saw a picture at the top of the screen accompanied by three other pictures at the bottom. Children were asked to select the picture from the bottom row that rhymed in Dutch with the object on the top row. The location of the target picture at the bottom was randomized across trials. Detailed feedback was given for the practice trials: after the child's answer, both the target and the selected picture moved to the left corner of the screen and their associated words were shown in either green (correct) or red (incorrect). To ensure understanding, the experimenter then repeated the feedback and the instructions. All children understood the task after the five practice trials. They could complete the remainder of the task at their own pace. The outcome measure used as a predictor in the current study was the number of correct responses.

In the fingerspelling recognition test, videos of fingerspelled letter strings were presented one at the time on the screen. For each test item, four printed letter strings were then presented on a separate piece of paper and the child had to indicate which of the four strings was identical to the fingerspelled letter string. The test contained 26 items and gradually increased in difficulty from 2-letter strings to 8-letter strings. The mean length of the test items was 4.12 letters. The distracter strings differed from the target string in letter order, substitution or omission, or had no overlapping letters at all. The mean log frequency of the words was 2.03 (Baayen et al. 1993). Mean speech familiarity of the words among 6-year-old hearing children was 90.8% (Schaerlaekens et al. 1999). The Cronbach's Alpha coefficient of the 26 test items was 0.90. The outcome measure used as a predictor in the current study was the number of correct responses.

7.3.2. Dependent Measures

Text reading fluency. The text reading fluency text (CITO) is routinely administered nationwide to hearing children at mid second grade, i.e., around 8 years of age (Krom 2001). Following the test instructions, the text reading fluency score was calculated as follows: number performed correctly * (number performed correctly − total number of items completed/3)/(total number of items completed − total number of items completed/3).

Word reading fluency. The word reading fluency task was specifically designed for this study. The children performed a lexical decision over 72 letter strings, half of which were real words and half pseudowords. The log frequency of the real word stimuli ranged from 1.11 to 3.53 (mean log frequency of 2.05) (Baayen et al. 1993); real word stimuli and pseudoword stimuli had an average of 16.03 (words) and 15.64 (pseudowords) orthographic neighbours (1 letter difference), respectively. To increase the likelihood that each of the words in the test was familiar to the children, the words were selected from a (spoken) lexical database for children and were familiar to at least 90% of hearing 6-year-old children (Schaerlaekens et al. 1999). In addition, the words occurred at least 10 times (out of 202.526 entries) in a database for written words in children's literature (Staphorsius et al. 1988). The word and pseudoword stimuli were between 3 and 6 letters long (mean length was 4.0 and 4.3 letters, respectively). Accuracy and reaction times were analysed as dependent variables.

Data analyses. A series of group comparisons were conducted to inform the subsequent regression analyses. First, a small group of children had a CI fitted at the time of testing. To test for possible differences in the performance between the deaf children with and without CI, we ran separate independent samples *t*-tests for each of the dependent variables at T2 and T3. Second, we contrasted the performance of all deaf children for the dependent variables at T2 and T3 to scores from the group of age-matched hearing children attending the same school year to assess deaf children's performance relative to a group of typical readers. Third, we ran independent samples *t*-tests comparing year 3 and year 5 (at T1) children to check whether there were differences in the performance of deaf children depending on age at the time of testing. Based on the results from these *t*-tests (details below), all deaf children were treated as a single group independently of having a CI fitted or not. Furthermore, age was introduced as a first step in all regression analyses.

Stepwise linear regression analyses were conducted to identify possible predictors of word (accuracy and RTs) and text reading fluency (number correct out of total completed, corrected for guessing) of the deaf children at time 2 and time 3. For T2 performance analyses, T1 measures of age, spoken (VocSP) and signed (VocSL) receptive vocabulary, speech-based (PhoSP) and sign-based (PhoSL) phonological awareness, fingerspelling (FSP), and phonological short-term memory (STM) were introduced as predictor variables. Age was introduced in step one, followed by VocSP and VocSL in step two. The remaining variables were included in the third step to explore their unique contribution above and beyond age and vocabulary. PhoSP, PhoSL, FSP, and STM were introduced as the final step. Variables were retained in the model based on *p*-values. For T3 performance analyses, age was introduced in step one, followed by word reading accuracy and RTs at T2. Then, VocSP and VocSL were introduced to the model. Finally, to identify their possible unique contribution above and beyond age, performance at T2 and vocabulary, PhoSP, PhoSL, FSP, and STM were introduced in step four.

8. Results

Due to a technical issue, the word reading fluency data at T2 from two participants (one with and another one without CI) were not recorded. They were included in the study as all the other measures were collected.

8.1. Influence of CI

Independent samples *t*-tests showed that the deaf children with and without a CI did not perform significantly differently in word or text reading fluency assessment at T2 and T3 (all *ps* > 0.7) and were therefore treated as a single group in all the analyses. Figure 2 shows the violin plots and *t*-test results for each of the study measures.

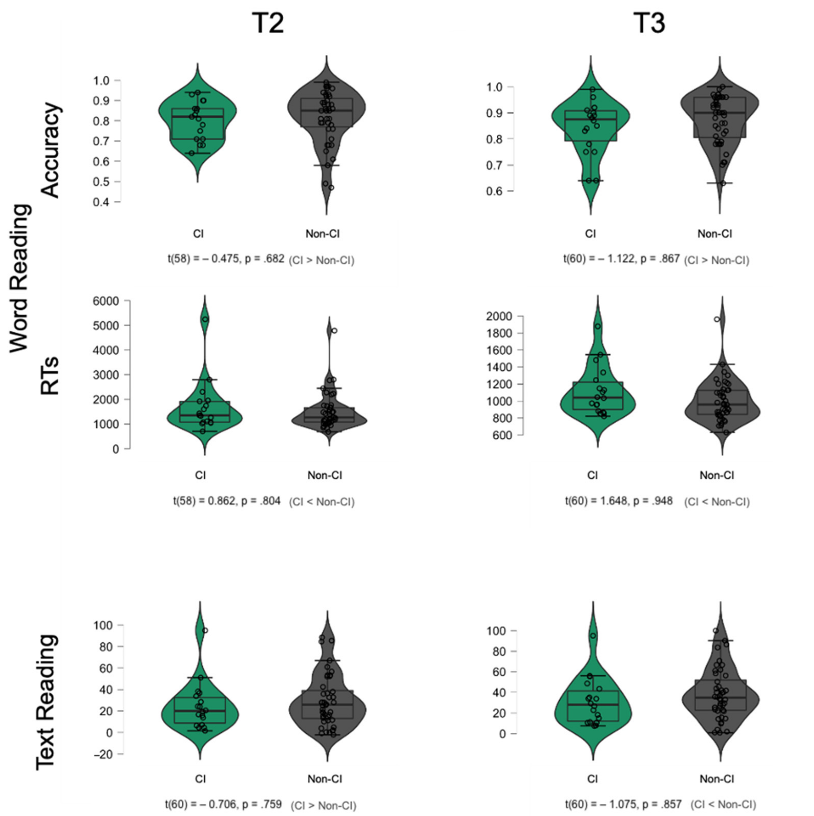

Figure 2. Response distributions and results from the independent sample *t*-tests for deaf children with and without CI at all the study measures.

8.2. Deaf Children's Performance in Comparison to Age-Matched Hearing Children

As expected, hearing children outperformed deaf children in both the word and the text reading fluency task at both T2 and T3. Details of these analyses can be found in Appendix B.

8.3. Influence of Age

Independent samples *t*-test comparing year 3 and year 5 deaf children's performance on the predictor variables collected at T1, and on word and text reading fluency measures at T2 and T3 showed that older children (year 5) outperformed younger children on all T1 measures (all *ps* < 0.008; see Table 3). Older children also showed higher word and text reading accuracy at T2 and T3 (all *ps* < 0.001. There were no significant differences in RTs in the word reading fluency test at either T2 or T3 (both *ps* > 0.9).

Table 3. Mean scores and statistical comparisons of year 3 (Y3) and year 5 (Y5) deaf children on predictor variables at time 1, and word and text reading fluency at time 2 (T2) and time 3 (T3) and results of the independent samples *t*-tests comparing both groups. At time 1 (T1), year 3 children were approximately 8 years and year 5 children were approximately 10 years of age. Significant predictors are bolded.

		Y3		Y5		Difference	t	df	*p*
		Mean	**SD**	**Mean**	**SD**				
T1	Vocabulary-Speech (VocSP)	21	16	44	25	−23	−4.214	60	**<.001**
	Vocabulary-Sign (VocSL)	22	13	36	14	−14	−4.122	60	**<.001**
	Phonological awareness Speech (PhoSP)	22	7	31	6	−9	−5.294	60	**<.001**
	Phonological awareness Sign (PhoSL)	29	5	31	3	−3	−2.504	60	**.008**
	Fingerspelling (FSP)	18	5	23	3	−5	−4.581	60	**<.001**
	Short term memory (STM)	7	2	8	2	−1	−2.483	60	**.008**
T2	Word reading accuracy	75	12	88	8	−12	−4.647	58	**<.001**
	Word reading RTs	1696	754	1419	878	277	1.311	58	.903
	Text reading	17	18	38	23	−20	−3.819	60	**<.001**
T3	Word reading accuracy	82	9	91	7	−9	−4.055	60	**<.001**
	Word reading RTs	1108	298	965	193	143	2.256	60	.986
	Text reading	25	18	47	24	−22	−4.134	60	**<.001**

Based on these findings, age was added as a first step in the stepwise regression analyses to explore the effect of each of the predictors of children's reading performance beyond the effect of age.

8.4. Predictors of Deaf Children's Reading Performance

Correlations between predictors and dependent variables.

The correlations among the predictor variables and word and text reading performance for deaf children at time 2 and time 3 with age partialled out are shown in Figure 3. As can be seen, all the predictor variables showed a significant correlation ($p < 0.05$) with at least one of the dependent measures even after controlling for the variance linked to age. Therefore, all predictor variables were included in the stepwise regression analyses (see Cates et al. 2021 for a similar approach in a recent study with deaf adult readers).

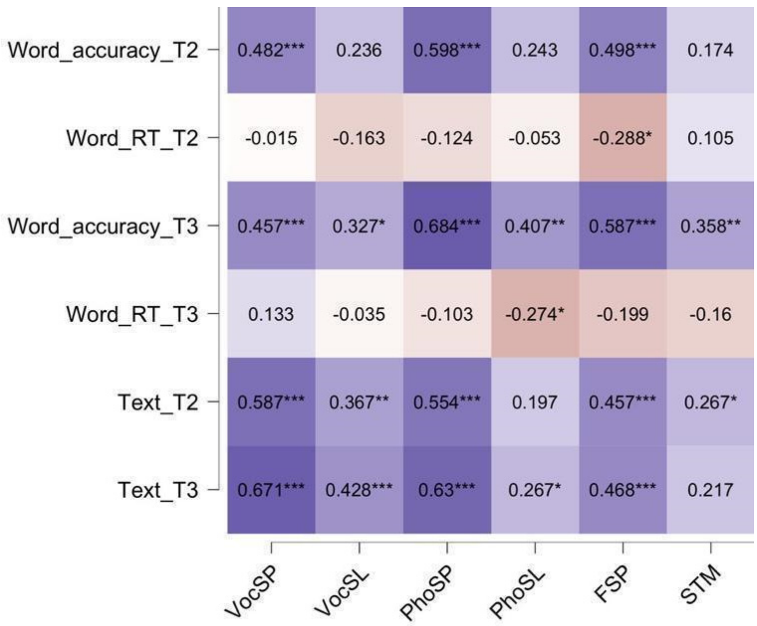

Figure 3. Correlation between predictors (*X*-axis) and dependent variables (*Y*-axis) with age partialled out. *** $p < .001$, ** $p < .01$, * $p < .05$.

8.5. Prediction of Word Reading Fluency at T2

Word reading accuracy. In step 3 of the analysis, the variables age, VocSP, FSP, and PhoSP were entered into the regression equation, explaining 58% of the total variance of the accuracy of word reading at T2 (see Table 4 and Appendix C).

Table 4. Regression coefficients for word accuracy at T2. Significant predictors are bolded.

							95.0% CI			
		B	**Std. Error**	**Beta**	***t***	***p***	**LB**	**UB**	**Tolerance**	**VIF**
1	(Constant)	0.335	0.112		2.981	**.004**	0.110	0.560		
	Age	0.004	0.001	0.492	4.302	**<.001**	0.002	0.007	1.000	1.000
2	(Constant)	0.489	0.106		4.617	**<.001**	0.277	0.701		
	Age	0.002	0.001	0.254	2.190	**.033**	0.000	0.004	0.758	1.320
	Vocabulary-Speech (VocSP)	0.002	0.001	0.483	4.159	**<.001**	0.001	0.003	0.758	1.320
3	(Constant)	0.458	0.095		4.817	**<.001**	0.268	0.648		
	Age	0.001	0.001	0.089	0.798	.428	−0.001	0.003	0.650	1.538
	Vocabulary-Speech (VocSP)	0.002	0.001	0.395	3.723	**<.001**	0.001	0.003	0.724	1.381
	Fingerspelling (FSP)	0.010	0.003	0.416	3.906	**<.001**	0.005	0.015	0.718	1.393
4	(Constant)	0.455	0.092		4.965	**<.001**	0.272	0.639		
	Age	0.000	0.001	0.054	0.498	.620	−0.001	0.002	0.637	1.569
	Vocabulary-Speech (VocSP)	0.001	0.001	0.236	1.900	.063	0.000	0.002	0.493	2.029
	Fingerspelling (FSP)	0.007	0.003	0.294	2.526	**.014**	0.001	0.012	0.562	1.778
	Phonological awareness Speech (PhoSP)	0.005	0.002	0.326	2.271	**.027**	0.001	0.009	0.368	2.718

Word reading latency. In step 2 of the analysis, the variables FSP and STM were entered into the regression equation, explaining 15.8% of the total variance (see Table 5 and Appendix C).

Table 5. Regression coefficients for word RTs at T2. Significant predictors are bolded.

							95% CI			
		B	**Std. Error**	**Beta**	***t***	***p***	**LB**	**UB**	**Tolerance**	**VIF**
1	(Constant)	2758.122	436.987		6.312	**<.001**	1883.398	3632.846		
	Fingerspelling (FSP)	−57.182	2.251	−0.348	−2.824	**.006**	−97.719	−16.645	1.000	1.000
2	(Constant)	2551.981	434.910		5.868	**<.001**	1681.089	3422.873		
	Fingerspelling (FSP)	−86.077	23.847	−0.523	−3.610	**.001**	−133.829	−38.324	0.679	1.472
	STM	11.353	51.579	0.310	2.140	**.037**	7.068	213.637	0.679	1.472

8.6. Prediction of Word Reading Fluency at T3

Word reading accuracy. In step 4 of the analysis the variables age, word fluency accuracy at T2, PhoSP, and FSP were entered into the regression equation, explaining 78% of the total variance (see Table 6 and Appendix C).

Word reading latency. In step 2 of the analysis, the variables age and PhoSL were entered into the regression equation, explaining 16.2% of the total variance (see Table 7 and Appendix C).

To summarize, age, speech-based vocabulary, fingerspelling, and phonological awareness of speech were predictive of word reading fluency at time 2. One year later, age, speech-based vocabulary, fingerspelling, and phonological awareness of speech were still predictive of word reading accuracy while only sign-based phonological awareness was predictive of word reading latency of responses at T3.

Table 6. Regression coefficients for word accuracy at T3. Significant predictors are bolded.

							95.0% CI			
		B	**Std. Error**	**Beta**	***t***	***p***	**LB**	**UB**	**Tolerance**	**VIF**
1	(Constant)	0.495	0.092		5.387	**<.001**	0.311	0.679		
	Age	0.003	0.001	0.471	4.072	**<.001**	0.002	0.005	1.000	1.000
2	(Constant)	0.279	0.061		4.558	**<.001**	0.156	0.401		
	Age	0.001	0.001	0.079	0.953	.345	−0.001	0.002	0.758	1.319
	Word accuracy T2	0.645	0.067	0.799	9.689	**<.001**	0.512	0.779	0.758	1.319
3	(Constant)	0.373	0.062		6.027	**<.001**	0.249	0.496		
	Age	0.000	0.001	−0.007	−0.087	.931	−0.001	0.001	0.687	1.456
	Word accuracy T2	0.485	0.076	0.601	6.396	**<.001**	0.333	0.637	0.487	2.055
	Phonological awareness Speech (PhoSP)	0.004	0.001	0.342	3.530	**.001**	0.002	0.006	0.458	2.184
4	(Constant)	0.381	0.060		6.344	**<.001**	0.260	0.501		
	Age	0.000	0.001	−0.041	−0.519	.606	−0.001	0.001	0.660	1.516
	Word accuracy T2	0.437	0.077	0.541	5.686	**<.001**	0.283	0.591	0.445	2.245
	Phonological awareness Speech (PhoSP)	0.003	0.001	0.283	2.894	**.005**	0.001	0.006	0.422	2.369
	Fingerspelling (FSP)	0.004	0.002	0.190	2.159	**.035**	0.000	0.007	0.521	1.920

Table 7. Regression coefficients for word RTs at T3. Significant predictors are bolded.

							95.0% CI			
		B	**Std. Error**	**Beta**	***t***	***p***	**LB**	**UB**	**Tolerance**	**VIF**
1	(Constant)	1696.88	272.300		6.232	**<.001**	1151.81	2241.95		
	Age	−6.140	2.517	−0.305	−2.439	**.018**	−11.178	−1.102	1.000	1.000
2	(Constant)	2025.96	304.924		6.644	**<.001**	1415.37	2636.57		
	Age	−4.449	2.564	−0.221	−1.736	.088	−9.583	0.684	0.907	1.103
	Phonological awareness Sign (PhoSL)	−17.004	7.876	−0.275	−2.159	**.035**	−32.776	−1.233	0.907	1.103

8.7. *Prediction of Text Reading Fluency at T2*

In step 3 of the analysis, the variables age, VocSP, and FSP were entered into the regression equation, which explained 56% of the total variance (see Table 8 and Appendix C).

Table 8. Regression coefficients for text fluency at T2. Significant predictors are bolded.

							95.0% CI			
		B	**Std. Error**	**Beta**	***t***	***p***	**LB**	**UB**	**Tolerance**	**VIF**
1	(Constant)	−56.420	22.536		−2.504	**.015**	−101.500	−11.341		
	Age	0.782	0.207	0.437	3.767	**<.001**	0.367	1.197	1.000	1.000
2	(Constant)	−21.561	19.439		−1.109	.272	−60.458	17.337		
	Age	0.282	0.192	0.158	1.472	.146	−0.101	0.666	0.781	1.280
	Vocabulary-Speech (VocSP)	0.579	0.104	0.597	5.566	**<.001**	0.371	0.787	0.781	1.280
3	(Constant)	−27.370	17.908		−1.528	.132	−63.217	8.477		
	Age	0.032	0.190	0.018	0.169	.866	−0.348	0.412	0.669	1.494
	Vocabulary-Speech (VocSP)	0.505	0.098	0.520	5.159	**<.001**	0.309	0.700	0.744	1.345
	Fingerspelling (FSP)	1.674	0.481	0.357	3.483	**.001**	0.712	2.636	0.721	1.388

8.8. *Prediction of Text Reading Fluency at TIME 3*

In step 3 of the analysis, the variables age, word fluency accuracy at T2, VocSP, and FSP were entered into the regression equation, explaining 68% of the total variance (see Table 9 and Appendix C).

Table 9. Regression coefficients for text fluency at T3. Significant predictors are bolded.

							95.0% CI			
		B	Std. Error	Beta	*T*	*p*	LB	UB	Tolerance	VIF
1	(Constant)	−61.631	23.326		−2.642	**.011**	−108.323	−14.940		
	Age	0.913	0.216	0.486	4.237	**<.001**	0.482	1.345	1.000	1.000
2	(Constant)	−103.854	20.078		−5.172	**<.001**	−144.060	−63.648		
	Age	0.350	0.198	0.186	1.765	.083	−0.047	0.748	0.758	1.319
	Word accuracy T2	126.107	21.861	0.609	5.769	**<.001**	82.331	169.884	0.758	1.319
3	(Constant)	−55.885	20.034		−2.790	**.007**	−96.018	−15.753		
	Age	0.119	0.177	0.064	0.674	.503	−0.235	0.474	0.699	1.431
	Word accuracy T2	78.020	21.370	0.377	3.651	**.001**	35.210	12.830	0.582	1.719
	Vocabulary-Speech (VocSP)	0.484	0.104	0.482	4.664	**<.001**	0.276	0.691	0.581	1.721
4	(Constant)	−47.228	19.622		−2.407	**.019**	−86.553	−7.904		
	Age	0.001	0.178	0.001	0.008	.993	−0.354	0.357	0.643	1.555
	Word accuracy T2	52.835	23.190	0.255	2.278	**.027**	6.361	99.309	0.457	2.188
	Vocabulary-Speech (VocSP)	0.493	0.100	0.491	4.935	**<.001**	0.293	0.693	0.580	1.723
	Fingerspelling (FSP)	1.153	0.491	0.237	2.347	**.023**	0.169	2.137	0.564	1.773

To summarize, age, speech-based vocabulary, and fingerspelling proved to be the strongest predictors of text reading fluency at both T2 and T3 (as expected, word reading fluency at T2 explained additional variance in text reading fluency at T3).

9. General Discussion

The current study investigated the predictive value of receptive speech- and sign-based vocabularies, speech and signed-based phonological awareness, fingerspelling ability, and STM on word and text reading fluency in deaf children in bilingual education programmes in year 3 (~8 years old) and year 5 (~10 years old) across a time-span of 2 years. A small subgroup of children in these programmes wore a CI at the time of the study. A group of age-matched hearing children also completed the word and text reading fluency tasks at T2 and T3 to evaluate deaf children's performance against norms for their peers with normal hearing. We found that (1) speech-based vocabulary predicted word reading accuracy and text reading fluency both at T2 and T3, (2) fingerspelling ability was a strong predictor of word and text reading fluency at both T2 and T3, (3) speech-based phonological awareness predicted word reading accuracy at T2 and T3 but did not predict text reading fluency, and (4) fingerspelling and STM predicted word reading latency at T2 while sign-based phonological awareness predicted this outcome measure at T3.

In line with most previous research, deaf children obtained lower text reading fluency scores and word reading accuracy than hearing children at both T2 and T3. However, word reading latencies at T2 and T3 were similar for deaf and hearing children (see Appendix B for details). Finally, there were no differences in the performance between the deaf children without CI and the small group of children with CI. In the rest of this section, we will discuss each of these findings.

9.1. Speech-Based Vocabulary, Fingerspelling, and Speech-Based Phonological Awareness Predict Reading Accuracy

Our finding that vocabulary is a strong predictor of word and text reading abilities in deaf children in bimodal bilingual education in the current study provides new evidence in favour of the simple view of reading for deaf readers (Gough and Tunmer 1986; Chamberlain and Mayberry 2000). Within this theory of reading development, word decoding and linguistic comprehension are the two necessary components for successful reading acquisition. Loading strongly on the linguistic comprehension component, vocabulary has consistently been identified as the strongest predictor of reading in deaf children and adults (see, e.g., Wauters et al. 2021; Cates et al. 2021). As discussed in the introduction, previous work had either measured only speech-based receptive vocabulary (e.g., Moreno-Pérez et al. 2015) or had measured expressive vocabulary, allowing children to respond in their spoken language, their sign language, or a combination of both (e.g., Kyle et al. 2016). Measuring expressive vocabulary as a whole also makes sense in light of findings that receptive and expressive vocabularies have loaded into a single language factor in hearing children (see e.g., Anthony et al. 2014; Bornstein et al. 2014). However, it does not allow assessment of each language separately. Assessing receptive vocabulary in both language modalities enables us to explore the unique contribution of speech-based and sign-based vocabularies. We found that despite being positively correlated to speech-based vocabulary (r = 0.404, $p < 0.01$), signed-based vocabulary did not predict word or text reading fluency in the current study. This suggests a stronger link of early reading abilities with spoken than signed vocabulary for the deaf children in bimodal bilingual education in the current study.

At first sight, this result seems inconsistent with the findings of one of the few previous studies of literacy outcomes in deaf children in bilingual education. Scott and Hoffmeister (2016) studied deaf children attending middle- and high-school (years 6 to 12) classes at deaf bilingual schools in North America. Their results showed that SL proficiency was the stronger predictor of reading comprehension. Interestingly, the authors also found evidence of a stronger impact of English proficiency on reading comprehension at lower levels of word reading fluency. Therefore, it is possible that our findings reflect an earlier stage in reading development when linguistic knowledge might hold a heavier weight in explaining reading comprehension. The correlations that we observed between SL vocabulary and each of the dependent variables (Figure 3) seem consistent with this interpretation. Specifically, we observed a small positive correlation between signed-based vocabulary and text reading fluency at T2 (r = 367, $p < 0.01$) but a moderate correlation at T3 (r = 0.428, $p < 0.001$), suggesting a stronger relationship at later stages of development. In a similar vein, DeLana et al. (2007) found a correlation between reading achievement and number of years using SL. However, the existing knowledge base is small, with many methodological differences between studies. Future studies should establish whether this suggested developmental pattern can also be shown in a comprehensive longitudinal study, where other important factors are controlled for. In a review of a small number of available studies, Mayer and Trezek (2020) propose that, together with the use of hearing aids or CIs, initial signed and spoken language proficiency are important factors to control for in studies of reading abilities with deaf children. We also acknowledge that, while the children in the current study were regularly exposed to NGT in the classroom, teachers' level of NGT proficiency varied and detailed information on the quantity and quality of their bilingual input was not available. These are important factors to consider in future studies of the relation between sign language proficiency and reading performance in deaf children. In addition, it is possible that the strong inter-correlations between the different predictor variables observed here reflect common specific teaching practices in the Netherlands (see below), such as explicitly linking written words, signs, fingerspellings, and—sometimes—mouth patterns to improve deaf children's knowledge of written words (Hermans et al. 2007). Future studies could describe the extent to which practices, such as chaining, are in fact used in the classroom and how these relate to children's reading outcomes. In summary, the present study highlights the utility of assessing both speech- and sign-based linguistic comprehension in studies of reading development in deaf children to disentangle their unique contributions to reading development and the complex relationships between both languages at different linguistic levels.

We would like to point out here again that the test administrator pronounced each of the words while in clear view of the child, allowing the deaf children to rely on visual speech information to complete this test. Although we did not measure speechreading ability separately, a previous study using a very similar assessment of receptive vocabulary (Moreno-Pérez et al. 2015) only found a moderate correlation with speechreading ability (r = 0.37, $p = 0.006$). The moderate correlation suggests that an assessment of receptive vocabulary measures more than just speechreading ability. The extent to which speech-based vocabulary is linked to speechreading ability—as an important channel through which many deaf children acquire speech-based vocabulary—is a question that future research should address. This might be especially relevant for deaf readers, as speechreading ability has also been proposed to play an important role in enhancing phonological knowledge in deaf readers (Buchanan-Worster et al. 2020; Kyle et al. 2016). Future research could also examine whether a picture-based receptive vocabulary task may show stronger correlations with the reading performance of deaf children than the format with printed words used in the current study.

While speech-based phonological awareness predicted word reading accuracy at T2 and T3, it did not predict text reading fluency at either T2 or T3. This result contrasts with studies in hearing children finding that phonological decoding and reading comprehension are related at all ages across development (see García and Cain 2014 for a recent meta-analysis). However, our finding is consistent with previous research showing a limited role for phonological awareness in some studies of reading development in deaf children (e.g., dependent on their language background and CI use), and studies suggesting that vocabulary might be a stronger predictor of reading comprehension for deaf children than hearing children (Mayberry et al. 2011; Moreno-Pérez et al. 2015; Kyle et al. 2016). Dutch, as Spanish or Italian, is considered to have a transparent orthography. The consistent correspondence between graphemes and phonemes in transparent orthographies might facilitate readers' access to phonological information from words during word recognition (Katz and Frost 1992). However, in the case of deaf readers, the use of phonological codes from words during word recognition might not be associated with better reading comprehension. A recent study with adult deaf readers of Spanish (Gutierrez-Sigut et al. 2017) showed clear activation of phonological codes in behavioural and electrophysiological responses during word recognition. However, the size of the phonological effects was not correlated with reading comprehension in deaf readers, suggesting that deaf readers might more strongly rely on other linguistic abilities in reading comprehension. For example, recent research in adult deaf readers suggests that visual and orthographic factors might play a more important role in deaf people's reading comprehension (e.g., Emmorey et al. 2021; Gutierrez-Sigut et al. 2019, 2022). The present findings suggest that the contribution of speech phonology to reading comprehension is also limited even during early stages of reading acquisition in some groups of deaf children. However, much more research is needed to fully understand how much, what type, and at which stages phonological knowledge of speech is needed or beneficial for reading development in different groups of deaf children.

Sign-based phonological awareness only predicted word reading latencies at T3. This result seems consistent with the findings by Ormel et al. (2012) that deaf children are sensitive to phonological information in sign translation equivalents of Dutch words during visual word recognition. Similar results have been found in deaf teenagers (Villwock et al. 2021) and deaf adult readers (Morford et al. 2011, 2017). This result is also in line with other recent studies showing positive correlations between sign language knowledge and reading abilities (Scott and Hoffmeister 2016; Crume et al. 2021; Keck and Wolgemuth 2020; Holmer et al. 2016). It remains unclear, however, why this variable only impacted word reading fluency at T3 and why it only affected word reading latency, not accuracy or text reading fluency. Nevertheless, this is an intriguing result that highlights the importance of including sign-based linguistic measures in reading studies involving deaf children who sign, and more research on the potential role of sign-based phonological awareness in reading acquisition for deaf children in bimodal bilingual education is required.

A final key finding of the present experiment was the strong predictive power of fingerspelling. Although only a handful of studies to date have investigated the role of fingerspelling in the reading development of deaf children (e.g., Haptonstall-Nykaza and Schick 2007; Miller et al. 2021), it appears to be strongly related to reading abilities in deaf children and adults (e.g., Padden 2006; Miller et al. 2015; Stone et al. 2015; Sehyr et al. 2016). Fingerspelling might be an important skill for deaf children to support reading acquisition because the mapping between fingerspelled handshapes onto letters may facilitate orthographic segmentation and word decoding. This seems in line with recent findings from an ERP study by Emmorey et al. (2017), who found less differentiated N170 responses to written words (relative to symbol strings) in skilled adult deaf readers than adult hearing readers, suggesting differential neural tuning to print for deaf readers. It should be noted that, although fingerspelling was not correlated with speech-based vocabulary in the current study, it was positively correlated with sign vocabulary and both speech- and sign-based phonological awareness. This pattern of correlations seems consistent with the view that the manual-visual component of fingerspelling can provide a bridge between signs on the one hand and written word forms on the other hand.

Although the underlying mechanism is still unclear, fingerspelling may tap into phonological or orthographic processing. A number of researchers have conceptualized the role of fingerspelling as a link between the printed words and their phonological representations (e.g., Haptonstall-Nykaza and Schick 2007; Sehyr et al. 2016). For example, fingerspelling might provide phonological or prosodic information about words through cadence of movement and therefore contribute to more robust phonological-lexical representations (Haptonstall-Nykaza and Schick 2007). The above-mentioned correlation between speech-based phonological awareness and fingerspelling ability supports this view. Furthermore, in hearing children, it is commonly accepted that phonology stabilises letter representations and makes orthographic processing and orthography-to-meaning mappings more efficient. Given the underspecified phonological access and knowledge for many deaf children, it is possible that fingerspelling can take on this role of stabilising letter representations. Stone et al. (2015) hypothesise that fingerspelling strengthens (printed) word decoding accuracy and word recognition automaticity through shared underlying processes with visual orthographic processing (e.g., perceiving and decoding sequences of letter representations). In contrast, Miller et al. (2021) proposed that fingerspelling might link to orthographic learning independently of phonological skill. Finally, it is possible that fingerspelling enriches representations of written letters through a motor component ('embodied letters'), in the same way as number gestures have been argued to support the acquisition of (stable) symbolic number representations in hearing children (e.g., Di Luca and Pesenti 2011; Fischer 2012). The present results confirm the important role of fingerspelling in the reading acquisition of deaf bimodal bilingual children. However, further research is needed aimed specifically at investigating the specific role of fingerspelling and its relationship to both phonological and orthographic knowledge.

9.2. Different Predictors for Reading Latencies vs. Accuracy

Fingerspelling and STM explained some of the variance in the word reading latencies at T2 while sign-based phonological awareness accounted for some of the variance at T3. Here, we observed a positive correlation between STM and both speech-based phonological awareness and fingerspelling. However, as in previous studies (Kyle and Harris 2006; Waters and Doehring 1990), we did not find evidence for a strong relationship between STM and word or text reading accuracy. Previous research shows that children with good STM skills also tend to have good phonological skills and, conversely, phonological encoding can enhance STM performance (Alloway et al. 2005; Marschark et al. 2002). Some researchers have therefore suggested that STM only plays a role in reading development to the extent that phonological skills do (Durand et al. 2005). Given the limited contribution of speech-based phonological awareness to the word and text reading abilities of the deaf children in the current study, it may therefore not be surprising that we also found a limited role for STM.

It is important to note that the variance in the word and text reading accuracy in the current study was explained relatively well by the factors included in the stepwise regression analysis. In contrast, although fingerspelling, STM, and sign-based phonological awareness accounted for some of the variance in word reading latencies at T2 or T3, these factors explained less variance than for word reading accuracy. One possible explanation is that word reading latency is also—or even more so—influenced by other factors, for example, factors related to visual and/or orthographic processing. Several studies have found similar or even faster word reading latencies for deaf readers compared to hearing readers, sometimes in combination with lower accuracy levels (e.g., Fariña et al. 2017; Hanson and Fowler 1987; Morford et al. 2017). Similarly, recent studies showed stronger identity priming effects in adult deaf vs. hearing readers (Gutierrez-Sigut et al. 2017; Gutierrez-Sigut et al. 2018), so-called 'hyperpriming'. To account for such findings, Bélanger and Rayner (2015) proposed the 'word-processing efficiency hypothesis', which stipulates that skilled deaf readers are more "efficient" than hearing readers at processing written words because they bypass phonological codes and therefore have stronger connections between orthography and semantics, and because they are strongly attuned to the visual-orthographic makeup of words. Since word recognition speed is important for fluent reading, future studies should investigate the predictive contribution of visual/orthographic processing measures in explaining the variance in the word and text reading fluency of deaf children.

9.3. Word and Text Reading in Deaf Children with and without CI

Cochlear implants (CIs) provide increased access to speech for many deaf children, often improving spoken language development (e.g., De Raeve 2010; Marschark et al. 2007; Vermeulen et al. 2007). This improvement in spoken language skills, together with the wider availability of early implantation worldwide, has favoured educational policies where implanted children attend mainstream education (see, e.g., Langereis and Vermeulen 2011). However, having a CI, even if fitted early (i.e., before 24 months), does not guarantee reading levels comparable to hearing peers. While some studies have found that children with CI read at an age-appropriate level (see, e.g., Archbold et al. 2008; Mayer et al. 2016), other research has found that word decoding, reading comprehension, and reading-related skills, such as vocabulary, phonological awareness, and speechreading ability, are comparable between children with CIs and deaf children with hearing aids (e.g., Harris et al. 2017).

Reading performance for the subgroup of children with a CI in the current study did not differ from the deaf children without a CI. However, it is important to keep in mind that these children attended a bimodal bilingual education programme and were not in mainstream education or schools for the deaf with more emphasis on spoken language. In addition, the children in the present study were born before universal hearing screening was in place and had their implant fitted after two years of age, which is much later than deaf children in many countries (including the Netherlands) nowadays. There is a growing body of research indicating that children implanted under 24 months of age can match the progress of normally hearing peers in some areas of language development (Schauwers et al. 2004; De Raeve 2010). Moreover, CI technology has significantly advanced over the years, including possibilities for bilateral implantation. This finding therefore should not be generalised to deaf children whose hearing loss is diagnosed soon after birth and receive implants within the first year of life. At the same time, it is important to keep in mind that there are many countries where (early) implantation is not yet common practice early during development for deaf children (see Knoors et al. 2019 for an overview). Moreover, over two decades of research of language outcomes in deaf children with CIs shows that, despite increased access to the spoken language and on average positive results on speech perception and vocabulary, reading outcomes of children with CIs are highly variable and often remain below the level of hearing children of the same age.

9.4. Relation with Bimodal Bilingual Educational Practices

The implementation of bilingual deaf education in the Netherlands in 1998 resulted in the development of national frameworks and bilingual curricula were developed for Sign Language of the Netherlands (SLN), spoken and written Dutch, and for reading instruction, including web-based multi-modal reading materials (Reading Miles programme; de Klerk et al. 2015). Not expecting automatic transfer of language proficiency between spoken Dutch and SLN (see, e.g., Mayer and Wells 1996; Hermans et al. 2008a), schools for the deaf explicitly stimulated links between the various representations of concepts, such as signs, fingerspelling, written, and spoken words. Didactic strategies, such as chaining and sandwiching (Padden and Ramsey 2000), were used and spoken vocabulary training explicitly linking signs and spoken words was introduced, following insights from research in sign and spoken word processing in deaf children (Giezen et al. 2014) and other previous research showing that these didactic practices led to a significant association of written and sign vocabulary (Hermans et al. 2008b; Hoffmeister 2000; Strong and Prinz 2000) and to improved spoken word learning (van Berkel-van Hoof et al. 2016; Hermans et al. 2021). Didactic coaching of teachers facilitated implementation of these reading strategies by teachers in the classroom. Research results showed that teacher coaching using video-feedback was especially promising (Wauters and de Klerk 2014). Our results, particularly the strong predictive power of fingerspelling, likely reflect these explicit educational practices. These practices may stimulate representational knowledge of print and cross-linguistic transfer between the signed and written language modality similar to research showing positive effects of bilingualism and bilingual education on literacy development in hearing children (see, e.g., Bialystok 2018; Baker et al. 2016 for reviews). However, it should be emphasized that it is unclear from the current results, whether our findings reflect to what extent specific bilingual education practices exercised in the bimodal bilingual classroom resulted in dual language acquisition of signed and written language abilities.

To conclude, speech-based vocabulary and fingerspelling might be the main contributors to reading acquisition in deaf children in bimodal bilingual education, although other factors, such as STM and sign-based phonological awareness, might affect word reading speed at later stages. Speech-based phonological awareness seems to have a more limited role in reading development for these children compared to their hearing peers. Altogether, our results support the use of fingerspelling as an effective tool to support printed word decoding by linking the signs and the sublexical (orthographic and phonological) representations of words. Finally, we would like to stress the importance of more research into sign- and speech-related contributors to reading acquisition in fully bimodal bilingual co-enrollment programmes that are implemented in an increasing number of places across the globe (e.g., Hong Kong, Brisbane, Toronto), where deaf and hearing children attend school together and signed and spoken languages are assigned an equal educational role in the classroom, involving deaf and hearing teachers as role models in the school (Tang et al. 2014).

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data is stored at Radboud University's data repository and available upon request to the first author.

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Appendix A

Fingerspelling test

The answer options in the test always contained the following options:

V	incorrect vowel
C	incorrect consonant
D	entirely different
CA	correct answer

Schae. (Schaerlakens) and Staph. (Staphorsius) refer to word frequency values.

Items		Schae.	Staph.	Answer options							
20.	nu	92	586	V	na	CA	nu	C	mu	D	al
1.	zee	96	91	C	mee	V	ze	CA	zee	D	wie
2.	bal	93	30	C	dal	CA	bal	V	bel	D	rat
3.	een	97	5607	D	tas	CA	een	V	aan	C	nee
7.	dag	98	207	V	deeg	D	voet	C	dak	CA	dag
11.	pen	99	11	C	gen	D	lat	V	peen	CA	pen
15.	man	98	124	CA	man	V	maan	D	kies	C	nam
9.	dun	95	15	V	deen	D	kas	V	gun	CA	dun
2.	mis	97	11	V	mie	C	nis	CA	mis	D	erg
9.	teen	99	1	D	roos	C	neet	V	ton	CA	teen
18.	weer	92	477	D	hand	V	waar	C	veer	CA	weer
19.	deur	90	48	C	deun	D	iets	V	dier	CA	deur
17.	gauw	99	72	V	gouw	C	pauw	CA	gauw	D	blad
3.	niet	92	1974	V	noot	D	prop	C	tien	CA	niet
1.	mooi	98	89	D	vork	CA	mooi	V	maai	C	hooi
12.	zuur	98	3	CA	zuur	V	zeer	D	dier	C	guur
15.	zusje	87	21	C	lusje	V	zesje	CA	zusje	D	groet
23.	stuur	93	93	D	droom	CA	stuur	C	schuur	V	staar
1.	stout	98	4	CA	stout	V	staat	D	friet	C	fout
9.	pauze	93	7	V	poze	D	stoep	CA	pauze	C	gauw
4.	nuttig	18	5	CA	nuttig	V	nattig	C	nukkig	D	papier
37.	muziek	95	36	V	mozaïek	CA	muziek	D	radijs	C	publiek
11.	zouden	81		C	houden	D	roepen	CA	zouden	V	zeiden
15.	kiezen	91	19	D	buiten	V	kazen	C	kieren	CA	kiezen
28.	bushalte	91	2	C	rusthalte	D	voetbalt	CA	bushalte	V	busholte
30.	luchtbed	71	2	V	lichtbed	CA	luchtbed	C	luchtbel	D	computer

Items	English translations								
20.	[now]	V	[after]	CA	[now]	C	[mu]	D	[already]
1.	[sea]	C	[along]	V	[she]	CA	[sea]	D	[who]
2.	[ball]	C	[valley]	CA	[ball]	V	[bell]	D	[rat]
3.	[one]	D	[bag]	CA	[one]	V	[on]	C	[no]
7.	[day]	V	[dough]	D	[foot]	C	[roof]	CA	[day]
11.	[pen]	C	[gene]	D	[slat]	V	[carrot]	CA	[pen]
15.	[man]	CA	[man]	V	[moon]	D	[molar]	C	[took]
9.	[skinny]	V	[dane]	D	[greenhouse]	V	[award]	CA	[skinny]
2.	[wrong]	V	[noodle]	C	[niche]	CA	[wrong]	D	[bad]
9.	[toe]	D	[rose]	C	[nit]	V	[barrel]	CA	[toe]
18.	[weather]	D	[hand]	V	[true]	C	[feather]	CA	[weather]
19.	[door]	C	[tune]	D	[anything]	V	[animal]	CA	[door]
17.	[soon]	V	[shire]	C	[peacock]	CA	[soon]	D	[leaf]
3.	[not]	V	[nut]	D	[plug]	C	[ten]	CA	[not]
1.	[beautiful]	D	[fork]	CA	[beautiful]	V	[mow]	C	[hay]
12.	[sour]	CA	[sour]	V	[pain]	D	[animal]	C	[lurid]
15.	[sister]	C	[knot]	V	[six]	CA	[sister]	D	[greeting]
23.	[wheel]	D	[dream]	CA	[wheel]	C	[shed]	V	[stare]
1.	[naughty]	CA	[naughty]	V	[state]	D	[fries]	C	[mistake]
9.	[break]	V	[posture]	D	[sidewalk]	CA	[break]	C	[soon]
4.	[useful]	CA	[useful]	V	[wet]	C	[fitful]	D	[paper]
37.	[music]	V	[mosaic]	CA	[music]	D	[radish]	C	[audience]
11.	[would]	C	[hold]	D	[call]	CA	[would]	V	[said]
15.	[choosing]	D	[outside]	V	[cheeses]	C	[cracks]	CA	[choosing]
28.	[bus stop]	C	[rest stop]	D	[football]	CA	[bus stop]	V	[bus cave]
30.	[air bed]	V	[light bed]	CA	[air bed]	C	[bubble]	D	[computer]

Speech phonological awareness

Item	Target picture (1)	Picture 2	Picture 3	Picture 4
1	haan [rooster]	maan [moon] at position 3	boek [book]	geit [goat]
2	klok [clock]	sok [sock] at position 1	post [post]	poes [cat]
3	tas [bag]	jas [coat] at position 3	jurk [dress]	zeep [soap]
4	bad [bath]	gat [hole] at position 2	zit [sit]	kar [wheelbarrow]
5	kring [circle]	ring [ring] at position 1	wolk [cloud]	ruit [window]
6	boek [book]	broek [trousers] at position 2	jurk [dress]	kaal [bold]
7	paard [horse]	taart [pie] at position 3	zit [sit]	straf [punishment]
8	mug [mosquito]	rug [back] at position 1	hoog [high]	kus [kiss]
9	mes [knife]	fles [bottle] at position 3	jas [jacket]	bal [ball]
10	kip [chicken]	wip [teeter] at position 3	pet [cap]	kin [chin]
11	koe [cow]	moe [tired] at position 1	poes [cat]	jeuk [itchy]
12	huis [house]	muis [mouse] at position 3	reis [trip]	druif [grape]
13	roos [rose]	boos [angry] at position 2	boom [tree]	zoet [sweet]
14	duur [expensive]	vuur [fire] at position 1	raam [window]	boer [famer]
15	fout [mistake]	koud [cold] at position 1	boot [boat]	leeg [empty]
16	bos [forest]	mos [moss] at position 3	vol [full]	baas [boss]
17	man [man]	pan [pot] at position 1	raam [window]	lamp [lamp]
18	taart [pie]	zwaard [sword] at position 2	worst [sausage]	vaas [vase]
19	baas [boss]	kaas [cheese] at position 3	reis [trip]	muur [wall]
20	nek [neck]	hek [fence] at position 1	nacht [night]	post [post]
21	bus [bus]	zus [sister] at position 1	bank [bench	raak [hit]
22	boot [boat]	brood [bread] at position 1	kam [comb]	fout [mistake]
23	vis [fish]	mis [incorrect] at position 3	zit [sit]	bril [glasses]
24	blad [leaf]	gat [hole] at position 3	berg [mountain]	das [tie]
25	sterk [strong]	kerk [church] at position 2	been [leg]	dik [fat]
26	kin [chin]	spin [spider] at position 3	kip [chicken]	zuur [sour]
27	soep [soup]	stoep [pavement] at position 1	post [post]	buik [belly]
28	krant [newspaper]	hand [hand] at position 3	verf [paint]	melk [milk]
29	zon [sun]	ton [barrel] at position 3	kam [comb]	boer [farmer]
30	dik [fat]	blik [tin] at position 1	traan [tear]	lip [lip]
31	pijn [pain]	trein [train] at position 2	riem [belt]	lijm [glue]
32	tang [pliers]	wang [cheek] at position 2	gans [goose]	kan [jar]
33	brand [fire]	krant [newspaper] at position 3	helft [half]	woord [word]
34	kraan [faucet]	zwaan [swan] at position 1	koorts [fever]	raam [window]
35	gras [grass]	das [tie] at position 1	baas [boss]	tong [tongue]
36	wijn [wine]	trein [train] at position 2	duif [pidgeon	klok [clock]
37	worst [sausage]	dorst [thursty] at position 1	storm [storm	huis [house]
38	neus [nose]	reus [giant] at position 2	tuin [garden	kok [chef]
39	zout [salt]	koud [cold] at position 3	gang [hall]	post [post]
40	blad [leaf]	gat [hole] at position 1	pan [pot]	kin [chin]

Pictures used in this test are part of an educational tool 'Leesladder' [Reading ladder; Irausquin and Mommers 2001].

Appendix B

Independent samples *t*-tests revealed that at T2, the hearing children showed faster RTs and higher accuracy than the deaf children in the word reading fluency task (both *p*s < 0.011). At T3, the hearing children showed higher accuracy ($p < 0.001$), but not faster RTs ($p = 0.916$), than the deaf children in the word reading task. The hearing participants also had significantly higher text reading fluency scores in the text reading task at both T2 and T3 (both *p*s < 0.001). Figure A1 shows the average values and *t*-test results for each of the study measures. Similar results were observed for the year 3 and year 5 groups independently (see Table A1 for details).

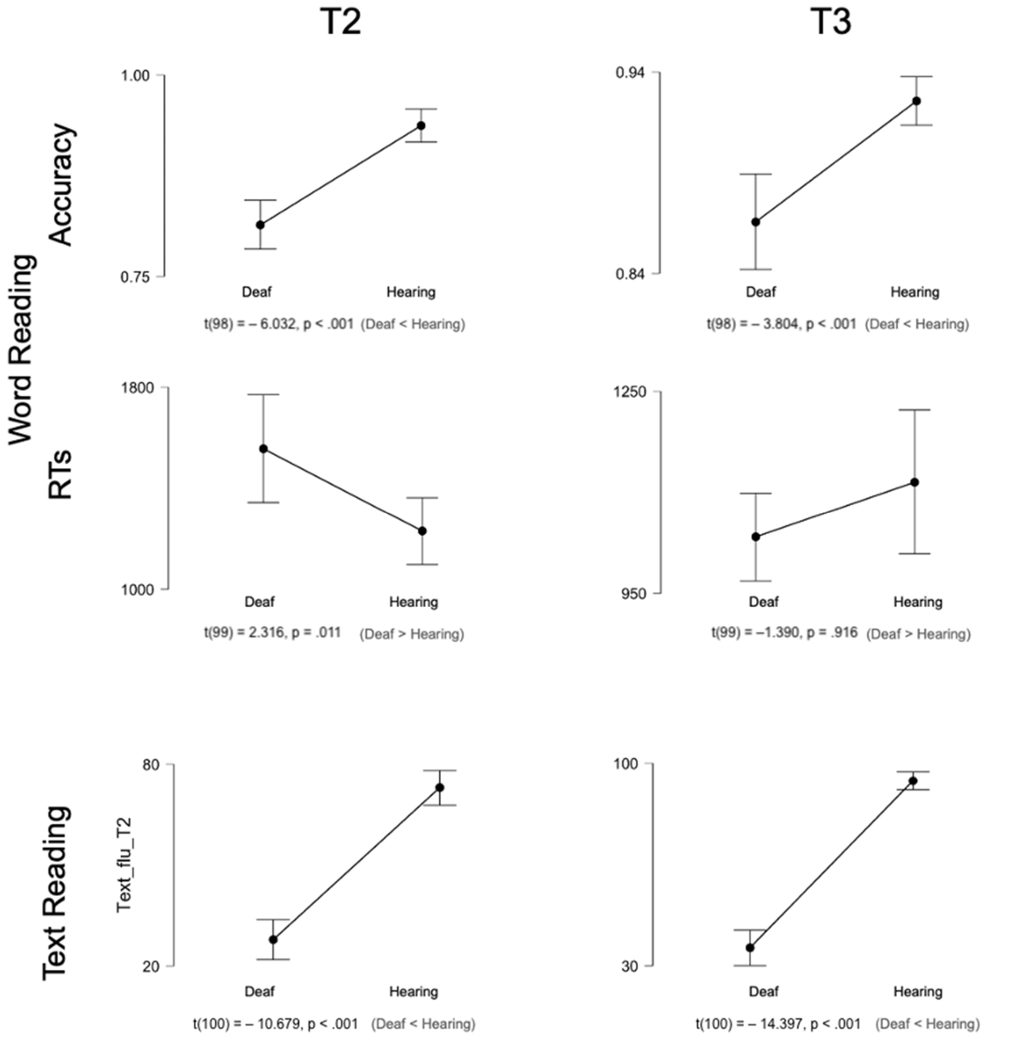

Figure A1. Average word reading accuracy and response times, and average text fluency accuracy at T2 and T3. Error bars represent the confidence intervals (95%). The figure also shows the results from the independent sample *t*-tests for deaf and hearing participants in all the study measures.

Table A1. Behavioural data. Independent samples *t*-tests between deaf and hearing groups and separated by age group. Significant differences are bolded.

		T2								T3							
		Deaf		Hearing			One Sample *t*-Test			Deaf		Hearing			One Sample *t*-Test		
		Mean	SD	Mean	SD	Difference	t	df	*p*	Mean	SD	Mean	SD	Difference	t	Df	*p*
All	Word reading accuracy	82	12	94	6	−12	−6.032	98	**<.001**	87	9	93	4	−6	−3.804	99	**<.001**
	Word reading RTs	1557	823	1231	415	326	2.316	98	**.011**	1034	258	1115	329	−82	−1.39	99	.916
	Text reading	28	23	73	16	−45	−1.679	100	**<.001**	36	24	94	10	−58	−14.397	100	**<.001**
Yr. 3	Word reading accuracy	75	12	92	9	−17	−5.477	48	**<.001**	82	9	92	4	−9	−4.248	48	**<.001**
	Word reading RTs	1696	754	1499	414	197	1.065	48	.146	1108	298	1304	300	−196	−2.274	48	.986
	Text reading	17	18	66	18	−49	−9.402	48	**<.001**	25	18	91	13	−66	−14.321	48	**<.001**
Yr. 5	Word reading accuracy	88	8	95	2	−8	−4.145	48	**<.001**	91	7	94	3	−3	−1.623	49	.056
	Word reading RTs	1419	878	963	176	456	2.282	48	**.013**	965	193	917	230	48	0.791	49	.216
	Text reading	38	23	80	12	−42	−7.443	50	**<.001**	47	24	97	3	−50	−9.113	50	**<.001**

Appendix C

Table A2. Model summary for word accuracy at T2.

					Change Statistics				
Model	R	R^2	R^2 adj	Std. Error	R^2 Change	*F* Change	df1	df2	Sig. F Change
1	0.492 a	0.242	0.229	0.103	0.242	18.508	1	58	<.001
2	0.647 b	0.418	0.398	0.091	0.176	17.297	1	57	<.001
3	0.737 c	0.543	0.518	0.082	0.125	15.254	1	56	<.001
4	0.763 d	0.582	0.552	0.079	0.039	5.159	1	55	.027

a Predictors: (Constant), Age; b Predictors: (Constant), Age, VocSP; c Predictors: (Constant), Age, VocSP, FSP; d Predictors: (Constant), Age, VocSP, FSP, PhoSP.

Table A3. Model summary for word RTs at T2.

					Change Statistics				
Model	R	R^2	R^2 adj	Std. Error	R^2 Change	*F* Change	df1	df2	Sig. F Change
1	0.348 a	0.121	0.106	778.545	0.121	7.973	1	58	.006
2	0.432 b	0.186	0.158	755.591	0.065	4.577	1	57	.037

a Predictors: (Constant), FSP; b Predictors: (Constant), FSP, STM.

Table A4. Model summary for word accuracy at T3.

					Change Statistics				
Model	R	R^2	R^2 adj	Std. Error	R^2 Change	*F* Change	df1	df2	Sig. F Change
1	0.471 a	0.222	0.209	0.085	0.222	16.580	1	58	<.001
2	0.840 b	0.71	0.696	0.0525	0.484	93.88	1	57	<.001
3	0.872 c	0.760	0.747	0.048	0.053	12.460	1	56	.001
4	0.882 d	0.778	0.762	0.046	0.019	4.660	1	55	.035

a Predictors: (Constant), Age; b Predictors: (Constant), Age, Word Accuracy T2; c Predictors: (Constant), Age, Word Accuracy T2, PhoSP; d Predictors: (Constant), Age, Word Accuracy T2, PhoSP, FSP.

Table A5. Model summary for word RTs T3.

					Change Statistics				
Model	R	R^2	R^2 adj	Std. Error	R^2 Change	*F* Change	df1	df2	Sig. F Change
1	0.305 a	0.093	0.077	250.800	0.093	5.951	1	58	.018
2	0.402 b	0.162	0.132	243.240	0.069	4.661	1	57	.035

a Predictors: (Constant), Age; b Predictors: (Constant), Age, PhoSL.

Table A6. Model summary for text fluency at T2.

					Change Statistics				
Model	R	R^2	R^2 adj	Std. Error	R^2 Change	*F* Change	df1	df2	Sig. F Change
1	0.437 a	0.191	0.178	21.060	0.191	14.190	1	60	<.001
2	0.685 b	0.470	0.452	17.197	0.278	30.981	1	59	<.001
3	0.749 c	0.561	0.539	15.774	0.092	12.129	1	58	.001

a Predictors: (Constant), Age; b Predictors: (Constant), Age, VocSP; c Predictors: (Constant), Age, VocSP, FSP.

Table A7. Model summary for text fluency at T3.

					Change Statistics				
Model	R	R^2	R^2 adj	Std. Error	R^2 Change	*F* Change	df1	df2	Sig. F Change
1	0.486 a	0.236	0.223	21.484	0.236	17.948	1	58	<.001
2	0.720 b	0.518	0.501	17.220	0.281	33.276	1	57	<.001
3	0.808 c	0.653	0.634	14.745	0.135	21.749	1	56	<.001
4	0.827 d	0.684	0.661	14.184	0.032	5.509	1	55	.023

a Predictors: (Constant), Age; b Predictors: (Constant), Age, Word accuracy T2; c Predictors: (Constant), Age, Word accuracy T2, VocSP; d Predictors: (Constant), Age, Word accuracy T2, VocSP, FSP.

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