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Examining the role of phonological awareness, speech-based phonological recoding, and orthographic processing on reading development in deaf bilinguals of ASL and English

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Examining the role of phonological awareness, speech-based phonological recoding, and orthographic processing on reading development in deaf bilinguals of ASL and English

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Examining the role of phonological awareness, speech-based phonological recoding, and orthographic processing on reading development in deaf bilinguals of ASL and English.

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This dissertation targets the role of speech-based phonology on reading development in deaf and hard of hearing (DHH) children. Researchers have long debated the role of spoken language phonics knowledge and phonological awareness on reading development in DHH children without access to speech sounds (Allen et al., 2009; Wang et al., 2008). Phonological awareness, which is the metalinguistic awareness of basic units of speech and the ability to consciously manipulate the linguistic units within words and sentences (Castles & Coltheart, 2004; Liberman & Shankweiler, 1985; Wagner & Torgesen, 1987), relates to reading skill in typically developing hearing children (Goswami & Bryant, 1990). Hearing readers of orthographic scripts begin reading by sounding out words and is dependent on the association between graphemes and speech sounds. However, our understanding of the processes by which DHH children read is vague at best as some investigations have shown a positive association between reading and spoken language phonological awareness in DHH children (Campbell & Wright, 1988; Dyer et al., 2003), while others have failed to find such a correlation (Izzo, 2002; Kyle & Harris, 2006; Leybaert & Alegria, 1993; Miller, 1997).

I test the degree to which speech-based codes are active in adolescent DHH readers who grew up with robust exposure to a signed language thought childhood and school. Chapter 1 provides an overview of the relevant literature pertaining to the two reported studies. Chapter 2 discusses phonological awareness of speech and sign, as well as a variety of approaches to testing phonological awareness. Within this Chapter I introduce the methodology and results from the first half of the first study. Chapter 3 will then introduce eye-tracking and reading, as well as the eye-tracking results from the first study. Chapter 4 describes the last study of the dissertation, which tests the impact of spelling knowledge and speech-based homophony on reading and lexical decision tasks in DHH students. Finally, Chapter 5 provides a discussion of the three content Chapters together.

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Chapter 1: Introduction

This dissertation presents a series of investigations targeting the role of speech-based phonology on reading development in deaf and hard of hearing (DHH) children. Researchers have long debated the role of spoken language phonics knowledge and phonological awareness on reading development in DHH children without access to speech sounds (Allen et al., 2009; Wang et al., 2008). Phonological awareness, which is the metalinguistic awareness of basic units of speech and the ability to consciously manipulate the linguistic units within words and sentences (Castles & Coltheart, 2004; Liberman & Shankweiler, 1985; Wagner & Torgesen, 1987), relates to reading skill in typically developing hearing children (Ehri, 2014; Goswami & Bryant, 1990; Share, 2005). Hearing readers of orthographic scripts begin reading by sounding out words and are dependent on the association between graphemes and speech sounds. In contrast, our understanding of the processes by which DHH children read is vague at best. While some investigations have shown a positive association between reading and spoken language phonological awareness in DHH children (Campbell & Wright, 1988; Dyer et al., 2003), others have failed to find such a correlation (Izzo, 2002; Kyle & Harris, 2006; Leybaert & Alegria, 1993; Miller, 1997).

The average reading level of DHH adults in the US has been reported to be far below the 9th grade national average among typically hearing adults (Easterbrooks & Beal-Alvarez, 2012). Some researchers and educators suggest that DHH children struggle with literacy acquisition due to a lack of access to speech sounds, resulting in deficient phonological awareness of spoken language. As a result, the approach to language and literacy instruction for DHH children typically involves dependence on residual hearing, use of hearing aids or cochlear implants, and learning to speechread and speak in order to provide DHH children with sufficient spoken language input for successful literacy acquisition (Burden & Campbell, 1994; Leybaert & Alegria, 1993). Multiple publications have suggested that DHH non-signing children with superior knowledge of spoken language phonology and superior speech ability are more advanced readers than those with inferior speech skills (Alegria, Charlier, & Mattys, 1999; Harris & Beech, 2006; Paul & Lee, 2010; Paul, 2001, 2008; Wang et al., 2008). In contrast, investigations of DHH signing children have suggested that signers may not depend on phonological knowledge of speech as a strategy but instead take advantage of general linguistic skill, meta-linguistic phonological skills, and signed language ability supplied by early and robust access to sign (Allen et al., 2009; Mayberry et al., 2011; Mayberry & Lock, 2003; McQuarrie & Parrila, 2014; Petitto et al., 2016).

I test the degree to which speech-based codes are active in adolescent DHH readers who grew up with robust exposure to a signed language thought childhood and school. Chapter 1 provides an overview of the relevant literature pertaining to the three content chapters. I begin with a discussion of phonological awareness of speech and reading in hearing readers of orthographic scripts, followed by an overview of theories that do not necessarily require speech-based codes and reading by hearing readers of non-orthographic scripts and the Simple View of Reading (Gough & Hoover, 1990). Finally, I discuss early reading for DHH readers from the perspectives of spoken language phonological awareness, signed language ability, and the Simple View of Reading (Chamberlain & Mayberry, 2000; Stone et al., 2015). Within this discussion, I outline the relationship between phonological awareness of speech and reading without auditory access to speech. Following this, I discuss reading in DHH signers that considers the visual modality of language, particularly phonological awareness of signed languages, fingerspelling, vocabulary knowledge, and visual aspects of spoken language.

Chapter 1 concludes with a summary and introduction to the content chapters that inform my dissertation.

Chapter 2 discusses phonological awareness of speech and sign, as well as a variety of approaches to testing phonological awareness. I consider the relationship between spoken and signed language phonology, as well as the relationship between phonological awareness and reading in DHH and hearing adolescents. Chapter 3 introduces eye-tracking and reading as well as visual skills in DHH signers. I test the degree to which DHH and hearing readers are sensitive to homophonic and non-homophonic errors in text using eye-tracking data. Chapter 4 considers phonological and orthographic processing during single word reading. I report data from an online study that was designed to meet limitations to in-person research during the COVID19 pandemic. I test impact of spelling knowledge and speech-based homophony on reading and lexical decision tasks in DHH and hearing readers. Finally, Chapter 5 provides a discussion of the three content chapters together.

Early reading for hearing children

Phonological awareness of speech and reading

The knowledge of the sounds of a language and how they relate to print is one of the many aspects of reading development that has been widely discussed[1]. One is said to have acquired phonological awareness of a spoken language when they are able to detect, understand, and manipulate the sound structure independent of word meaning (Lonigan et al., 2009; Wagner & Torgensen, 1987). Wagner and Torgensen (1987) first proposed that phonological awareness, particularly regarding phonological memory for lexical access, is essential for successful print

[1] Here, the focus is on the relationship between knowledge of speech sounds and reading ability. It is important to note that many additional factors impact reading development. A brief introduction to those factors and how they relate to reading ability can be found in Appendix A.

literacy. Since then, a large proportion of studies investigating variations in reading skill have implicated deficits in phonological awareness as the primary underlying factor for reading problems experienced by early readers.

The relationship between phonological awareness and reading has been claimed to depend on the Alphabetic Principle, which is the knowledge that words are comprised of letters, and that letters correspond to speech sounds (Ehri, 2009; Ehri, 2014; Liberman, Shankweiler, & Liberman, 1989). According to the Developmental Bypass Theory (Pennington et al., 1987) and the Dual-Route Access Model (Glushko, 1979), languages with alphabetic orthographies (i.e., writing systems that contain phonetic information) require phonological decoding, in which each grapheme is mapped to the corresponding speech sound. Shallow orthographies, such as Spanish or Italian that have nearly one-to one correspondence of letter-to-sound, while deeper orthographies such as English or French, a single grapheme or letter can correspond to multiple sounds (e.g., *c*, which can be pronounced as [k], [s], and, when part of the -ch- grapheme, as part of [t͡s]). This phonological decoding strategy is most prominent during early, novice reading, as well as when encountering unfamiliar words as fluent readers progress. The phonological representation in turn activates the word meaning. As reading ability progresses, readers begin to engage in sight-word reading for familiar words, depending less on phonological decoding (Harm & Siedenberg, 2004; Jared et al., 2016; Pennington et al., 1987; Share, 2005).

While phonological awareness is highly predictive of later reading outcomes for very young hearing readers, the strength of this relationship quickly weakens as reading skill is attained, suggesting that the relationship between phonological awareness and reading is reciprocal (Carrillo, 1994; Ehri, 1995; Nithart et al., 2011; Share, 2005). Phonological awareness comes online early in the language learning process, prior to the introduction of print. Children as young as four demonstrate syllable and rhyme awareness of their spoken language (De Loureiro et al., 2004; Stainthorp & Hughes, 1998; Ziegler & Goswami, 2005). However, it isn't until reading is introduced and phonological skills are required in a school setting that these skills emerge (Duncan, Seymour, & Hill, 1997; Lonigan, Burgess, & Anthony, 2000; Martin et al., 2003; Stainthrop & Hughes, 1998). Many scholars and educators consider phonological awareness necessary for successful reading, but the formation of concrete and testable phonological knowledge is dependent on reading instruction and practice (Morais et al., 1986; Nithart et al., 2011).

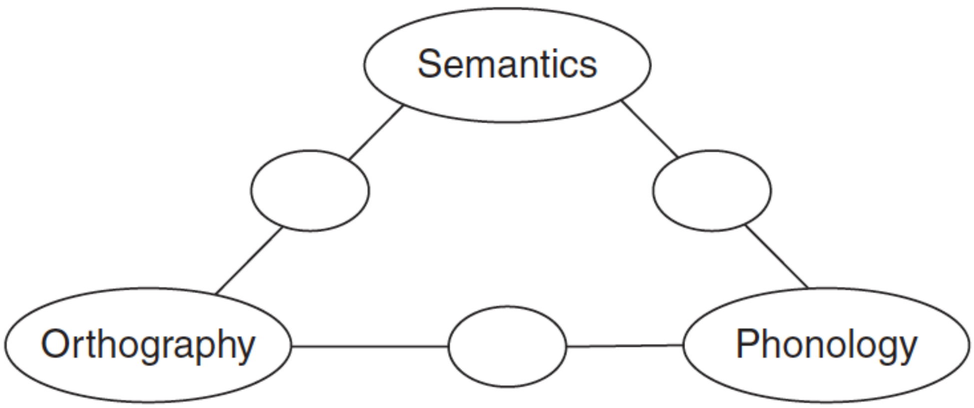
Some scholars consider the ability to engage in phonological decoding impossible without first completely developing the phonological system of that language (Muter et al., 2004). Early spoken-language phonological skills have been reported to predict future reading outcomes, and some scholars believe that the only way to become a fluent, adult-like reader is to have complete development of a spoken language phonological system (Castles & Coltheart, 2004; Lundburg, Olofsson, & Walls, 1980). Current practices of early reading instruction for all children relies heavily on letter-to-sound correspondences (National Reading Panel, 2000).

The Triangle Model of Reading

One model of reading proposed for alphabetic scripts is the Triangle Model (Harm & Seidenberg 2004) which accounts for the fact that phonological activation remains present for skilled adult readers and suggests that phonological decoding is present for all readers and is not fully replaced by sight-word reading. Considering evidence that early and late reading is impacted by speech-based phonological decoding, knowledge of the correspondence between letters and sounds, and the ability to retrieve lexical information of a written word, the Triangle Model describes reading as dependent on the knowledge of how letters comprise words (i.e., orthography), the knowledge of how letters relate to sounds (i.e., phonology), and the ability to retrieve the meaning of words from the lexicon (i.e., vocabulary; Figure 1.1).

Figure 1.1

The Triangle Model of Reading



Note: From Harm & Seidenberg (2004)

Models such as Dual-Access (Glushko, 1972) and Developmental Bypass Theory (Pennington et al., 1987) place great emphasis on the transition from the indirect route of phonological decoding of print as a primary reading strategy to sight-word reading as reading practice advances. The Triangle Model acknowledges that sight-word reading becomes available as reading skills progress, but both early- and late-stage reading is marked by both phonological and orthographic decoding to retrieve semantic information about written words. The meaning of most words is computed by both phonological and orthographic information, but the contribution of both codes will vary as a function of reader skill, word frequency, and the script being read.

Recent studies have indicated that sound-based phonology is active very early in the reading process in highly skilled hearing readers. (Leinenger, 2014; Leinenger, 2018). Leinenger and colleagues (2018) investigated the timeline of English phonological activation during reading via eye-tracking in hearing readers. The researchers employed survival analysis and compared the percentage of fixations that survived on a control target to the percentage of fixations that survived in a manipulation of the target. This analysis can indicate the timing of phonological activation due to its sensitivity to the earliest observable effect of a manipulation on behavior (Leinenger, 2018; Liu et al., 2017; Reingold et al., 2012; Sheridan & Reingold, 2012a). The results suggested that English phonology is activated early, and phonological codes are developed and employed rapidly during reading in highly skilled hearing readers, providing further support for the Triangle Model and use of speech-based codes for skilled, adult readers.

Hearing readers and a deviation from speech-based codes

There are myriad reasons why the method of instruction requiring direct mapping of grapheme-to-phoneme may be inadequate or indeed inappropriate for some early readers, regardless of hearing status. Most importantly, letter-to-sound correspondence does not sufficiently target how the language sounds, particularly in languages with deep orthographies such as English. Deep orthography refers to a writing system in which sounds do not correspond exactly to the written grapheme, while shallow orthographies have almost 1-to-1 mapping of sound to letter. Compared to other alphabetic systems, English has a deep orthography with inconsistent mappings of speech sounds to letters (e.g., *gh* in *through*, *ghost,* and *enough*; *p* in *parrot*, *pterodactyl*, and *phantom*) compared to shallow alphabetic languages such as Italian (e.g., *p* corresponds to the same sound in *prego* (‘you’re welcome’), *pizza, parlare* (‘speak’)).

In addition, phonological decoding is not always the most appropriate method of reading instruction, particularly when considering the various writing systems of the world that are not alphabetic. In character-based writing systems such as Chinese, there is minimal correspondence between the written character and the phonological representation of the word, though some characters contain phonetic radicals which are added to help with word pronunciation. Learning to read a logographic system appears to require orthographic awareness and knowledge of how words and characters are constructed of orthographic components, not necessarily phonological awareness (Dye, Hauser, & Bavelier, 2008; Tan et al., 2001).

Traditional Chinese is a morpho-syllabic script in which characters carry meaningful marks to show semantic information in the left or upper symbol and syllable associations in the right or bottom phonetic radical. 72% of the character compounds contain semantic and phonetic radicals that provide some of phonetic information corresponding to spoken Chinese, but only 20% of those compounds contain complete phonetic information consistent with pronunciation (Jones, 2013; Shu et al., 2003; Zhou, 1978). Students learning to read Chinese require several complex skills, such as visual analysis to decode phonetic and semantic radicals embedded in characters, knowledge of stroke sequences when combining features, orthographic processing of phonetic and semantic information, and, for hearing children, the homophone analogy in which all possible diacritics for one sound must be activated (Huang & Hanley, 1995; Tan et al., 2005; Wenling et al., 2002). To aid with standardized pronunciation of spoken Chinese and to benefit reading acquisition, the Pinyin system was developed and introduced as an ancillary tool (Sheridan, 1990). Pinyin used diacritic markings to differentiate between the four tones of spoken Chinese, and hearing readers of Chinese demonstrate homophony effects when encountering homophones. Hearing children process Chinese script using morphological strategies, and morphological awareness has recently been introduced as an instructional strategy to teach Chinese (Anderson & Kuo, 2006; Jones, 2013; Nagy et al., 2013)

Brain imaging studies have demonstrated differences in readers when processing more- and less-transparent orthographies (Bar-Kochva & Breznitz, 2012; Paulesu et al., 2000; Simon et al., 2006). Paulesu and colleagues (2000) compared areas of brain activity and reported that readers of English (which has a relatively deep orthography) demonstrated activation in areas associated with irregular word reading and whole word retrieval, while readers of Italian (which has a relatively shallow orthography) recruited areas associated with phonemic processing. Similar conclusions were drawn in a study of French monolinguals and French-Arabic bilinguals. Compared to French, the dialect of Arabic has a far deeper orthography, as Arabic writing systems often do not include vowels. Both groups had activation in the brain associated with spelling-to-sound conversion when reading French, but the bilingual readers no longer showed the same activation when reading Arabic. These findings suggest different mechanisms are involved when reading different types of script and orthographies and demonstrate the flexibility that bilingual readers have based on language experience (Simon et al., 2006).

Hearing readers and the Simple View of Reading

The Simple View of Reading (SVR; Hoover & Gough, 1990; Gough & Tumner, 1986; Juel, Griffith, & Gough, 1986) has also been discussed as a model for reading. The SVR does not emphasize phonological decoding of print to speech or deny that reading is a complex skill, but instead suggests that these complexities are restricted to two components: decoding ability and linguistic competence. Here, decoding is defined as the ability to see a word in print, access the mental lexicon, and retrieve word meaning and extrapolating that knowledge to previously unknown words. Linguistic competence is operationalized as the ability to understand language (e.g., able to accurately answer comprehension questions after listening to a narrative; Gough & Tunmer, 1986; Hoover & Gough, 1990; Juel, 1988; Juel, Griffith, & Gough, 1986; Tunmer & Hoover, 1992). Hoover and Gough (1990) explained that reading may not be as complex as experimental psychology had long suggested, particularly considering far more complex cognitive tasks (e.g., problem solving, thinking, reasoning, evaluating, conceptual understanding) can be accomplished by people who cannot read. SVR proposes equal contribution of decoding and linguistic competence for successful reading, and that successful reading cannot occur with one of these components but not the other.

According to the SVR, reading is the use of a code to retrieve lexical information. Though the phonological code is a successful tool for decoding, the code can also be orthographic. Phonics knowledge and the alphabetic principle is an available and particularly salient code, but the content of that code and the best mechanism for acquiring that code still needs to be addressed (Hoover & Gough, 1990). The major task faced by readers is accessing the mental lexicon for known words that had not been previously seen represented in print (Gough & Hillinger, 1980; Gough & Tunmer, 1986; Glushko, 1979). As reading develops children take advantage of their knowledge of how letters comprise words (Henderson, 1982). SVR requires only that the acquired representational system can quickly and accurately access the mental lexicon for "proper, arbitrary orthographic representations" (pp. 131; Hoover & Gough, 1990).

Hoover and Gough (1990) further speculated about the implications of this model on reading instruction. In contrast to natural language, decoding skills require formal instruction (Calfee & Drum, 1986; Gough & Hillinger, 1980; Hoover & Gough, 1990; Stanovich, 1986). Phonological codes are often exploited by pairing a stimulus cue (e.g., the letter 't') to a response (e.g., the speech sound /t/). Children are instructed to use this code to associate printed letters with corresponding sounds and "sound out" unknown words. However, considering that print novelty is ubiquitous for a novice reader (Gough & Hillinger, 1980; Hoover & Gough, 1990; Jorm & Share, 1983), the SVR suggests that orthographic codes could be instructed instead. If a child learns the systematic relationship between letters and graphemes and spoken words, the associative process between letters and sounds may not be necessary (Hoover & Gough, 1980).

Though phonics instruction and the association between letters and sounds may be beneficial for many struggling readers (Gough & Hillinger, 1980; Barr, 1984; Flesch, 1981; Williams, 1985), phonics may be one of multiple codes available to acquire sight-word reading (Hoover & Gough, 1990). The SVR view posits that poor reading is a result of a combination of these factors: inadequate decoding skill despite strong linguistic comprehension, inadequate linguistic comprehension ability despite strong decoding skill, or inadequate decoding and linguistic comprehension. As such, poor readers would be expected to demonstrate a negative relationship between decoding and linguistic comprehension, or no relationship at all if both skills are absent. Evidence from one longitudinal study of 254 bilingual students over five years of data collection suggested that these assumptions do indeed hold true when predicting pre-kindergarten, pre-reading abilities and later reading abilities in first, second, third, and fourth grades (Hoover & Gough, 1990). The SVR has been supported in a several studies regarding reading development in children (Aaron, Joshi, & Williams, 1999; Joshi & Aaron, 2000; Kendeou, Savage, & van den Broek, 2009). One study reported a factor analysis for reading outcomes in data from 116 four-year-old and 103 six-year-old Canadian students. Results demonstrated that of the many components tested including oral reading fluency, vocabulary skill, listening comprehension, phonological awareness, and letter identification, components fell into two major factors demonstrating decoding and linguistic competence as the strongest predictors of reading outcomes (Kendeou, Savage, & van den Broek, 2009).

Some supporters of the SVR have suggested that decoding skills should have the greatest influence on later reading ability for readers of deep orthographies (Florit & Cain, 2011). Hearing readers already have linguistic competence when arriving at school, but they must learn how the writing system represents their spoken language, which they must learn to decode. The more efficiently readers can decode, or the faster and more accurate their decoding skills are, the more cognitive resources can be focused on higher-level comprehension (Catts et al., 2006; Cunningham et al., 1990; Florit & Cain, 2011; Gough et al., 1996; Jackson & McClelland, 1979). The relationship between decoding and reading comprehension differs between alphabetic orthographies depending on orthographic depth. Deep orthographic systems and languages with many irregular spelling patterns such as English require additional decoding instruction and practice, which results in a relatively slower rate of reading acquisition compared to shallow orthographies (Ellis et al., 2004; Florit & Cain, 2011; Seymour et al., 2003). Early readers of shallow orthographies such as Spanish and Italian may have a weaker relationship between decoding and reading comprehension as well as a stronger relationship between linguistic comprehension and reading comprehension compared to early readers of deeper orthographies (Müller & Brady, 2001).

Florit and Cain (2011) aimed to test the components of the SVR for readers of deep and shallow orthographies considering original claims that knowledge of the alphabetic principle and phoneme-grapheme correspondence is necessary to acquire decoding abilities (Gough & Tunmer, 1986; Hoover & Gough, 1990). Using a meta-analysis approach, researchers compiled 33 empirical studies reporting data from typically developing participant readers from grades 1 – 5 on measures of reading comprehension, decoding (e.g., word reading, recognition, and identification, pseudo-word reading, and non-word reading), and linguistic comprehension (e.g., listening comprehension, language comprehension, passage comprehension, and narrative comprehension). Results demonstrated that the relative impact of decoding skills and linguistic comprehension on reading fluency was influenced by orthographic depth. Readers of English were more influenced by decoding skills than linguistic comprehension during early reading, and this relationship remained strong as years of schooling increased, further supporting claims that reading development is slower for deep orthographies (Ellis et al., 2004). Readers of shallow scripts patterned differently, as linguistic comprehension was a stronger predictor of reading comprehension. This further aligns with evidence that decoding is acquired faster for those readers, freeing up cognitive resources for higher comprehension processes (Ellis et al., 2004; Florit & Cain, 2011). Florit and Cain suggested that readers of transparent scripts are likely to benefit from both oral and written text comprehension support because their decoding is acquired during the earliest stages of reading, but readers of deep orthographies like English require instruction regarding how to decode written text.

Yoncheva and colleagues (2015) tested components of the SVR. Adult participants were taught one of two novel scripts, one with selective attention to grapheme-phoneme mappings and the other with whole-word processing. One script was phonological in nature and participants learned the language by corresponding each embedded letter to a sound. The other script prevented decoding and entire words had to be memorized. Participants were trained on their scripts before completing post-training reading tasks while recording event-related potentials (ERPs). The test stimuli were either words that had been trained or words that were untrained but decodable. The results demonstrated that both trained and untrained words were accessed sublexically. However, the results also demonstrated that untrained words required more cognitive effort, perhaps demonstrating effortful decoding. The authors emphasized the importance of decoding during reading instruction to provide readers with a basis for later decoding of unfamiliar words and self-learning during reading.

In summary, while some models of reading of alphabetic scripts consider speech-based phonological decoding to be central to print literacy (Ehri 2014; Harm & Siedenberg, 2004;

Pennington et al., 1987; Share 2005), other models (i.e., SVR; Hoover & Gough, 1990) and evidence from the reading of non-alphabetic scripts (Bar-Kochva & Breznitz, 2012; Florit & Cain, 2011 Paulesu et al., 2000; Simon et al., 2006; Siok & Fletcher, 2001; Tan et al., 2001) have suggested that speech-based codes are not necessarily required for successful reading development of hearing children.

Early reading in DHH children

There are two primary views regarding the dependence on speech-based codes and reading acquisition in DHH children. One perspective assumes a functional equivalence between DHH and hearing readers, proposing that phonological awareness of speech and phonics skills are essential for successful literacy acquisition for all children regardless of hearing status. As such, all children will achieve optimal reading fluency via phonics and instruction of sound-letter correspondence, though DHH children are likely to be delayed due to a lack of auditory access to speech sounds (Paul 2001, 2008; Paul & Lee, 2010; Wang et al. 2008). Another group of researchers suggest that phonological awareness of speech may not be essential for DHH children to successfully learn to read (Allen et al., 2000; Mayberry et al., 2011). These theories consider aspects of the visual language signal such as signed language and fingerspelling and suggest that DHH and hearing students read in qualitatively different manners (Bélanger et al., 2018; Chamberlain & Mayberry, 2000; Cooley & Quinto-Pozos, in submission; Stone et al., 2015).

Phonological awareness of speech and reading for DHH readers

According to the Qualitative Similarity Hypothesis (QSH; Paul & Lee 2010; Paul 2001, 2008), DHH students should find greatest success in learning to read via methods that are qualitatively similar as hearing peers, particularly regarding grapheme-to-sound correspondences and phonological decoding. Paul and Lee (2010) provided a summary of literature in support for the QSH for DHH readers based on reading ability, cognitive development, and linguistic structural knowledge of readers with other disabilities. The QSH was first proposed for child readers with language impairments and disabilities and second language English learners and was later expanded to DHH readers. Essentially, according to the QSH, all good readers regardless of hearing status or disability will become increasingly advanced because of their ability to continue reading and self-learn. Unfortunately, struggling readers will not gain sufficient practice and thus will not experience significant self-learning because of their struggles. Following the National Reading Panel (2000), to become a successful reader, one must know both the script that they are learning as well as an understanding of how the script relates to the sounds of the spoken language (Narr, 2008; Trezek & Malmgren, 2005; Trezek & Wang, 2006; Trezek et al., 2008).

According to the QSH, DHH readers are likely to be age-delayed due to lack of auditory access to speech sounds and will find greater success in reading by acquiring knowledge of speech sounds from alternative routes such as speechreading and visual phonics. The QSH has been advanced by several studies in the literature, as some studies report a similar sequence of language skill development for DHH readers when taught to read in the same way as hearing readers (King & Quigley, 1985; Leybaert & Alegria, 1993; Mayer, 2007; Paul, 1998, 2003; Schirmer & McGough, 2005). In addition, positive associations between reading ability and phonological awareness of speech (Campbell & Wright, 1988; Dyer et al., 2003) and speechreading ability have been reported (Arnold & Kopsel, 1996; Campbell & Wright, 1988; Geers & Moog, 1989; Harris & Moreno, 2006; Kyle & Harris, 2006). Finally, some studies have demonstrated a strong intercorrelation between phonology, syntax, and working memory for

DHH readers, which has been considered evidence that DHH readers use a speech-based phonological code in working memory to process syntax and other factors required for higher level reading comprehension (Adams, 1990; Paul, 1998, 2003, 2009; Paul & Lee, 2010; Snow et al., 1998; Stahl & Nagy, 2006; Trezek et al., 2010).

There also exists evidence that DHH children acquire some degree of phonological awareness of speech through the practice of reading, like hearing children. Studies have demonstrated that young DHH children do not arrive at school with strong phonological knowledge of speech (McQuarrie & Parrila, 2009; Izzo, 2002; Miller, 1997), but DHH adults and skilled young DHH readers do have knowledge of speech-based phonology (Hanson & Fowler, 1987; Hanson & McGarr, 1989; McQuarrie & Parrila, 2009; Sehyr et al., 2017).

A variety of visual communication systems have been invented to manually represent spoken phonemes and syllable structures with the hands and face to make aspects of spoken language phonology visually salient and accessible to DHH individuals to benefit their reading acquisition. Methods such as See the Sound (STS) and Visual Phonics (VP) involve systems of hand cues and corresponding written symbols that represent aspects of the phonemes and grapheme-phoneme relationships. These systems were devised as an abstract, modality-independent method of visually conveying phonemic units so that DHH students are better able to conceptualize spoken phonics (Narr 2008; Trezek & Wang 2006; Trezek et al. 2007).

Cued speech is another commonly cited communication system developed to visually convey spoken language information to DHH children to benefit phonological decoding of print to speech. This method has been used in different countries and involves a series of hand gestures beside the mouth and slightly removed from the face that correspond to the phonemes of a spoken language (Alegria, Charlier, & Mattys 1999; Aparicio et al., 2017).

Signed Exact English (SEE) and Manually Coded English (MCE; Gustason & Zawolkow, 1993; Rendel et al., 2018) are communication systems used in the US that convey a variety of spoken English morphology and syntax with existing ASL signs and fingerspelling. These systems were developed and have been used in a variety of school and clinical settings to provide DHH children with a visual form of a spoken language with the goal of making learning to read easier.

Finally, perhaps the most widely discussed visual source of spoken language phonological information is speechreading. Many scholars have suggested that the information derived during speechreading may provide the basis for the development of a speech-based phonological code in DHH children (Burden & Campbell, 1994; Dodd, 1980; Leybaert & Alegria, 1993), and that speechreading may act as a proxy for phonological information without access to sounds. Studies have demonstrated that higher speechreading skill predicts greater reading fluency in DHH children (Arnold & Kopsel, 1996; Campbell & Wright, 1988; Geers & Moog, 1989; Kyle & Harris, 2006) and DHH adults (Mohammed et al., 2006). Kyle and Harris (2008) demonstrated that phonological awareness and speechreading skills are correlated in DHH children, and that there is a strong relationship between speechreading and phonetic spelling errors in both good and poor DHH readers. Further, results showed that speechreading skills alone were predictive of reading skill, not phonological awareness, indicating that the relationship between speechreading and literacy that has been cited is not due to phonological sensitivity acquired through speechreading.

Several studies in the literature support the active use of speech-based codes in DHH signers during reading and fingerspelling comprehension (Guiteirrez-Sigut et al., 2019; Hanson & Fowler, 1987; Hanson & McGarr, 1989; McQuarrie & Parrila, 2009; Sehyr et al., 2017). This sensitivity may be due to explicit instruction of the connection between letters and sounds (Narr, 2008; Trezek & Wang, 2006; Trezek et al., 2007) or the reciprocal nature between reading ability and testable phonological awareness skill (McQuarrie & Abbott, 2013; McQuarrie & Parrila, 2009; Nithart et al., 2011). However, considering evidence from hearing readers of non-orthographic scripts (Bar-Kochva & Breznitz, 2012; Paulesu et al., 2000; Simon et al., 2006; Siok & Fletcher, 2001; Tan et al., 2001) and the fact that many profoundly deaf individuals who are early users of a signed language become successful readers (Allen & Morere, 2020; Qi & Traxler, 2000), it may be the case that the use of speech-based codes is not required for DHH signers to become successful readers.

DHH signers and a deviation from speech-based codes

In contrast to evidence in support of the QSH, various investigations have found little or no evidence of phonological coding in DHH readers (Campbell & Wright, 1988; Chamberlain, 2002; Harris & Beech, 1998; Izzo, 2002; Leybaert & Alegria, 1993; Miller, 2006). Some scholars have suggested that the literacy struggles in DHH populations have been overstated as many DHH students and adults achieve great success in reading (Miller, 2012; Qi & Mitchell, 2012; Traxler, 2000), and multiple studies have demonstrated increased efficiency in reading patterns in DHH child and adult signers compared to hearing non-signers (Belanger et al. 2012, 2015, 2018; Costello et al., 2021; Emmorey & Lee, 2021; Fariña et al., 2017; Traxler et al., 2021).

In a meta-analysis of reading skill in DHH children by Mayberry and colleagues (2011), data from 57 studies from seven countries was analyzed, including data from 2,078 deaf participants ages 4 - to 64 – years old. All studies chosen reported proficient use of at least one communication system or language, such as natural signed or spoken languages, cued speech, sign supported speech, or a combination of methods. If phonological coding skills are, indeed, necessary for DHH children and adults to become successful readers, these skills should be consistently and strongly related to reading outcomes across all studies. If not, they will emerge as inconsistently related to reading outcomes among other tested factors. The results demonstrated that while English phonological awareness and sound phonological decoding skills accounted for 11% of the variance in reading outcomes for DHH children, 35% of variance was attributed to general language skill. This meta-analysis demonstrated that phonological coding and speech-based phonological skill did not account for reading fluency any better than speech intelligibility, age, IQ, and memory span.

Perhaps the most essential contribution to literacy development in DHH children is an effective communication system at home. General language comprehension skills in a signed language have been repeated associated with reading fluency for DHH children (Allen et al., 2009; Harris & Beech, 1998; Mayberry et al., 2011). Proficient users of Signed Exact English (SEE) and ASL reportedly have less language skill variation than DHH children who grew up without a signed language, suggesting that the language skills acquired by a visual language can bypass the signed or spoken modality of the target second language and result in fluency. DHH children may take advantage of their first (signed) language to learn their second (written) language (Luckner & Handley, 2008; Luckner et al., 2005, 2006; Moores, 2008; Schirmer & McGough, 2005).

In addition to evidence suggesting little engagement with speech-based codes while reading, it has been repeatedly theorized that signed language knowledge contributes to reading proficiency in DHH students, particularly those who attend bilingual schools (Hrastinski & Wilbur, 2016; Mayberry & Lock, 2003; McQuarrie & Abbott, 2013). Hrastinski and Wilbur

(2016) reported an analysis of academic achievement in DHH signers of ASL who attended an ASL-English bilingual school. Data from 108 students from grades 6th-11th revealed that signed language fluency leads to optimal print literacy acquisition, as ASL proficiency alone stood out as the strongest predictor of academic achievement, particularly reading skill.

Finally, evidence from DHH readers of non-alphabetic scripts such as Mandarin Chinese can provide insight into reading development without speech-based phonological decoding on reading. While hearing readers are impacted by homophonic didactics in Chinese characters, DHH readers do not demonstrate the same sensitivity (Jones, 2013). Chinese sign language has been developed to represent the morphological structure of Chinese characters (Dai & Wen, 2002; Yau, 1977), and DHH readers of Chinese are not similarly sensitive to phonetic radicals in script (Jones, 2013). Indeed, in her observational study of reading instruction for Chinese DHH children, Jones (2013) reported that connecting characters with phonology was not beneficial for these readers, but instead visual presentation of symbols with signs and emphasis on the morphological structure of written Chinese was indeed beneficial.

Phonological awareness of sign language and reading

It has been repeatedly theorized in the literature that phonological awareness of signed language contributes to reading skill for DHH signers. Signed languages have phonological structure in the same way that spoken languages do, as they are comprised of meaningless articulatory components that are combined to create meaningful words and signs (Brentari, 1998; Brentari, 2015; Petitto et al., 2016; Sandler, 1989; Sandler, 2017). In spoken language, consonants and vowels comprise the phonological inventory of a language, with highly constrained rules governing the composition of these sounds into meaningful segments. In signed languages, these meaningless articulatory components are handshape, location, and movement

(Stokoe, 1960; Stokoe et al., 1965), as well as palm orientation (Battison, 1987). The building blocks of signed and spoken language phonology are inherently different, although each language modality exhibits sublexical structure.

One major difference between the modalities is the amount of information available in each signal. Spoken language segments are combined sequentially to create meaningful units while signed language components are combined and attended to simultaneously. Signed languages provide sufficient information simultaneously such that only 35% of a sign needs to be attended to, in contrast to the 83% of a spoken word that must be heard for comprehension (Emmorey & Corina, 1990; Grosjean, 1980). Another difference concerns iconicity. Signed languages have iconic properties that are pervasive throughout all levels of signed language linguistic structure (Aronoff et al., 2005; Meir et al., 2013; Padden et al., 2013; Perniss et al., 2010; Taub, 2001).

Despite these differences, signed languages have some of the same general phonological components such as of syllable and rhyme structures, which may result in phonological awareness of signed languages. In spoken English, syllables are the primary linguistic processing unit distinguished by changes in rhyme, intonation, and stress and contain essential phonological segments, onset and rime. The onset is the first sound in the syllable, while the rime is the mostly highly sonorant portion of the syllable, typically a vowel. While the internal structure of signed syllables is still debated (Berent, 2013; Brentari, 1998; Sandler & Lillo-Martin, 2006), most phonological models of sign language propose that movements are syllabic and that a signed syllable either contains a single movement (e.g., MOVE; Figure 1.2) or simultaneous movements, such as a change in handshape during a change in location (e.g., SEND; Figure 1.3). Following this model, disyllabic signs contain two distinct movements, such as in complex compound signs (e.g., OVER-SLEEP; Figure 1.4; Sandler, 2017). In English, one type of syllable rhyme can be described as words with different onsets and the same rime (e.g., 'spoon' and 'moon'; Sterne & Goswami 2000). In ASL, signs have been suggested to rhyme with one another when two of the three articulatory components are the same, and one is different (e.g., CANDY and APPLE which share movement and location, but have different handshapes; Figure 1.5; Meade et al., 2018). Many tests of phonological awareness incorporate manipulation of words and signs at the level of syllable and rhyme.

Figure 1.2

ASL sign for MOVE

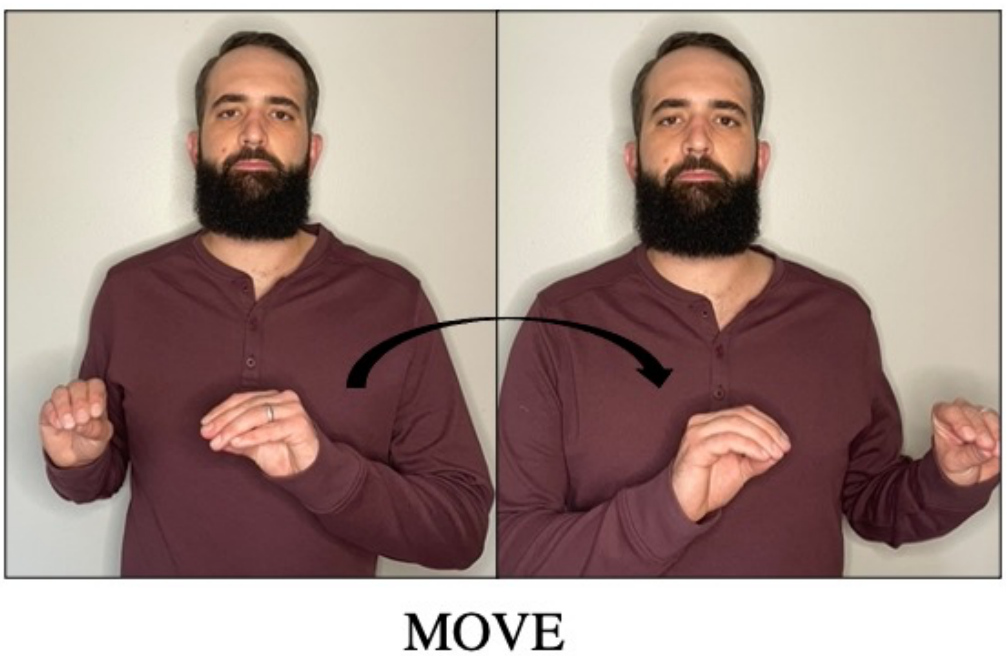


Figure 1.3

ASL sign for SEND

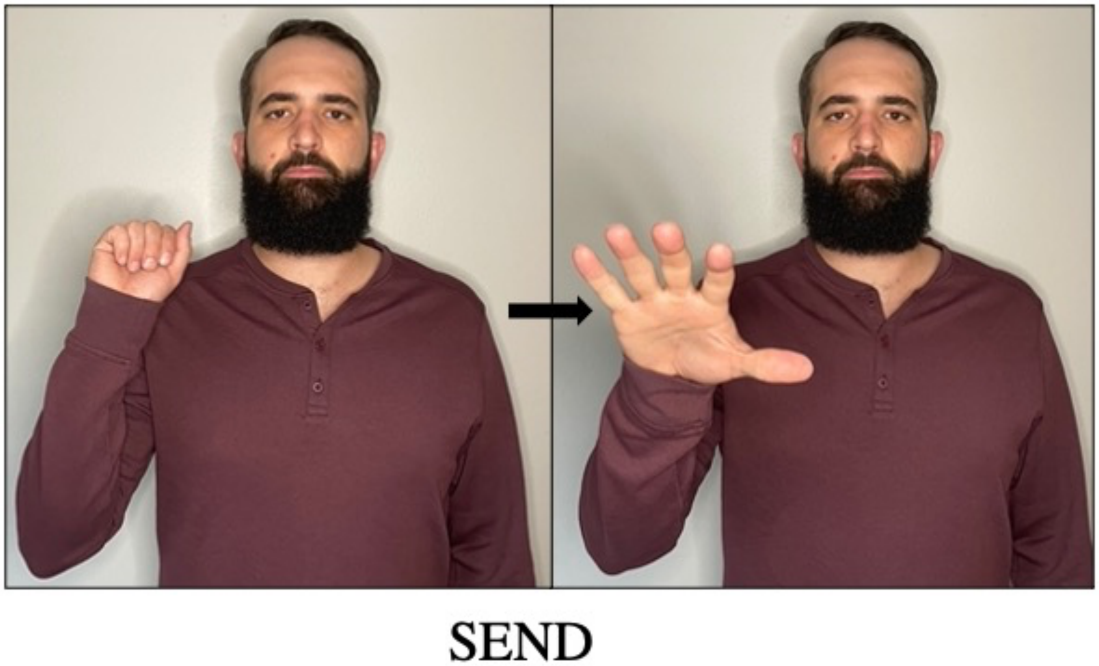


Figure 1.4

ASL sign for OVER-SLEEP

Figure 1.5

ASL signs for CANDY and APPLE

Fingerspelling

Fingerspelling is a contributing factor to reading acquisition for DHH signers. ASL contains a system of hand configurations representing the 26 letters of the English orthography. Though ASL has a broad vocabulary of signs, some English words (e.g., proper nouns, jargon in medical or legal fields, etc.) have no translational equivalent in ASL and instead are fingerspelled. Fingerspelling can also be used to differentiate between concepts that share the same ASL sign or concepts that do not have an established sign. Some ASL signs are initialized as well, which means that the handshape of the sign corresponds to the manual alphabet's handshape for the letter with which the word begins. This system is often used to teach reading to DHH children in bilingual education settings and it can be a significant aid for deaf children learning to read as they may already have a concept of the alphabetic system of the spoken language when they begin reading instruction (Padden & Hanson, 2000; Stone et al., 2015).

Children who have early and robust exposure to a signed language typically begin to acquire fingerspelling without emphasis on it as a system and as a part of the acquisition of the rest of the language. Young signers may not be fully aware of either the serial aspect of fingerspelling and that one item after another to comprise a word, or its connection to orthography. Early in development, fingerspelled words are processed holistically as if they were individual entries in the signed lexicon. This mirrors hearing children's acquisition of two-word phrases as individual lexical entries (e.g., 'thank-you' as one word) or contractions (e.g., 'wanna' before understanding the decomposed form of 'want' + 'to'). As DHH children are exposed to the concept of the alphabetic principle and the combination of letters to create words (ages 4 – 6), they begin to understand that fingerspelled items are comprised of serially presented units that reflect English orthography (Akamatsu, 1985; Padden, 2006; Padden & Hanson, 2000; Stone et al., 2015).

Fingerspelling skill has been shown to be predictive of reading fluency in DHH children (Allen, 2015; Emmorey & Petrich, 2012; Padden & Hanson, 2000; Stone et al., 2015). Padden and Hanson (2000) suggested fingerspelling plays a key role in reading development, and it serves as "the missing link" between ASL and English. Stone and colleagues (2015) tested fingerspelling, ASL fluency, and both verbal and non-verbal IQ on reading outcomes in DHH signers. Results indicated that fingerspelling skill predicted reading fluency significantly more so than ASL alone. While general sign language fluency and fingerspelling skills are highly connected to reading skill, the two systems seemingly work independently via different cognitive and literacy mechanisms skilled DHH readers (Padden & Hanson, 2000; Sehyr et al., 2017).

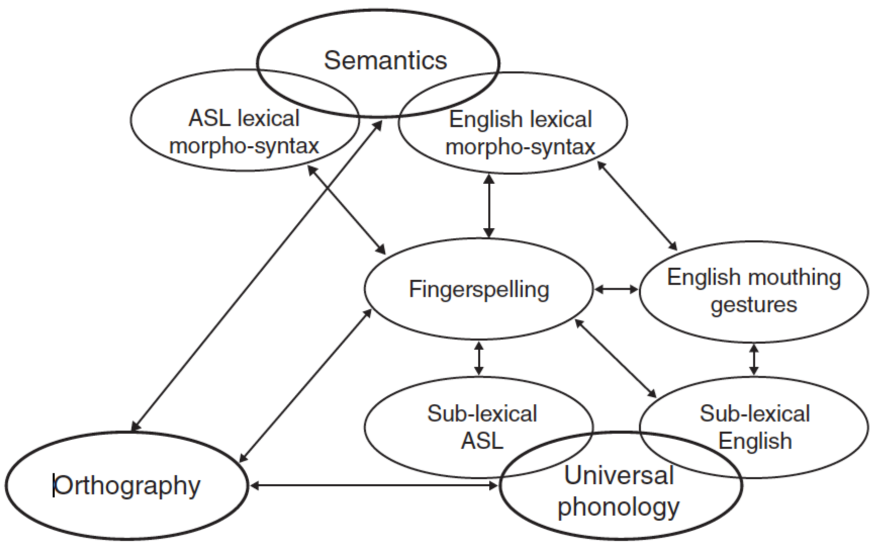
Scholars and educators have suggested that fingerspelling fluency can result in phonological sensitivity to the spoken language it represents. One approach to testing phonological sensitivity is the phonological similarity effect, which has been widely discussed in the literature for hearing readers. In serial recall of word lists, phonologically similar words are harder to recall than phonologically dissimilar words (Baddeley, 1986; Baddeley, 1998; Conrad & Hull, 1964; Henry, 1991; Hitch et al., 1983). Reports have demonstrated the phonological similarity effect for DHH readers. When presented with a written or fingerspelled list of words, adult DHH signers who are skilled readers have been reported to be less accurate when recalling both written and fingerspelled items that were phonologically related on speech-based parameters (Krakow & Hanson, 1985; Poizner et al., 1981; Wilson & Emmorey, 1997) as well as based on visual similarity of fingerspelled items (Sehyr et al., 2017). These findings suggest that DHH signers who are skilled readers are not only sensitive to speech-based phonology when processing written words, but that fingerspelling activates speech-based codes.

Visual Sign Phonology (VSP)

Reading development for DHH signers is complex and dependent on multiple linguistic components in the visual signal. Studies have demonstrated correlations between signed and spoken language fluency (Freel et al., 2011; Hrastinski & Wilbur, 2016; Simth et al., 2013), and DHH readers who are native users of a signed language tend to have higher and more homogenous reading outcomes (Andrews et al., 2015; Qi & Mitchell, 2000; Wolsey et al., 2018). As such, scholars have suggested that DHH signers acquire sublexical English information during reading and while processing English mouthing gestures, use fingerspelling knowledge to understand letters and the serial nature of written words, and connect ASL signs with English vocabulary to bridge the gap between the two languages. To account for this, one model of reading for DHH readers expanded the triangle model of reading (Harm & Seidenburg, 2004) to incorporate some of the many components of linguistic skill and knowledge provided by the visual language signal. Petitto and colleagues (2016) suggested that phonological awareness does not have to be sound-specific per se for fluent reading skill. Instead, DHH children develop visual sign phonology (VSP) which provides the basis of phonological segmentation skill necessary for adult-like reading. All the phonological information provided in the visual signal (such as, written English, English mouthing gestures, ASL and fingerspelling) provide the necessary basis for phonological segmentation skill in DHH children (Figure 1.6).

Figure 1.6

Visual Sign Phonology



Note: From Petitto et al. (2016) VSP Model of Reading

Neither signed nor spoken language phonological awareness alone are sufficient for reading. Following the VSP model, children exploit general phonological sensitivity to discover other core aspects of their language, such as vocabulary, morphological structure, and syntactic structure. All levels contribute to language comprehension and literacy. The basic phonological sensitivity necessary to self-learn other aspects of language, regardless of signed or spoken modality.

Wolsey and colleagues (2018) tested components of the VSP model in a pre- and post-intervention study with DHH children who attended ASL-English bilingual schools. Researchers tested a variety of linguistic factors including ASL receptive skills, pre-literacy alphabetic knowledge, and ASL-English bilingual skills. Bilingual skills were tested by story retelling, in which participants were read a story and asked to retell it in sign, and story reading, in which participants were asked to read a book to the experimenter in ASL. A total of 25 students were involved in the study and groups were separated by ASL receptive skill. Ten students with poorer ASL skill were put in the intervention group and the other 15 were controls. The intervention included ASL-English bilingual Shared Book Reading (SBR) in which an educator and child reader interact while reading a book using a top-down model. SBR interventions have reportedly benefitted a variety of struggling readers (Andrews et al., 2017; Stobbart & Alant, 2008; Val Kleeck, Vander Woude, & Hammett, 2006; Williams, 2012).

Students first watched a video of Deaf adult signers signing the story, then watched the teacher read the story to the entire class using a large cardboard book. Next, students came to the front of the classroom individually and were encouraged to sign each page of the cardboard book while the teacher and peers engaged in a discussion of each page of the story. Finally, the book was laid aside and each student retold the story in ASL with teacher and peer support. Following the classroom intervention, students chose a favorite section of the story, drew a part of that favorite section and wrote an explanation of that section, then explained the drawing in ASL to the teacher, who wrote the English gloss to label the drawings. Students continued this cycle with more stories over 10 weeks and were recorded signing each story. The results demonstrated that the ASL-English SBR intervention improved students' ASL abilities, Further, though the experimental group included students who struggled with ASL receptive skills, no ASL abilities were detected between groups post-intervention. Additionally, intervention group students' English skill increased, further supporting the relationship between ASL and English fluency for reading ability. Importantly, no relationship between speech-based phonological awareness and reading ability was detected, but that intervention students made more spelling-based errors than sound-based errors, which the authors suggested is related to the strong emphasis on fingerspelling and chaining on literacy instruction for DHH students. The authors concluded that bilingualism can be exploited to benefit language ability in either target language and that DHH signers with stronger ASL ability are likely to be stronger readers.

DHH readers and the Simple View of Reading

The SVR has been proposed a few times regarding DHH signing readers (Chamberlain & Mayberry, 2000; Stone et al., 2015; Wauters, van Gelder, & Tijsseling, 2021; Wauters et al., 2006). Chamberlain and Mayberry (2000) applied the Simple View of Reading to signed language and suggested that this model may be the most applicable when explaining reading development in DHH children considering the emphasis on linguistic comprehension. In order to exacmine the efficacy of this model, researchers compared the findings of Hoover & Gough (1990) to data from three separate studies with DHH signers of manually coded English (MCE). The original paper reported a correlation between listening and reading comprehension in English for Grades 1, 2, 3, and 4 were $r = 0.46$, $r = 0.71$, $r = 0.80$, and $r = 0.87$ respectively. They further reported that listening comprehension accounted for 35% of the variance in early readers' reading comprehension and 65% for older readers. Moores et al. (1987; 1990) reported a correlation of $r = 0.3$ between signed language proficiency interviews and a composite of five standardized reading tests. Mayberry et al. (1989, 1994, 1999) reported strong correlations between MCE story comprehension and written story comprehension ($r = 0.67$) and standardized measures of reading (*r* = 0.68). Finally, Hoffmeister (2000) reported a correlation of *r* = 0.38 between MCE sentence comprehension and standardized measures of reading. Chamberlain and Mayberry (2000) point out while the similarity in reading variability accounted for by linguistic comprehension in DHH and hearing readers is striking, a direct study would be required to interpret this similarity.

In their study, Wauters and colleagues (2021) tested the components of the SVR on reading development in DHH readers learning to read Dutch. Test groups included 38 adult DHH readers, 24 of whom primarily used the signed language of the Netherlands (NGT), eight who primarily used spoken Dutch, and an additional six who used a combination of sign and speech. Results demonstrated that both decoding and linguistic comprehension were correlated with DHH readers. When DHH readers were split into more- and less-skilled decoders, only the less-skilled decoders demonstrated significant relationships between measures of decoding and reading ability. Vocabulary knowledge alone explained for most of the variance in reading outcomes. Researchers concluded that vocabulary knowledge is the strongest predictor of reading ability. Though this study advances the SVR for less-skilled DHH decoders but fails to do the same for more skilled decoders, this study included only adult signers (mean age 46; range 30 – 73), 67% of whom read below a 6th grade reading average. Further, not all participants reported early and robust access to NGT at home. It may be the case that language comprehension due to significant signed language experience is stronger than general language comprehension for those who may not use one primary modality to communicate. Further, it is difficult to test the SVR in individuals who are not proficient readers as reading and language comprehension are significantly interrelated and the impact of orthographic depth on all components (Florit & Cain, 2011; Gough & Tunmer, 1986; Hoover & Gough, 1990; Kendeou et al., 2009).

Various studies have leveraged lexical decision tasks (to be described more in Chapter 4) to address phonological and orthographic processing in DHH signers. The transposed letter (TL) effect is commonly exploited to test orthographic processing. TL words are actual words of the target language manipulated by swapping two consonants (e.g., '*medicine'* - *'mecidine'*) and are often mistaken for real words, which allows researchers to assess the quality of orthographic representations during lexical decision tasks (Emmorey & Lee 2021; Fariña et al. 2017). Lexical decision task data with skilled DHH readers have demonstrated stronger impact of orthographic processing compared to phonological processing, unlike hearing readers (Bélanger et al., 2012; Emmory & Lee, 2021; Fariña et al., 2017; Meade et al., 2020). Costello and colleagues reported ERP data from two lexical decision tasks designed to differentiate between the influence of orthography and speech-based phonology on lexical access of a shallow orthography (written Spanish) in deaf and hearing children: a phonological coding task and an orthographic coding task. Results indicated that DHH signers were significantly faster in response times than hearing readers. Further, no difference between accuracy was found between groups, suggesting that both groups are sensitive to orthographic manipulations. The authors concluded that deaf signers are not sensitive to speech-based cues, unlike their hearing peers.

Where do we go from here?

The goal of this dissertation is to fill a gap in our knowledge of reading acquisition in DHH children who have had early, robust exposure to sign language from birth. To do so, I tested English and ASL phonological skills of DHH signers as well as the degree to which they engaged in phonological decoding of print to speech during several experimental tasks. I test speech- and sign-based phonological awareness and reading in DHH readers in three separate approaches. Chapter 2 tests phonological awareness of English and ASL, as well as the relationship between phonological awareness and reading. This serves to examine DHH readers' speech-based sensitivity as well as the relationship between English and ASL phonological awareness and reading. Chapter 3 leverages eye-tracking technology and experimental manipulations to test the active use of speech-based codes during error detection in sentences. Chapter 4 tests the role of speech-based codes and orthographic processing on lexical retrieval in DHH and hearing readers. Finally, Chapter 5 considers all evidence together and summarizes the limitations and future directions of the study.

Chapter 2: Phonological Awareness of Language in Two Modalities

Introduction

Central to the debate regarding reading development for DHH children is phonological awareness of speech. While the relationship between speech-based phonological awareness and reading has been established for hearing readers of certain orthographic scripts (Ehri, 2014; Rayner et al., 2006; Share, 2005), the same cannot be said for DHH readers (Allen et al. 2009; Wang et al. 2008). Further, for DHH children who grow up primarily using signed language, there may exist a relationship between signed language phonological awareness and reading (McQuarrie & Abbott, 2013; Petitto et al., 2016). Here, I consider the relationship between English and ASL phonological awareness in DHH signers, as well as the impact of phonological awareness on reading fluency.

I test the relationship between signed and spoken language phonological awareness and reading in hearing and DHH child readers. I report behavioral language data from nine DHH and 14 hearing readers ages 10-13. All participants completed the Woodcock-Johnson III-Test of Silent Reading Fluency (WCJ-SRF; Woodcock, McGrew, & Mather, 2001). To test English phonological awareness, I developed three instructional presentations to train DHH participants on two fundamental components of English phonology, namely syllables and rhymes, as well as the phonological structure of ASL. In addition, I created two picture-based measures of English phonology at the syllable and rhyme level, an ASL judgement task involving similarity judgements of two sequentially presented ASL signs, and speechreading tasks. In conjunction with the novel tasks, I report participant scores on the ASL-PA, which was previously developed and tested in adult DHH signers of ASL (Corina, Hafer, & Welch, 2014), and the Test of Child Speechreading (Kyle et al., 2014).

Testing phonological awareness of speech in hearing and DHH children

Wagner and Torgensen (1987) described phonological awareness as being “demonstrated by successful performance on tasks such as tapping out the number of sounds in a word, reversing the order of sounds in a word, and putting together sounds presented in isolation to form a word” (p. 192). Since then, phonological awareness has largely been tested using the same approach, targeting rhyme and syllable judgement, phoneme or syllable deletion (Rosner & Simon 1971; Tomblin et al. 1997; Alonzo et al. 2020), and the ability to flexibly arrange sounds to create meaningful utterances (Wagner & Torgensen 1987; Mattingly 1972; Lewkowicz 1980; Sterne & Goswami 2000).

Measures of syllable awareness involve syllabic length judgement tasks (Katz 1986; Pratt & Brady 1988; Swan & Goswami 1997; Sterne & Goswami 2000). These tasks can be difficult or inappropriate for DHH children due to dependence of auditory stimuli, often resulting in participants judging orthographic length and similarity. Further, hearing children have vast experience with rhyming and English word games due to nursery rhymes, patty cake games, etc., and the idea of words that rhyme and syllabic length is more intuitive for hearing children. As such, it is important to define and describe rhymes and syllables in spoken language in a visual manner to ensure that true speech-based phonology is being tapped by these tasks.

The issue of testing phonological awareness of speech for DHH children is complex, due in part to relative lack of measures available to test phonological awareness without dependence on auditory cues. Appropriate measures are necessary to properly assess the issue of phonological awareness of speech and sign on reading development in DHH signers. Testing phonological awareness of speech in DHH children has yielded mixed results. Wagner and Torgensen (1987) described phonological awareness as being “demonstrated by successful performance on tasks such as tapping out the number of sounds in a word, reversing the order of sounds in a word, and putting together sounds presented in isolation to form a word" (p. 192). Since then, phonological awareness has largely been tested using the same approach, targeting rhyme and syllable judgement, phoneme or syllable deletion (Alonzo et al., 2020; Rosner & Simon, 1971; Tomblin et al., 1997), and the ability to flexibly arrange sounds to create meaningful utterances (Lewkowicz, 1980; Mattingly, 1972; Sterne & Goswami, 2000; Wagner & Torgensen, 1987).

When considering tasks to target speech-based phonological awareness in DHH signers, it is important to use cues and stimuli that do not require normal hearing. Sterne and Goswami (2000) conducted an analysis of existing studies that investigated speech-based phonological awareness in signers. At the time, only seven such studies could be found. Four reported rhyme awareness in DHH signing children (Charlier & Leybaert, 2000; Dodd & Hermelin, 1977; Hanson & Fowler, 1987; Hanson & McGarr, 1989), two reported no evidence of rhyme awareness (Campbell & Wright, 1988, 1990), and one found mixed evidence (Harris & Beech, 1998). Interestingly, one of the studies that did report evidence of rhyme awareness (Charlier & Leybaert, 2000) and two of the studies that did not find evidence of rhyme awareness (Campbell & Wright, 1988, 1990) employed pictorial stimuli as opposed to reading-based tasks.

McQuarrie and Parrila (2009) suggested that evidence of speech-based phonological knowledge in DHH children and adults is due to limited methods of testing, noting that most studies prior to 2009 only targeted speech via rhyme awareness (except for Sterne & Goswami, 2000). The authors suggested that DHH children are more likely to have awareness of the larger units of spoken language phonology such as rhymes and syllables that are clear in the spelling of words. Finally, some publications regarding reading and speech knowledge in DHH readers use two item discrimination tasks with written English words, which may result in orthographic rather than phonological discrimination (e.g., correctly judging that 'fight' and 'night' rhyme because of the similarly spelled ending) or by a process of elimination (e.g., picking the correct target because the incorrect target is not a viable option; McQuarrie & Parrila, 2009; Sterne & Goswami, 2000). Results indicating sensitivity to orthographically visible phonological parameters would suggest that skilled DHH child and adult readers would have stronger phonological awareness of speech than less skilled DHH readers due to the ability to continue with reading practice.

Testing phonological awareness of signed languages

Methods for testing sign-based phonological awareness are similar to those for spoken language phonological awareness. Such tasks target phonological skill by manipulating components of words and similarity/difference judgements. For their study investigating the influence of ASL phonological awareness on reading abilities in DHH signers, McQuarrie and Abbott (2013) created a phonological-similarity judgement task manipulating the three major phonological components of ASL: handshape, movement, and location. Sign stimuli were chosen such that three possible pairings of signs could be presented: 1) Signs with all three phonological components in common; 2) Signs with two of three phonological components in common with all possible pairings; 3) Signs with one of three components in common. Items were presented via picture stimuli, and participants judged whether signs were similar or dissimilar. Results from 50 students ages 7 – 18 (mean age = 13 years, 5 months) demonstrated that ASL phonological discrimination skill increased with age and reading ability, and that reading ability correlated with signed first language phonological ability. The authors suggested that DHH signers use the metalinguistic knowledge of their first language to benefit the acquisition of a second language.

Another test of ASL phonological awareness targets manipulation of phonological parameters to create real signs (ASL-PA; Corina et al. 2014). For this task, participants view videos of two ASL pseudosigns and are instructed to combine phonological parameters from each pseudosign to create a real ASL sign chosen from an array of 3 possible real sign videos. For each item, one pseudosign has two parameters that will exist in the real sign (e.g., correct handshape and movement of RADIO, incorrect location) and one will contain the one remaining parameter (e.g., correct location of RADIO, incorrect handshape and movement). All videos are played simultaneously, such that both pseudosigns play concurrently with the three possible real ASL signs, and participants are allowed to replay the videos as many times as necessary. The study included three groups of signing participants: thirty-one native signers who learned ASL from birth, for early signers who began learning ASL before the age of 8, and sixteen late signers who were not exposed to ASL until after 8. The results indicated that age of acquisition of ASL for each participant significantly predicted ASL-PA scores. The native signers performed above the early and late acquirers. Further, the early and late exposed signers demonstrated more variability in their scores. Importantly, variation in repetition of stimulus videos did not differ between groups, which the authors suggested indicates that the task is tapping true phonological awareness of sign, not visual working memory or other higher cognitive processes.

Finally, DHH signers demonstrate categorical perception to signs while hearing non-signers do not. Speech sounds (as well as other stimuli) are perceived categorically instead of continuously, despite a continuous variation in form between related speech sounds (Emmorey, McCullough, & Brentari, 2003; Libermen et al., 1976). For example, the discerning factor between /ta/ and /da/ in English is voice-onset time (VOT), which is one continuous variable reflecting the amount of time between the onset of a sounds and the activation of voicing. Speakers of languages with these contrasts will consistently categorize /ta/ and /da/ at a distinct boundary between the VOTs of the two sounds, while non-speakers will demonstrate more continuous categorization of /ta/ and /da/ without a clear VOT boundary. This phenomenon represents phonological sensitivity to a language. To test categorical perception of ASL, Emmorey and colleagues (2003) tested DHH signers and hearing non-signers on categorical perception of two features: handshape and place of articulation. DHH signers demonstrated sharper categorical perception of features that are contrastive in ASL, but signers and hearing non-signers performed similarly on features that were not contrastive in ASL. The authors concluded that while both groups demonstrated categorical perception to these features, DHH signers had a unique sensitivity to those contrasts that are relevant for ASL (Emmorey et al., 2003).

We are currently lacking adequate measures for testing English and ASL phonological awareness in young DHH signers. As a result, it is difficult to assess phonological awareness of DHH signers, further impacting our ability to speculate on how signed and spoken language sublexical knowledge contributes to reading. I created measures to test phonological awareness of ASL and English in DHH signers to assess the relationship between signed and spoken language sublexical knowledge and how they related to reading.

Research questions

This chapter aims to answer the following research questions:

1. Do DHH and hearing readers perform similarly on measures of ASL and English phonological awareness?

2. Does performance on tasks of ASL and English phonological awareness predict English reading ability?

Considering that existing tasks have been shown to successfully predict reading and language ability, I expect that the tasks developed for this study will do the same. Finally, due to the inclusion of visual stimuli and careful descriptions of rhyme and of syllables for DHH participants, the measures of speech-based phonological awareness employed here are likely more accurately targeting sublexical language ability.

Methods

Links to all dynamic, instructional Presentations, dataset, and supplemental materials can be found in the following Open Science Framework (OSF) database: DOI 10.17605/OSF.IO/AN497

Participants

Data from fourteen hearing children (3 female; mean age 11;3: range 10-12;9) and nine DHH children (9 female; mean age 11;6: range 10-13) is presented. DHH participants all attended a bimodal bilingual residential school for the deaf at the time of data collection and throughout early childhood. All DHH participants reported using ASL as their primary mode of communication at home and at school. Though two participants reported using some amount of speech, all DHH signers came from deaf families with at least one Deaf parent. Six participants were reported by parents to have dB loss >70, and three were reported to have dB loss 40-55. All had normal or corrected-to-normal vision.

Criteria for DHH participants required that they acquired ASL from Deaf parents and reported using ASL as a primary language, at school and at home with family. Though participants were not excluded based on the use of hearing aids or use of cochlear implants, no participants in the DHH group reported amplification via hearing aids or cochlear implantation.

Criteria required hearing participants to be monolingual English speakers with no reported hearing loss and normal or corrected-to-normal vision. Participants were all typically developing with no report of learning delay or disability. None of the participants were homeschooled.

Previous studies have indicated a strong, positive correlation between family SES and literacy development in children (Reardon, Valentino, & Shores, 2012). I report two measures of SES: education level of mother and father (if applicable)[2], and yearly household income in Table 2.1. Hearing families report more bachelors and advanced degrees than DHH families for both caregivers. Further, only one of nine DHH family reports yearly household income above $100,000, while 13 of 14 hearing families report income at or above $100,000 yearly.

Table 2.1

SES of groups: Highest degree (mother and father, if applicable), and household income

		Deaf	**Hearing**
Mother highest degree			
	Advanced degree: MA, PhD, MD, JD	2	6
	College degree, BA or BS	2	6
	Some college, AA or tech degree	5	2
Father highest degree			
	Advanced degree: MA, PhD, MD, JD	0	2
	College degree, BA or BS	2	8
	Some college, AA or tech degree	4	3
	NA	3	1
Yearly Income (in US dollars)			
	> 150,000	0	6
	100,000-149,999	1	7
	50,000-99,999	2	0
	20,000-49,999	6	1

[2] None of the participants had same-sex parents. I report the highest degrees obtained by the mother and father of each participant, if applicable, considering evidence that maternal education level is more strongly related to child educational outcomes than paternal education level (Korat, 2009).

DHH participants were recruited by flyers and emails sent to the parents of DHH children at a residential school for the deaf, as well as via snowball recruitment methods leveraging networks of the parents of the participants. Hearing participants were recruited by flyer and email distribution to schools in Austin, TX, as well as postings on the university for faculty and staff.

Measures of English phonological awareness

To target speech-based phonological awareness, picture stimuli[3] were chosen to avoid cross linguistic activation from ASL signs or written English words. All participants completed a picture-learning task prior to completing these tasks to ensure the correct label was associated with each picture. All participants were presented with picture and were asked to label it. Hearing participants labeled each item with the English word, and DHH participants were able to either fingerspell or produce the ASL sign for the picture. If a participant mislabeled a picture, they were informed of the correct target label and asked to repeat it.

Word lists and general design were borrowed from Sterne and Goswami (2000). Constructed word lists were balanced and paired based on orthographic transparency. One original pair of rhyming words, *saw* and *four*, was changed to *saw* and *paw* to match American English. Second, only the measures of syllable and rhyme were adapted and used for the present study. Lastly, visual definitions and descriptions of syllables and rhymes were designed to ensure DHH readers understood the parameters being targeted. Hearing participants were asked if they understood English syllables and rhymes and to provide examples. All hearing participants provided correct definitions and did not receive English instruction.

[3] All photos are freely available, unattributed clipart pictures unless indicated otherwise.

English rhyme judgement task

The English rhyme judgement task required a similarity judgement of the English labels for three simultaneously presented pictures. Each presentation consisted of a target picture (e.g., a cat) above two other pictures: the distracter item and the rhyme item (e.g., a can and a hat). Subjects were instructed to pick the picture from the two choices below that rhymes with the target. Fifty rhyme pairs were presented, and accuracy and response time recorded in PsychoPy.

Stimuli were either orthographically congruous or incongruous, to determine whether DHH participants were targeting phonological rhyme or are judging orthographic similarity. Distractor items for this task were one of five possible types: 1. Totally dissimilar from the target (e.g., “bed” - “sock”); 2. Similar mouth shape as the target (e.g., “rope” - “comb”); 3. Shared initial consonant with target (e.g., “witch” - “wall”); 4. Shared initial consonant cluster with target (e.g., “snake” - “snowman”); 5. Shared initial onset-vowel with the target (e.g., “bricks” - “bridge”). Further, rhyme pairs were either orthographically similar (e.g., “clock” - “sock”) or dissimilar (e.g., “fly” - “eye”; full wordlist available in Appendix B1).

English rhyme task instructions were taught to DHH signers by associating picture stimuli with silent videos of an adult female speaker of English producing monosyllabic words. Participants first viewed a cartoon figure with arrows indicating that the person is looking at three pictures- one on top, with two below (Figure 2.1). Next, participants saw the same cartoon figure and array of three pictures, but arrows are replaced with thought bubbles and pictures are replaced with video clips of an adult male or female producing the monosyllabic label for the picture it replaces (Figure 2.2). In ASL, experimenters explained to participants that the person is now picturing the English labels for the picture based on the mouthing gesture. They were further instructed that they will be tasked with picking which picture on the bottom rhymes with the target picture above. Finally, DHH participants were shown the correct answer to which pictures sound alike (Figure 2.3).

Figure 2.1

Step 1 of rhyme instruction

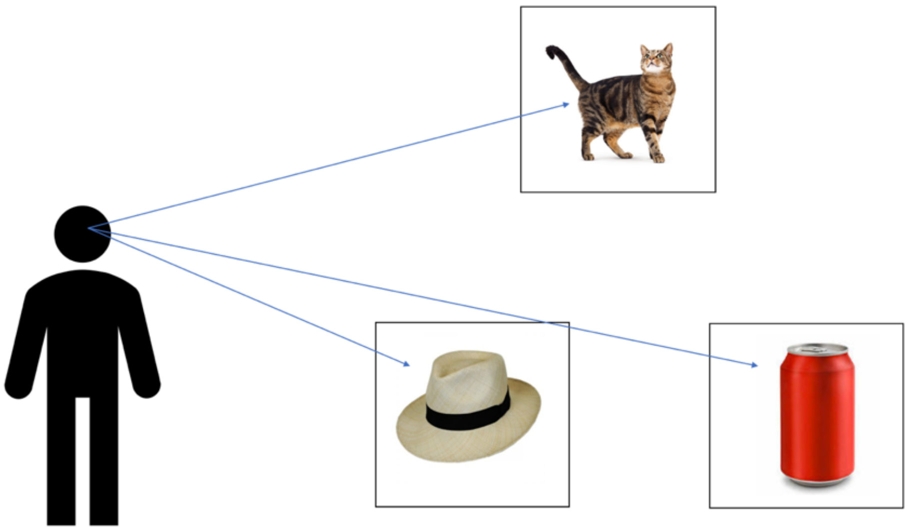
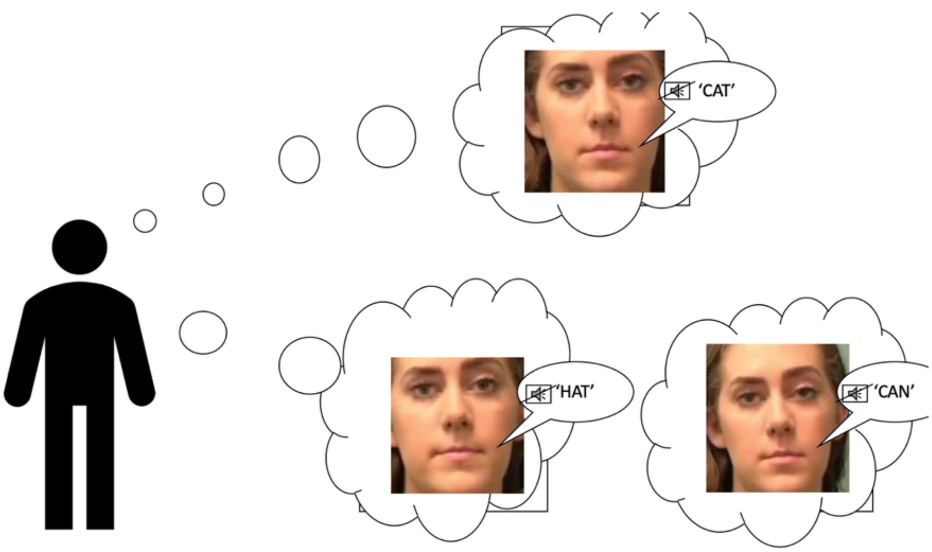


Figure 2.2

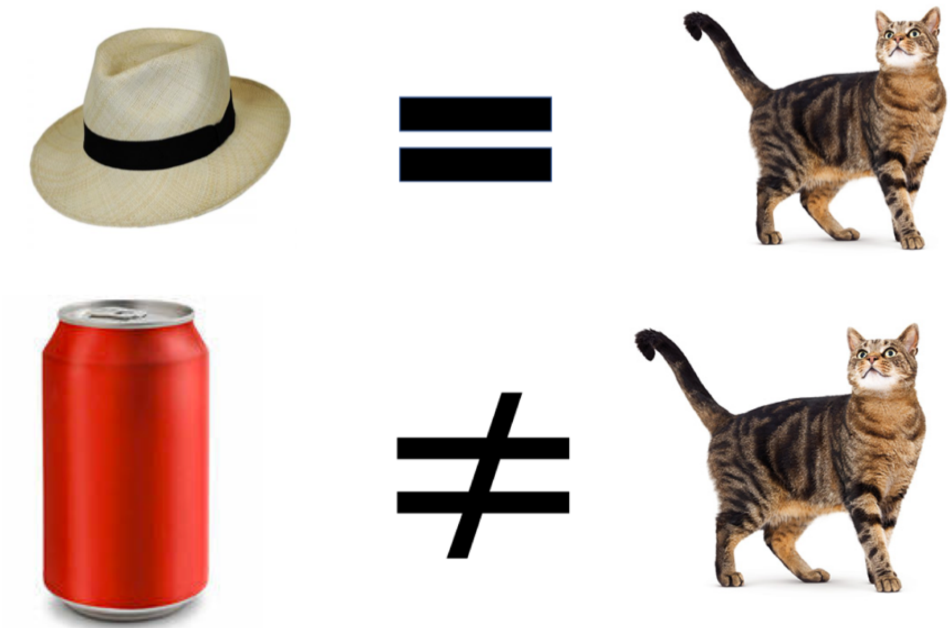
Step 2 of rhyme instruction



Note: The written word inside the speech bubbles were not original to the instructions and were included here for illustrative purposes.

Figure 2.3

English rhyme instruction correct answers



English syllable judgement task

The English syllable judgement task required a similarity judgement of two simultaneously presented pictures. This task was scripted and presented in PsychoPy, with accuracy and reaction time recorded. Participants were instructed to consider the English word for the two pictures presented then choose 'same' or 'different' on the computer based on the syllabic length of the word. Word pairs were either orthographically congruent based on the same number of written letters (e.g., four letters in monosyllabic words such as "bird" vs. "tree"; four letters in monosyllabic and disyllabic "cake" vs. "baby") or orthographically incongruent with different number of written letters (e.g., 'same' judgement of "switch" and "cake" or 'different' judgement of "switch" and "potato"; full word list can be found in Appendix B2). Distractor items consisted of orthographically congruent or incongruent stimuli in opposition to the target stimulus. Thirty-six items were tested.

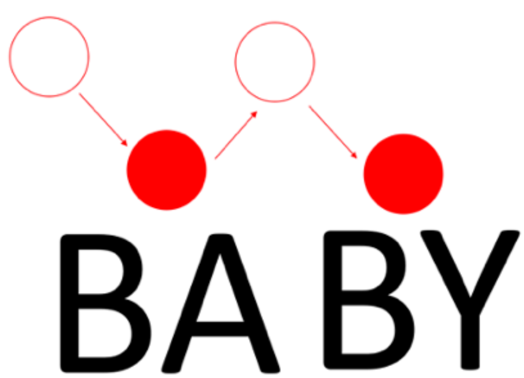
To teach the English syllable judgement task to DHH participants, the first example was given in the form of written words. When advanced, an empty circle that appeared above the word would move to the first syllable of the word and fills in with red ink. For a single syllable word (e.g., 'hat'; Figure 2.4), the circle would move towards the top of the word and fill in with red when it landed above it. For multisyllabic words (e.g., 'baby'; Figure 2.5), the red circle would become an outline and move back above the word and to the right, before falling back on top of the next syllable and filling in red again.

Figure 2.4

Visual depiction of a single syllable

Figure 2.5

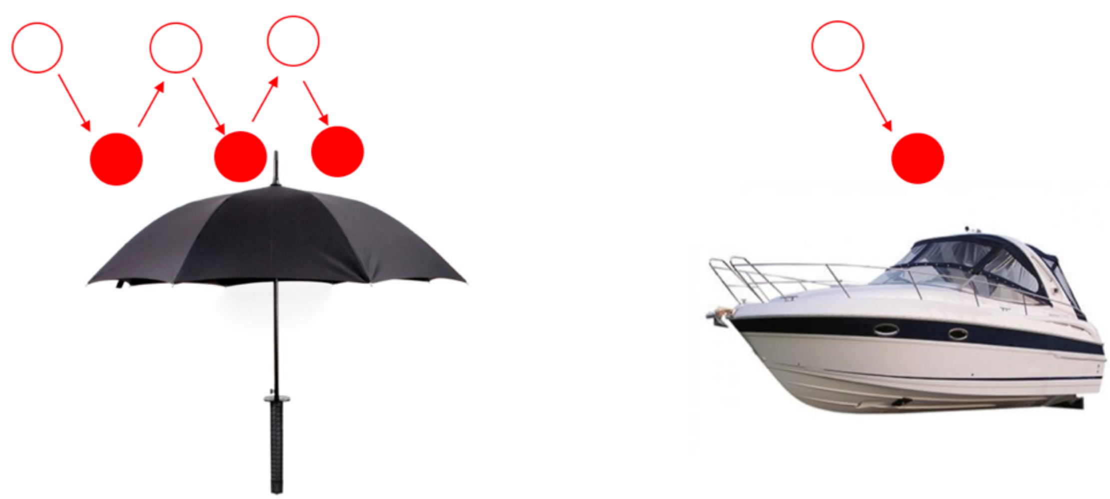
Visual depiction of two syllables



The next step in syllable instruction connected syllables with pictures instead of words so that participants connected picture stimuli with their English label. The same pattern of outline and full color circles as described above for written words representing the number of syllables in the label for the picture (Figure 2.6).

Figure 2.6

Visual description of syllables with pictures



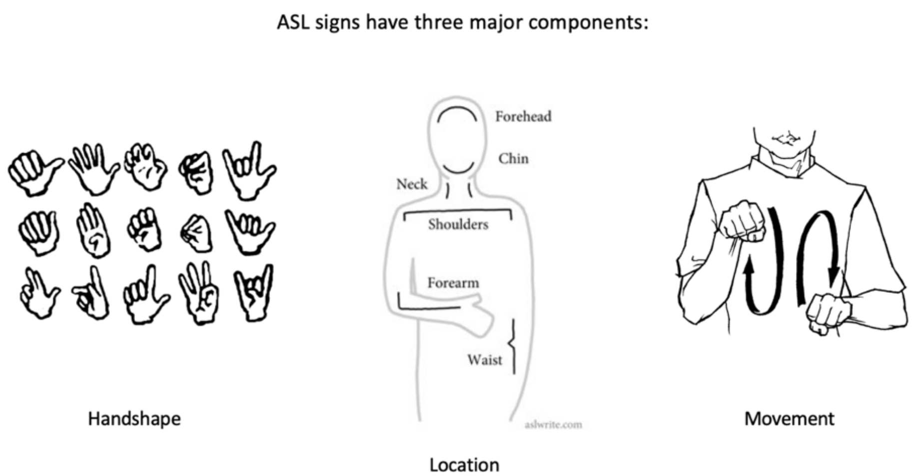
Measures of ASL phonological awareness

ASL-PA

I tested ASL phonological awareness via ASL-PA (Corina et al., 2014) and a novel ASL judgement task. Hearing participants were tested for ASL phonological sensitivity considering evidence that hearing non-signers are sensitive to some sign-based phonological parameters (Emmorey, McCullough, & Brentari, 2003). Prior to completion, hearing participants were provided with an instructional presentation informing them of what constitutes ‘similar and ‘dissimilar’ in ASL. First, the three major components of ASL, handshape, location, and movement (Figure 2.7), were highlighted. Next, they were shown two pairs of signs, one pair that shared two of three phonological components (e.g., MOTHER and FATHER; Figure 2.8) and one pair that shared no phonological components (e.g., MOTHER and NAME; Figure 2.9). DHH participants were asked if they understood the components and if they wanted the ASL instructional presentation. No DHH participants requested ASL phonological parameter instruction.

Figure 2.7

Phonological components of sign



Note: Handshape photo: https://aslfont.github.io/Symbol-Font-For-ASL/images/handshapes.png

Movement photo: https://images.app.goo.gl/g2Qq39XLFWtEtb5D8

Figure 2.8

Two similar ASL signs that differ only in place of articulation

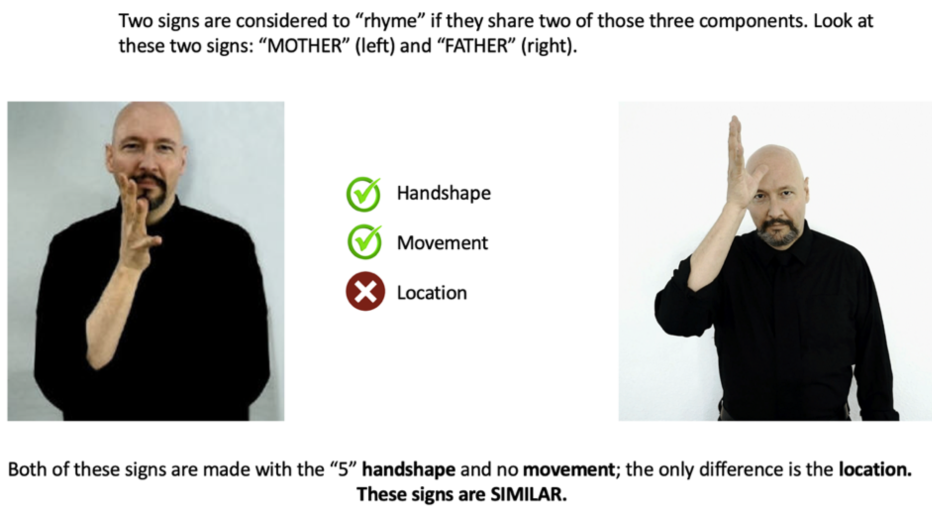
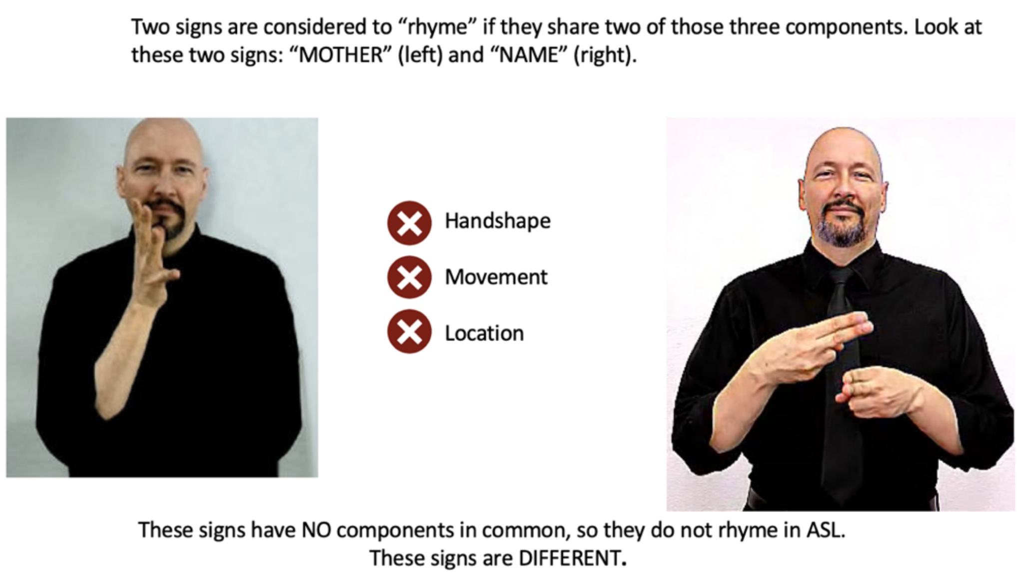


Figure 2.9

Two different ASL signs that differ along all formational parameters



Note: ASL example photos from lifeprint.com

The ASL-PA is a video-based test administered on a computer designed to examine phonological awareness of ASL signs. Participants were presented with video clips three real signs and two pseudosigns, which are possible, non-signs that follow phonological parameters of ASL that have either one or two phonological parameters in common with the correct target sign. Participants were encouraged to watch each video clip as many times as they needed to examine the two pseudosign forms and evaluate the three potential answers. Based on the two pseudosign forms, they were asked to isolate handshape, movement, and location properties of the two signs and combine them to create an existing ASL sign. Participants determined which of the three real signs presented below the pseudosigns could be made from combining the parameters of the pseudosigns. The test consisted of 20 distinct sign trials, though the original paper only reports the items out of 19 trials due to presentation issues. Participants wrote down their responses on provided paper.

ASL rhyme judgement task

The ASL rhyme judgement task was tested in conjunction with the ASL-PA. This task was originally developed for a different study measuring phonological awareness of DHH children. Participants judged if the pair of signs are similar (two phonological components in common) or different (no components in common). Reaction time and accuracy were recorded via PsychoPy.

Stimuli included clips of one Deaf male native signer and one Deaf female native signer signing individual signs. All video stimuli were one second long. Signs were paired as similar and shared two of three phonological components (e.g., UGLY and SUMMER which share movement and handshape but have different place; Figure 2.10), or different with no phonological components in common (e.g., GIVE and UGLY; Figure 2.11). Participants were instructed to judge the similarity of two sequentially presented videos of ASL. Similar signs (N = 24) share two features, including location and movement, or hand shape and movement.

Dissimilar signs (N = 24) do not share features. None of the stimuli were iconic signs, initialized signs or fingerspelling loan signs, and all signs had English translation equivalents and do not include facial expressions or mouthings.

Figure 2.10

Phonologically related ASL signs: UGLY and SUMMER

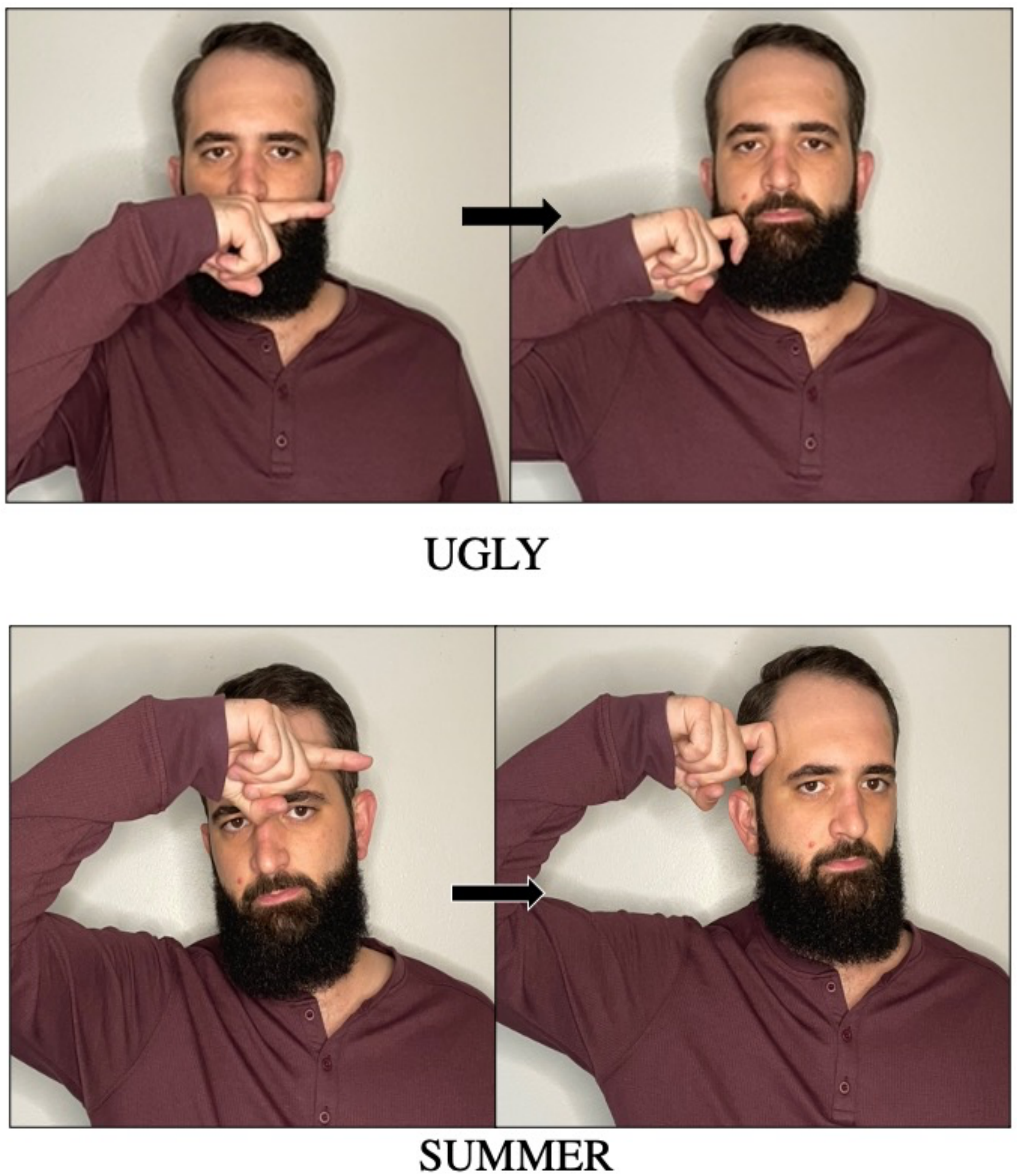
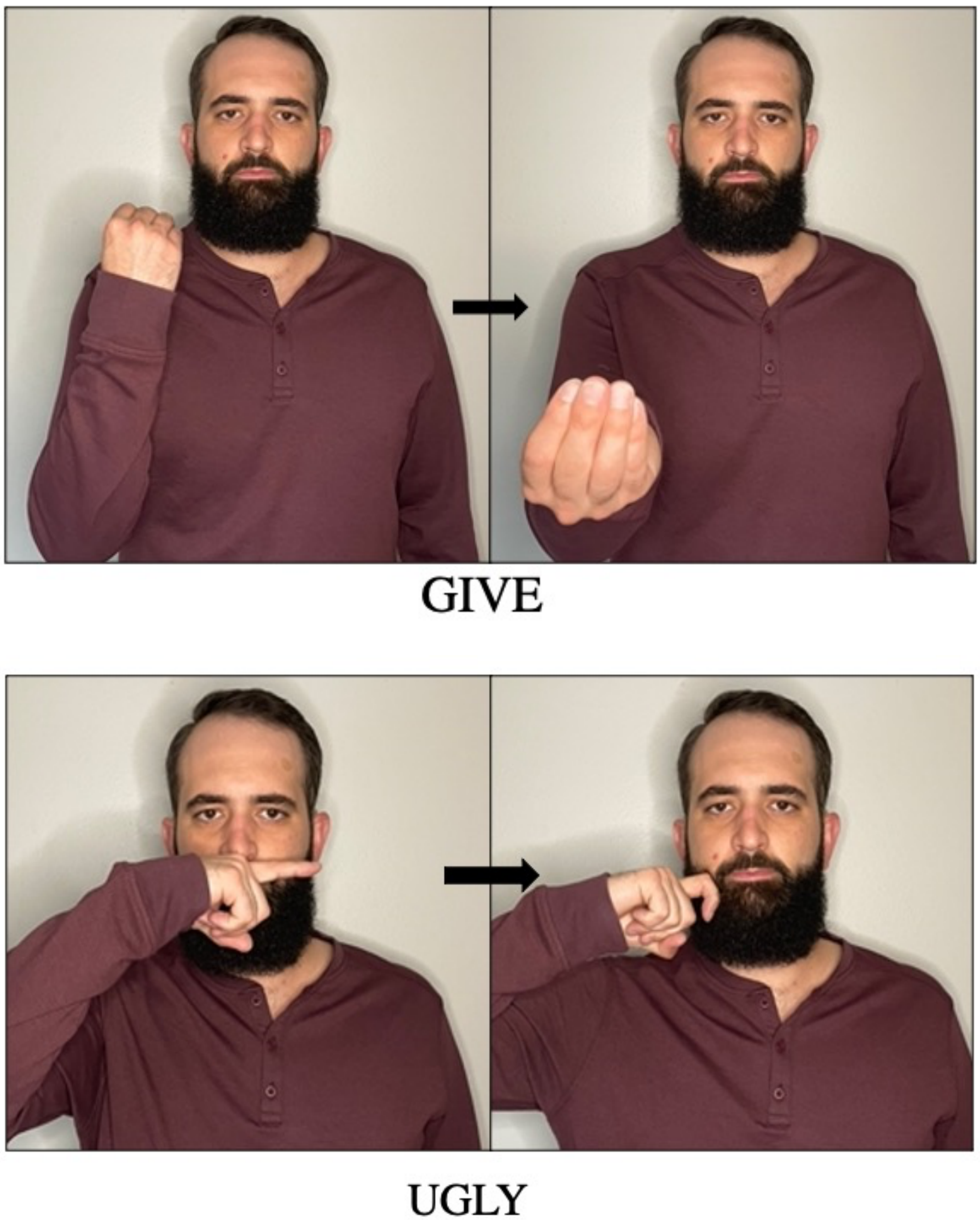


Figure 2.11

Phonologically unrelated ASL signs: GIVE and UGLY



Measures of speechreading ability

In addition to testing ASL and English phonological awareness, I tested speechreading ability of participants via the Test of Child Speechreading (ToCS; Kyle et al., 2013) and a novel speechreading rhyme task developed by the sign language lab at UT Austin with the Booth lab. The ToCS was developed with British English, which may have had an impact on the reliability of this task. British English differs from American English in several ways, including word-final ‘r’ words and realization of diphthongs (Yavas, 2020). This online portal-based task tests speechreading skills at different levels: word level (15 items), sentence level (15 items), and short story (not included in this study). For the Words subtest, participants watched a silent video of a talker (male or female; varied) saying the target word along with an array of 4 pictures. Participants were instructed to select the picture that best matches the silent word, based on the mouthing gestures of the talker. Target word items consisted of 30 different phonemes and 11 different visemes, or visually confusable phonemes that have very similar mouthing gestures (e.g., /p/ and /b/ or /d/ and /t/). Distractor photos were related to the target word in terms of visemic properties, sharing either the same initial or final viseme or the same vowel sound (e.g., *duck, fork,* and *dog*).

In the Sentences subtest, participants watched silent videos of a talker (male or female; varied) and clicked on the corresponding picture (of an array of 4). The distractor photos were developed from erroneous interpretations of each silent video by deaf and hearing adults and children after being asked what had been said by the talker. The rest of the distractors shared features similar to the target, as in the Words subtest.

Following the ToCS, participants completed the speechreading rhyme judgement task developed by the Booth lab at UT[4]. This is a computer-based task designed as a measure of phonological awareness of English mouthing gestures at the rhyme level. Participants were asked to judge whether pairs of silent, 1-second videos showing the face of a talker producing a monosyllabic word are similar or different.

Additional experimental measures

Participants also completed a passive reading paradigm while their eye-movements were recorded. A description of this task and the results will be described in Chapter 3.

Independent measure of reading fluency

Participants completed the Woodcock-Johnson Test of Academic Achievement, Third Edition (WCJ-SRF; Woodcock, McGrew, & Mather, 2001): Silent Reading Fluency as a supplemental measure of reading skill. This measure tests the reading speed and fluency of the test-taker. Participants were handed a test paper and pencil and instructed to silently read as quickly and accurately as possible for 3 minutes. There are 98 possible sentences. At the end of each sentence, test takers indicate whether the sentence was true by marking “yes” or “no” (e.g. ‘all milk is blue’, ‘a bird can fly’). The sentences are ordered from primer to adult. The purpose of this task is to investigate the speed of reading of each child (how many sentences read in 3 minutes) and accuracy of reading (correct responses).

Statistical analysis

Measures of phonological awareness were analyzed via ordinary least squares (OLS) regression with a main effect of group to understand whether these tasks accurately predict the

[4] James Booth and his lab have since left UT Austin for Vanderbilt University.

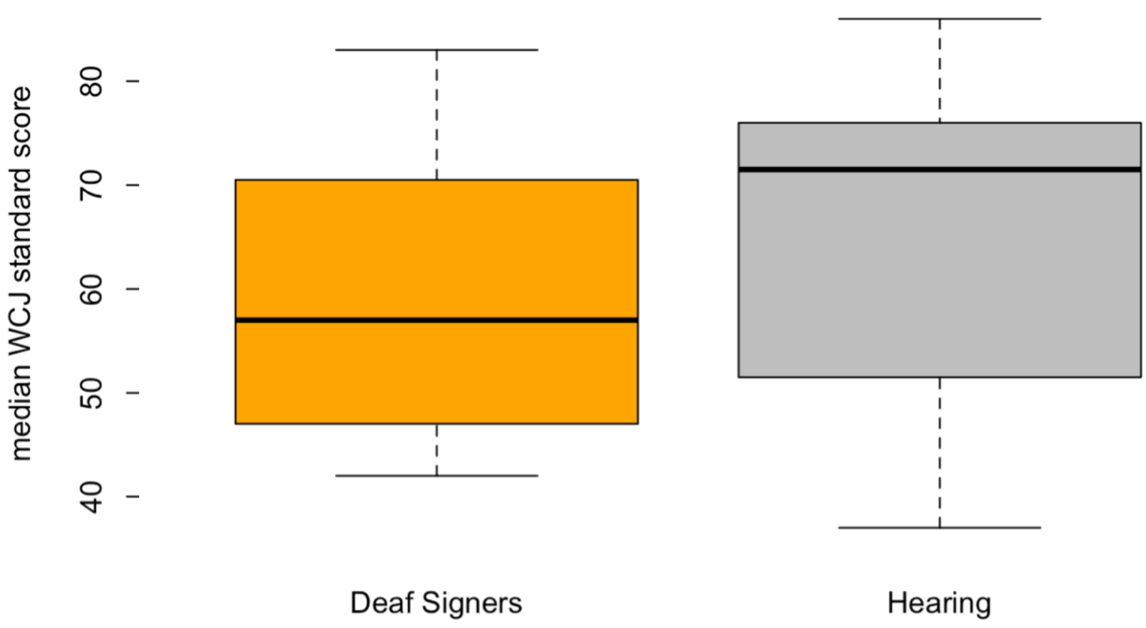
everyday language used by the participant: *%correct ~ group*. Additionally, I report OLS regression models of each task predicting WCJ-SRF standard scores: *%correct ~ WCJIII*.[5]

Results

DHH signers performed at age expectations on WCJ-SRF. The average chronological age of these DHH readers at time of participant was 11 years 7 months, and their average reading age equivalence based on raw scores according to the WCJ-SRF was 12 years 6 months. Additionally, hearing readers performed above expected reading level for their age. While the average chronological age of the hearing sample at the time of participation was 11 years 4 months, their average reading age equivalence on the WCJ-SRF was 17 years 7 months. Further, DHH and hearing readers' standard scores were not significantly different (*p* = 0.31; Figure 2.12).

Figure 2.12

WCJ-SRF standard scores by group



Note: error bars reflect standard deviation

[5] I report significant models here. See Appendix D for all model results.

Measures of English phonological awareness

Table 2.2 summarizes average scores and standard deviations on English phonological awareness tasks by group.

Table 2.2

English phonological awareness scores (percent correct)

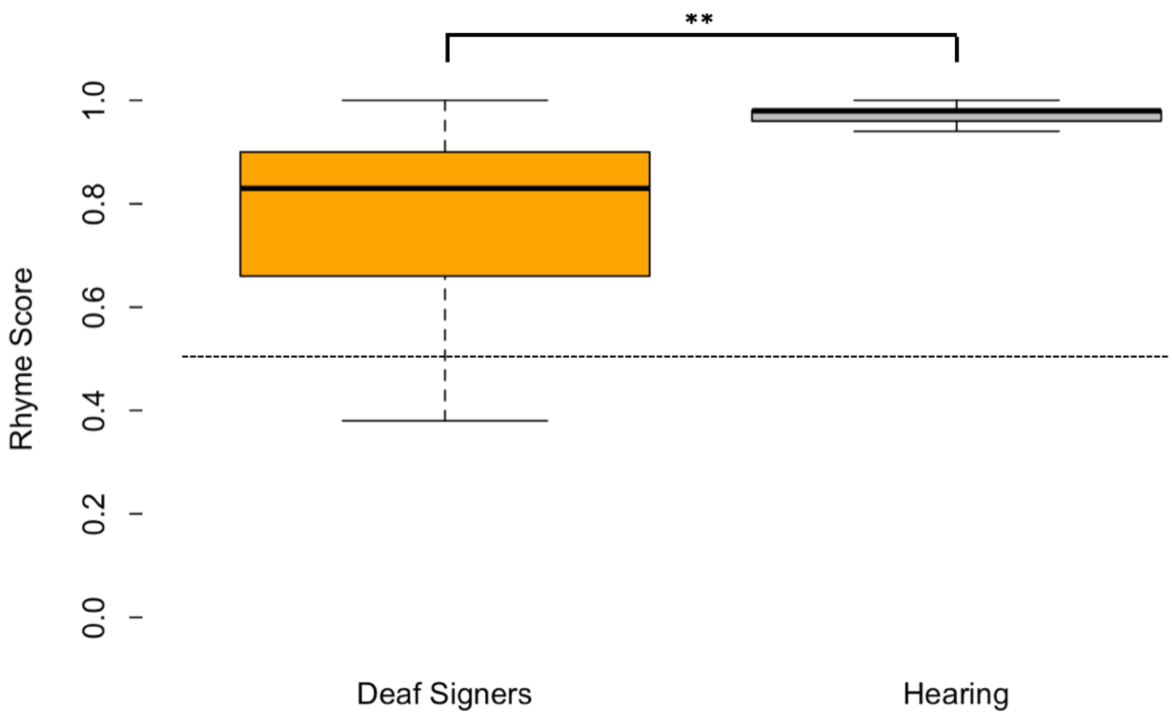
	English Rhyme Judgement	English Syllable Judgement
Deaf	77% (0.19)	67.94% (0.14)
Hearing	97.17 % (0.021)	83.28 (0.096)

English rhyme judgement task results

Hearing participants demonstrated nearly perfect scores on the rhyme awareness task, while DHH signers had a lower average with larger variation (Figure 2.13). An OLS regression indicates that rhyme awareness scores predict group status [F(1, 25) = 19.96, $t = 4.47$, $p < 0.001$); $R^2 = 1.35$, 95% CI [0.73, 1.98]]. Further, rhyme awareness scores predicted participant standard scores on the WCJ-SRF [F(1, 14) = 5.47, t (24) = 2.338, $p < 0.05$; $R^2 = 0.43$, 95% CI = [0.05 - 0.81]].

Figure 2.13

English rhyme judgement scores by group



Note: Significance: $p < 0.01$ = **; the horizontal line reflects 50% performance; error bars reflect standard deviation.

English syllable judgement task results

Hearing participants were more accurate than DHH signers on the syllable judgement task (Figure 2.14; F (1, 22) = 10.25, $t = 3.202$, $p < 0.01$; $R^2 = 1.11$, 95% CI [0.39, 1.83]). Syllable awareness scores did not predict standard scores on the WCJ-SRF ($p = 0.080$).

Figure 2.14

English syllable judgement score by group

Note: Significance: p < 0.01 = **; the horizontal line reflects 50% performance; error bars reflect standard deviation.

Measures of ASL phonological awareness

Table 2.3 summarizes average scores and standard deviations on ASL rhyme judgement task by group as well as average correct responses and standard deviations out of twenty items on the ASL-PA.

Table 2.3

ASL phonological awareness scores

	ASL Rhyme Judgement	ASL-PA (Corina et al. 2014)
Deaf	80.27% (0.068)	13.7 (3)
Hearing	65.33% (0.099)	13.12(3.8)

ASL-PA results

No significant differences between groups on the ASL-PA emerged (p = 0.72; Figure 2.15) and ASL-PA scores did not predict WCJ-SRF standard scores (p = 0.72).

Figure 2.15

ASL-PA scores by group

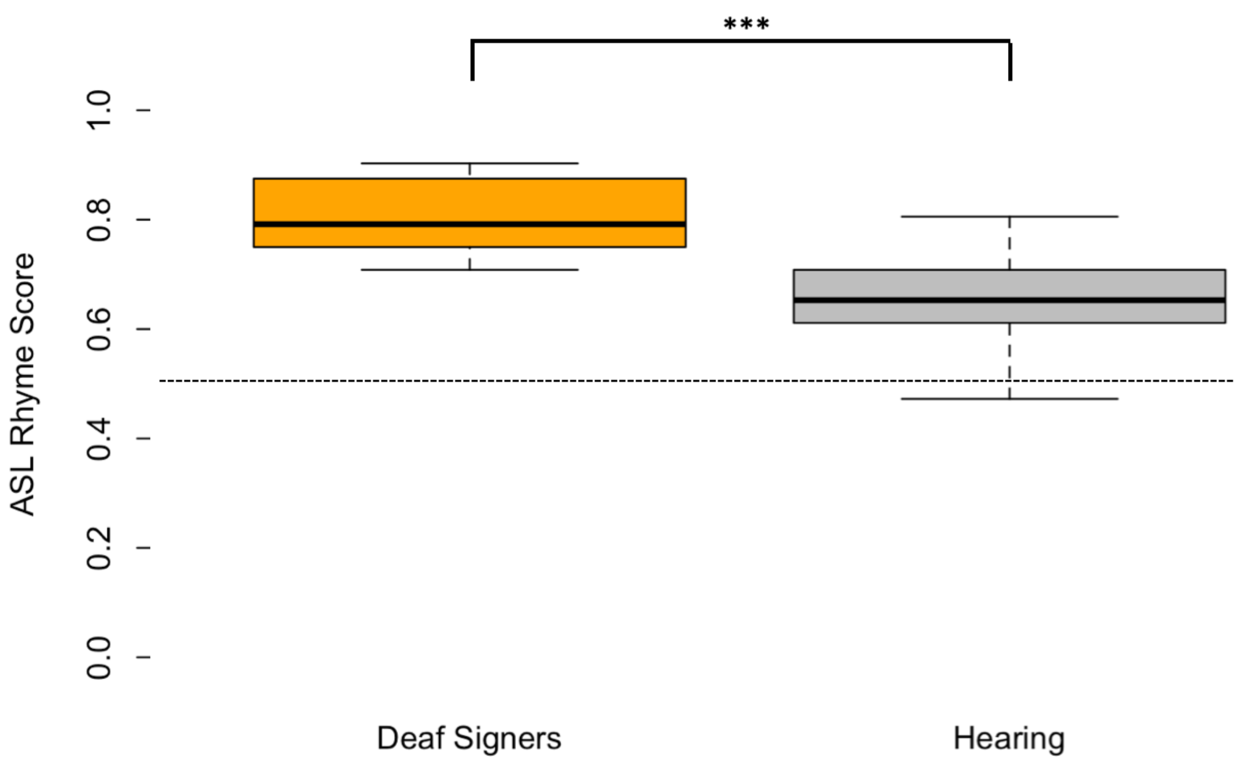
Note: the horizontal line reflects 50% performance; error bars reflect standard deviation.

ASL rhyme judgement task results

The results from the ASL Rhyme Judgement task developed by the sign lab at UT show that the signers in this group significantly outperformed hearing participants (see Figure 2.16). An OLS regression revealed that group predicted scores on this task [F (1, 25) = 17.53, t = -4.187, $p < 0.0001$; $R^2 = -1.3$, 95% CI [-1.95, -0.66]]. However, scores on this task did not predict WCJ-SRF standard scores ($p = 0.91$).

Figure 2.16

ASL rhyme judgement scores by group



Note: Significance: p < 0.001 = ***; the horizontal line reflects 50% performance; error bars reflect standard deviation.

Measures of speechreading ability

No measure of speechreading ability yielded significant results. See Table 2.4 for mean (*SD*) performance.

Table 2.4

Speechreading task results

	Speechreading Rhyme	ToCS: Words	ToCS: Sentences
Deaf:	66% (*5.7%)*	68% (*1.2%)*	44% *(2.4%)*
Hearing:	65% *(7.3%)*	60% *(1.2%)*	41% *(1.9%)*

Discussion

Chapter 2 aimed to understand the relationship between spoken and signed phonological awareness in young DHH signers, as well as the impact of both on reading fluency. Previous studies have demonstrated mixed results regarding the use of speech-based codes in DHH signers (Campbell & Wright, 1988, 1990; Charlier & Leybaert, 2000; Dodd & Hermelin, 1977; Hanson & Fowler, 1987; Hanson & McGarr, 1989; Harris & Beech, 1998; Sterne & Goswami, 2000), and it has been repeatedly theorized that the phonological code developed by early and robust access to sign contributes to reading ability in DHH children (Allen et al., 2009; McQuarrie & Abbott, 2013; McQuarrie & Parrila, 2009; Petitto et al., 2016).

Current results provide evidence in support of my first research question, considering that hearing students outperformed DHH readers on English syllable and rhyme awareness. These findings align with previous investigations indicating that hearing readers are sensitive to the phonological structure of their spoken language (De Loureiro et al., 2004; Ehri, 2014; Stainthorp & Hughes, 1998; Ziegler & Goswami, 2005). Results from measures of English syllable and rhyme awareness followed predictions, as hearing participants demonstrated overall better performance on both English tasks. DHH signers performed above chance on these measures, indicating some degree of sensitivity to speech-based phonology in this sample. The approach to testing speech-based phonological awareness in signers described here relied heavily on visual instruction of tasks and phonological components speech, considering that spoken rhyme and syllable manipulation are less intuitive and practiced for DHH than hearing children. Visual instruction prior to completion of the tasks may have benefitted DHH children's performance on the tasks, perhaps targeting speech-based phonological awareness more accurately.

Mixed results were found pertaining to the relationship between measures of phonological awareness and reading level, as measured by one silent reading fluency task. Scores on the English rhyme judgement task predicted scores on the WCJ-SRF. While no other measure of phonological awareness of either English or ASL predicted reading scores, syllable awareness scores approached significance. It may be the case that with more participants and greater statistical power, this task would ultimately predict group status as the rhyme task does. It is important to note that most investigations of speech-based phonology in DHH signers test the largest phonological units of speech, namely rhyme and syllable. While rhyme awareness is the most studied structure, syllable awareness of DHH readers has also been reported (Campbell & Wright, 1988; Harris & Beech, 1998; McQuarrie & Parrila, 2009; Sterne & Goswami, 2000). Additional investigations into syllable knowledge of both sign and speech will help us speculate on English syllable performance and its relationship to reading in DHH signers.

Interestingly, however, the two groups do not differ in scores on the ASL-PA (Corina et al., 2014). Perhaps the study with adults from by Corina and colleagues might provide some insight about the results of the current study. Corina et al. suggest that this task successfully predicts age of ASL acquisition, selecting native signers as having strongest ASL phonological awareness and late learners of ASL having weaker phonological awareness. When used in the current study, however, this task failed to select signers vs. non-signers. This may be due to the age of the participants in the current study, considering that the original study testing the ASL-PA in adult signers of ASL. Further, this discrepancy could be due to difference in testing practices between studies. Participants who completed the original tasks were able to watch sign videos as often as they wanted, but videos played simultaneously. In this study, while participants were allowed to watch videos as often as needed, videos played independently. This may have resulted in participants' ability to bypass pure linguistic phonological awareness and instead tap visual working memory. The original paper importantly points out that there were no differences in number of times the videos were viewed across participants, and number of presses did not impact ASL-PA scores. For this study, the presentation did not play videos simultaneously and I did not record the number of times that participants viewed each video. This may have an impact on scores, considering that higher cognitive processes such as visual working memory could be tapped instead of pure phonological awareness. In addition, hearing participants received a brief instruction of ASL phonological parameters which may have provided non-signers with enough knowledge of ASL phonology to perform well on the ASL-PA and ASL rhyme judgement task. Finally, it is difficult to assess expected and actual performance for hearing participants as the original study did not report data from hearing non-signers.

Finally, the similar performance between groups on the ASL-PA may be due to visual processing and categorical perception of visual stimuli. Categorical perception of sign language has been attested in non-signers, though the boundary is reportedly less sharp than that of signers due to expertise with the language (Emmorey et al., 2003). The non-signers in this group may have enough sensitivity to visually salient contrasts that they are able to decode unfamiliar visual language.

The DHH signers reported in this chapter read at or above age-expected levels, and hearing readers read above age-expected levels. This discrepancy in hearing and DHH readers' reading age in the current sample may be attributed to factors unrelated to access to speech. The overall SES of hearing readers in this study was greater than that of DHH signers as it relates to the highest degrees attained by parent(s) as well as household income. Children who come from higher SES backgrounds are often stronger readers than lower SES peers, particularly considering maternal education level (Korat, 2009; Reardon, Valentino, & Shores, 2012). I was unable to match DHH and hearing families in this study for SES which may contribute some degree of bias into reported reading levels.

Finally, ASL phonological awareness did not have a clear connection with English reading, particularly regarding the ASL rhyme judgement task. It has been repeatedly theorized that ASL phonological awareness contributes to reading performance of DHH signers (Hrastinski & Wilbur, 2016; McQuarrie & Abbott, 2013; Petitto et al., 2016). Current results do not necessarily support that theory, though this is a low-powered study. Despite this and considering that DHH readers underperformed hearing readers on measures of English phonological awareness, they still performed at expected levels. These findings do not align with previous studies suggesting that ASL and English phonological awareness are reciprocal skills (McQuarrie & Abbott, 2013) and that sublexical ASL knowledge contributes to sublexical English knowledge in DHH signers (Petitto et al., 2016), considering that ASL rhyme scores did not predict reading ability. Further, though ASL rhyme scores are approaching significance when predicting standard scores on the WCJ-SRF, the mechanism underlying the relationship ASL and

English phonological awareness and reading remains unclear. This suggests that other factors other than phonology and phonological awareness of speech or sign may be at play. Further investigations into the processes by which DHH children read are necessary to understand the role of speech knowledge on reading. The next two chapters of the dissertation discuss the role of speech-sounds on reading patterns in DHH students who are primary users of ASL.

Limitations

While this study has provided some degree of evidence surrounding phonological awareness of speech and sign in DHH readers, additional work must be done to further understand the relationship between phonology and reading. Although this study does not specifically address language ability of ASL or English per se, the DHH participants can be considered first language users of ASL considering that they grew up in signing households and attend an ASL-English bilingual school. More detailed reading tasks should be constructed in concert with ASL and English ability measures to understand which aspects of ASL knowledge are applied to the acquisition of print literacy in DHH signers. Additionally, I acknowledge that the current study is underpowered. To fully understand the relative success of the current measures and instructional guides, a larger study will need to take place. I further suggest that later studies should include both DHH signers and non-signers to ascertain the influence of the variety of language exposure experienced by DHH children on phonological awareness and reading skills.

Conclusion

The issue of reading development in DHH children is complex, considering the variability in degree of hearing loss, exposure to speech and sign language, school and language options, and many other factors. The current study concerns itself with the degree to which spoken and signed language awareness predicts reading performance. Current results suggest that while DHH signers have overall lower English phonological awareness compared to hearing peers, they are not significantly delayed in their expected reading level. Further, I suggest that the DHH signers benefit from receiving these visually based definitions of the speech segments being targeted, namely English syllable and rhyme. Unlike hearing children who are likely to have grown up with English-based nursery rhymes and games and thus have a more intuitive understanding of these segments, DHH children receive comparatively less exposure to speech structure. However, this warrants further investigation with a controlled study comparing performance with and without instruction.

Chapter 3: Speech-based phonological recoding during reading

Introduction

In this chapter, I discuss eye-tracking as a mechanism to examine eye-gaze behaviors during passive reading when encountering different error conditions. After an introduction of eye-tracking and a few particularly relevant paradigms, I introduce the homophone foil paradigm. I then briefly discuss visual processing skill and reading for DHH signers. Finally, I discuss the methods and materials, analysis, and results for the study.

Eye-tracking and reading

Eye-tracking is widely used behavioral measurement technique, providing insight into several cognitive processes underlying a variety of tasks, including reading (Rayner et al., 2006). To do so, most eye-trackers utilize infrared technology, which sends undetectable light to refract off the retina and cornea of the participant. The light refracted off the eye is calibrated to and recorded by the computer, allowing for detailed representations of the patterns that eyes perform while reading. Some experiments employ visual world paradigms, in which an array of objects or an artificial scene is presented on a computer screen, gaze-contingent moving window paradigms in which only a certain amount of information is provided outside of the fovea or area of focus (Belanger et al., 2012), and pupil reactivity to indicate stress, detection of a certain stimuli, and decision making (Cavanaugh et al., 2014).

It has been well established that similar groups of readers (e.g., adult readers, new readers, second language readers, etc.) have many eye-movement patterns in common (Ehri, 2014; Rayner, 1998; Rayner et al., 2006). In typical, adult-like reading, the eyes do not make smooth movements across all letters of each word. Instead, they jump from character to character, in movements called saccades, and use information in the periphery to predict the length of the next saccade. When saccade jumps are too long or an error is detected in text, readers often resolve the issue by performing regressive saccades, in which the eyes will jump back to words that had been missed in a previous saccadic movement or back to resolve an error.

Child readers' eye-movement patterns are distinct from adult readers. Early readers fixate longer on each resting point between saccades (>350 ms per fixation), demonstrate as many as 3-4 fixations per word depending on length, and 30% of all saccades are regressive. As reading difficulty increases or individual reading skill decreases, fixation length increases, more regressive saccades will be made proportionally to forward saccades, and forward saccades are shortened. By fourth grade, most typically developing children will perform adult-like eye-movement patterns when reading age-level material (Rayner, 1986; Rayner, 1998; Rayner et al., 2008). The average skilled adult-like reader will jump 7-9 letter spaces per saccade for average reading difficulty material, with 10-15% regressive saccades. Child-like eye-movement patterns with increased number of fixations, fixation durations, and regressions are indicative of disrupted reading or detection of an error (Rayner, 1998; Rayner et al., 2006), and can also point to reading delays or disorders such as dyslexia (Ashby, Rayner, & Clifton, 2005; Chace, Rayner, & Well, 2005).

The homophone foil paradigm

The homophone foil paradigm has been employed in a variety of contexts to target speech-based phonological activation during reading. When employing the homophone foil paradigm, sentences are constructed with a particular target word (e.g., *see*). These words are matched with their homophonic pair (e.g., *sea*) as well as an orthographically similar, non-homophonic pair (e.g., *set*). As such, homophonic errors have congruous phonology as the correct target, but incongruous orthography and semantics, while non-homophonic errors are incongruous in phonology, orthography, and semantics. Consider the following sentence:

Barbara peered out the window to ***see*** *if you were home.*

Readers who engage in phonological recoding are less likely to notice the homophonic error *sea,* as the correct phonological representation /si/ activates correct word meaning in context. Readers who no longer engage in phonological recoding are equally likely to notice a homophonic and non-homophonic error. As such, readers who do perform phonological recoding will be more disrupted by non-homophonic errors than homophonic errors due to correct phonological representation of correct and incorrect homophones. Readers who no longer perform phonological recoding should not present with differences between homophonic and non-homophonic errors, but both should differ significantly from a word that is correct in phonology, orthography, and semantics.

The homophone foil has been used in a variety of applications to understand the impact of homophonic and non-homophonic error words in text on reading behaviors. The original task was developed as a sentence verification task to address how phonology is involved in reading. In Doctor and Coltheart's (1980) study, participants were asked judge sentences and phrases (e.g., *She blew out the candles*) in which certain target words had been replaced by either real homophone pairs (e.g., *blue*), real-word control errors (e.g., *know*), nonword pseudohomophones (e.g., *bloo*), or non-homophonic pseudowords (e.g., *moe*). Results indicated that children ages 6-10 are more likely to accept homophonic and pseudo-homophonic error words than control errors. Several studies subsequently sought to build off the established work of Doctor and Coltheart's work, sparking a series of investigations and methodological improvements on the homophone foil sentence verification task (Colheart et al., 1986; Coltheart et al., 1988; Doctor & Coltheart, 1980; Jared et al., 2016; Johnston, Rugg, & Scott, 1987; Johnston et al., 1995).

Jared and colleagues (2016) used eye-tracking to investigate the role of phonology in the activation of word meanings in Grade 5 readers. In their multi-experiment article, they discuss the homophone foil paradigm of investigating phonological activation during reading and the developmental bypass theory. For their studies, sentence lists were developed, each containing a target word. Target words are either high frequency (HFT) or low frequency (LFT). Non-target words are also controlled for high frequency (HFD) and low frequency (LFD). Each target word (e.g., *see*) was paired with a homophone (e.g., *sea*) and a spelling control (e.g., *set*).

Theoretically, if an individual is reading via the indirect route, 'sea' activates the phonological representation, /si/, which activates word meanings for both 'sea' and 'see'. One prediction is that homophone foils would not cause disfluent reading when in the proper context. Another prediction is that homophone foils would take significantly more time than non-homophonic errors due to the time spent engaging in phonological decoding. Direct route readers who engage in sight-word reading should demonstrate no differences between error conditions, because both 'sea' and 'set' would be immediately recognized as the incorrect word for that position. See Table 3.1 for sample sentences by condition (full sentence list available in Appendix C).

Table 3.1

Example sentences from Jared et al. (2016)

Target word	No-change condition	Homophone foil	Spelling control
which (HFT, LFD)	The team captains decided **which** players they wanted.	The team captains decided **witch** players they wanted.	The team captains decided **whirl** players they wanted.
	David didn't know **which** chocolate bar he wanted.	David didn't know **witch** chocolate bar he wanted.	David didn't know **whirl** chocolate bar he wanted.
	The janitor showed us **which** recycling box is for paper.	The janitor showed us **witch** recycling box is for paper.	The janitor showed us **whirl** recycling box is for paper.
hear (HFT, HFD)	Sandra asked to **hear** her favorite song.	Sandra asked to **here** her favorite song.	Sandra asked to **hair** her favorite song.
	The crowd wanted to **hear** the president speak.	The crowd wanted to **here** the president speak.	The crowd wanted to **hair** the president speak.
	It is hard to **hear** the words of the song.	It is hard to **hair** the words of the song.	It is hard to **here** the words of the song.

Hearing 5th grade readers read 216 sentences in three blocks and were randomized such that each child read each sentence frame in one of each of the three conditions. Participants were all typically developing, average readers, and monolingual speakers of English. Results indicated that non-homophonic errors caused increased fixation durations and regressions for all participants. Homophone errors did cause some increase in fixation duration regressions, but not to the same extend as non-homophonic errors. The authors suggested that these results indicated that these readers were engaging in phonological decoding of print to speech, resulting in some homophonic errors being missed (Jared et al., 2016).

Eye-tracking studies with DHH signing children

Among the few studies of DHH signers that involve sign language narrative viewing (Bosworth & Stone, 2021), visual world paradigms targeting comprehension of sign, speech, and sign-supported speech (Lieberman & Borovsky, 2020; Lieberman, Borovsky, & Mayberry, 2018; Mastrantuono et al., 2017; Szarkowska et al., 2011; Thompson et al., 2006), and comprehension of subtitles during TV viewing (Cambra et al., 2014). Currently, fewer than a handful of publications exist that employ eye-tracking to investigate language use and reading in DHH child signers. These studies employ a variety of methods and approaches, including visual world, moving window, and passive reading paradigms.

Bélanger and colleagues (2018) employed a moving window paradigm with young DHH signers ages 7 – 15 (*M* = 10;9) who were categorized into groups of more- and less-skilled readers based on their performance on the Peabody Individual Achievement Test-Revised (PIAT-R; Markwardt, 1989). For these tasks, a gaze-contingent box allows for only a certain amount of information to be available such that as readers move their eyes across the sentence, the box moves with them. By changing the size of the window, the number of characters or words available outside the fixation point can be manipulated to test the extent to which readers process information at various distances outside of the fixation. Results showed that more skilled young DHH signers read faster than hearing readers as window size increases. The researchers suggest that such readers take greater advantage of their parafoveal vision than their hearing peers, as skilled readers' reading rate and saccade length increased as the window size increased, like adult DHH readers (Bélanger et al. 2015). The authors emphasize that DHH readers performed significantly fewer regressions, but similar overall comprehension scores compared to hearing readers. This suggests DHH signers are not negatively impacted by this behavior.

A similar study employed an invisible boundary paradigm to test the degree to which high-school aged DHH signers (*M* = 18.6, *SD* = 1.8) who are primary users of Chinese Sign Language take advantage of phonological and semantic information in upcoming text (Yan et al., 2015). Target characters were manipulated such that when first presented in a sentence, targets were one of five preview types: identical, orthographically similar, phonologically similar, semantically similar, and unrelated. Participants were instructed to read sentences for comprehension while their eye-movements were recorded. When the reader looked at a fixation point, a sentence would appear beginning at the same location of the fixation point. Sentences initially contained the manipulated character. Once the reader's gaze passed an invisible boundary just before the target, the correct target word replaced the manipulated character. Results indicated that DHH readers were more efficient than hearing readers in their use of semantic information in the parafovea as they demonstrated lower fixation durations after viewing semantically similar preview targets. Within the DHH group alone, more-skilled DHH readers were found to receive a phonological preview benefit, while less-skilled DHH readers did not. The researchers also pointed out that DHH and hearing readers differed in the overall patterns of early- and late-measures of eye-movements, particularly considering gaze duration.

In a later paper, Yan and colleagues (2020) reported eye-tracking data from DHH signers of Chinese Sign Language ages 13.7 – 20 (*M* = 17.37, *SD* = 1.74) when encountering homophonic and non-homophonic errors in text to examine whether DHH readers activate spoken Chinese phonology when reading. Chinese has a deep orthography with inconsistent orthography-phonology mapping (Zhou & Marslen-Wilson, 2000) but hearing readers have been shown to be sensitive to speech-based phonological features when encountering homophonic errors in text (Feng et al., 2001; Zhou et al., 2017). DHH participants were compared to both reading- and chronological-age matched hearing readers. In a sentence verification homophone foil task, participants read sentences that had either a correct target character, an incorrect homophone pair, or an unrelated character. Error detection was measured by first-pass measures of fixation duration as well as second pass measures of regression deployment and second-pass fixation durations. Results indicated that DHH and hearing readers differed in their sensitivity to homophony when reading Chinese. Hearing readers were less disrupted by homophonic errors than by unrelated characters. DHH readers demonstrated the same patterns of error detection when encountering both incorrect targets. The researchers emphasized that, while first-pass measurements did not suggest early phonological activation and recoding or meaningful differences between groups, second-pass measurements patterned differently. Hearing readers spent less time rereading homophonic errors than non-homophonic errors, while DHH readers appeared to treat homophonic and non-homophonic errors in the same way. Upon further analysis of the groups, while all hearing readers demonstrated an impact of homophony, only more-skilled DHH readers were sensitive to phonology. Importantly, reading-age matched hearing readers, who were younger than both the DHH group and the chronological-age matched hearing readers, demonstrate more significant impact of homophony, suggesting that hearing readers of Chinese similarly transition from phonological recoding as a primary strategy to whole-character reading. The authors concluded that hearing readers do not detect some incorrect homophone characters due to phonological recoding during reading. In contrast, DHH readers activate word meaning by orthography and identify both error types equally.

In summary, results from the few studies of eye-gaze behaviors during reading for middle- and high-school-age DHH readers suggest that they differed in reading strategies regarding parafoveal word processing compared to hearing readers (Bélanger et al., 2018; Yan et al., 2015). Additionally, DHH signers did not primarily depend on speech-based codes when resolving errors in text, while hearing readers did (Yan et al., 2020). More highly skilled DHH readers, however, had some degree of speech-based code activation when reading, regarding both parafoveal preview benefit (Yan et al., 2015) and when resolving homophonic and non-homophonic errors in text (Yan et al., 2020), though notably, both studies include older readers. All three studies also demonstrated DHH and hearing readers engage in some eye-movement behaviors differently, particularly considering readers' second encounter with words (Yan et al., 2020; Bélanger et al., 2018).

Visual processing and proposed reading efficiency for DHH readers

Another set of studies has concerned itself with measures of efficiency for DHH readers, rather than whether such readers leverage spoken language phonological codes during reading. In short, DHH readers who use signed language exhibit patterns of reading that could be claimed to be efficient, following certain metrics. According to the Word Processing Efficiency (WPE) Hypothesis, DHH readers use information beyond the fovea (or, focal point) more so than hearing readers, resulting in a greater ability to detect upcoming segments in text and gaining more information from a word in a single fixation than hearing readers. Further, DHH readers have been found to perform overall fewer fixations and longer saccades than hearing readers (Bélanger, Lee, & Schotter, 2018; Bélanger & Rayner, 2015; Costello et al., 2021; Traxler et al., 2021). Researchers who have discussed the WPE theorize that skilled adult DHH readers take advantage of visual information more efficiently than hearing readers, resulting in different reading strategies. Importantly, comprehension does not seem to be negatively impacted by these patterns.

Studies of visual processing by DHH individuals who have experienced early and robust exposure to a signed language have demonstrated a benefit in visual processing compared to hearing individuals. Studies targeting information processes in the parafovea have provided evidence that DHH signers process information in their peripheral vision more so than hearing non-signers for non-linguistic stimuli (Proksch & Bavelier, 2002) and letter and word stimuli (Dye, Baril, & Bavelier, 2007; Sladen et al., 2005; Stevens & Neville, 2006). Interestingly, this pattern is not detected for very basic, low-level visual processing (Bosworth & Dobkins, 1999; 2002a, 2002b; Bross, 1979; Bross & Sauerwein, 1980; Brozinsky & Bavelier, 2004; Finney & Dobkins, 2001; Mills, 1985; Poizner & Tallal, 1987). As a result, it is believed that sensory loss leads to changes in higher-level attention processing, particularly when processing information from multiple senses (Bavelier, Dye, & Hauser, 2006; Bavelier & Neville, 2002; Dye, Hauser, & Bavelier, 2008).

Previous research has also demonstrated an impact of differences in visual processing skills on reading ability for DHH and hearing individuals. Early studies demonstrated that DHH readers depend on a holistic, visual word processing strategy based on word knowledge of ASL and English (Hofsteater, 1959; Kuntz, 1998). Further, considering evidence of increased parafoveal processing in DHH readers, they could be expected to have stronger effects from written information outside of the focal point (Kennedy & Pynte, 2005). Subsequently, several theories have been advanced suggesting that DHH signers process word information outside of their fovea when reading, potentially further distancing their reading strategies from those of hearing individuals.

Bélanger and Rayner (2015) provided support for the WPE hypothesis by employing a moving window paradigm to assess reading rates of skilled vs. less skilled adult DHH readers.

By manipulating the amount of information available to the reader in their parafoveal vision, the authors showed that both skilled DHH and hearing readers' reading speed steadily increased as window size increased from 6-14 available characters, but only the skilled DHH readers demonstrated an increase in reading speed beyond 14 available characters. The authors suggested that DHH signers are more skilled at processing linguistic information beyond the fovea and benefit from the additional available information more so than hearing readers do.

DHH child signers have also been reported to use their peripheral vision to benefit their reading speed in a way that differs from hearing children (Bélanger, Lee, & Schotter, 2018; Costello et al., 2021; Villwock et al., 2021; Yan et al., 2015), even very early in the reading reading-development process (Bélanger, Lee, & Schotter, 2018). Bélanger and colleagues (2018) employed the moving window paradigm with young DHH readers were divided into poor vs. skilled readers. DHH and hearing children read multiple sentences with varying numbers of words/characters available beyond the fovea. As window size increased, the numbers of characters available in the parafoveal vision increased. Results showed that highly skilled young DHH readers demonstrate faster reading speed than hearing participants as window size increases. This study revealed that DHH early readers, much like adult DHH readers, take greater advantage of their parafoveal vision than their hearing peers, as skilled readers' reading rate increased as the window size increased.

Another version of the homophone foil paradigm was recently employed with DHH signers who primarily use Chinese Sign Language to target semantic and phonological parafoveal preview. This same pattern was replicated in more- and less-skilled DHH high school readers of Chinese who primarily use Chinese Sign Language (Yan et al., 2015). By manipulating available information in the parafoveal view to be orthographically, semantically, or phonologically related, experimenters were able to demonstrate that DHH readers are more efficient in their use of semantic information in upcoming text than hearing readers. Further, upon analysis of the DHH group alone, more-skilled DHH readers were found to receive a phonological preview benefit, while less-skilled DHH readers did not.

DHH signers also reportedly demonstrate higher rates of word-skipping. In a recent eye-tracking study, Traxler and colleagues (2021) compared word-skipping rates and overall reading comprehension of DHH signing college students to hearing monolingual English students as well as hearing bilinguals of English and Chinese. Results demonstrated increased rates of skipping in the DHH group. Further, while DHH readers' overall reading comprehension was lower than monolingual peers, their performance was similar to that of Chinese-English bilingual students. Results provide further support for the word processing efficiency hypothesis. While study participants were college-aged students who had fully acquired print literacy, these results emphasize that DHH signers are bilingual second language users of English who will pattern differently compared to monolingual readers.

Single word reading and lexical decision tasks have demonstrated shorter response times in DHH signers than hearing readers, without a negative impact on accuracy. Fariña and colleagues (2015, 2020) developed two lexical decision tasks to differentiate between the influence of orthography and speech-based phonology on lexical access of a shallow orthography (written Spanish) in deaf and hearing children: a phonological coding task and an orthographic coding task. Results indicated that DHH signers were significantly faster in response times than hearing readers. Further, no difference between accuracy was found between groups, suggesting that both groups are sensitive to orthographic manipulations. The authors concluded that deaf signers are not sensitive to speech-based cues, unlike their hearing peers.

Previous studies have demonstrated meaningful differences between DHH and hearing readers. DHH adults reportedly take advantage of more information in their parafoveal vision than hearing readers do (Dye, Hauser, & Bavelier, 2008) resulting in increased reading patterns (Bélanger et al., 2012; Bélanger & Rayner, 2015; Costello et al., 2011; Fariña et al., 2017; Traxler et al., 2021). However, currently lacking in the literature is an investigation of the eye-movement patterns and reading strategies of young DHH signers of ASL when encountering homophonic and non-homophonic errors in text. I aim to fill a small portion of that literature by leveraging eye-tracking and a version of the homophone foil paradigm (Jared et al., 2016; Yan et al., 2015; Yan et al., 2020) to address the impact of speech-based homophony on error detection for DHH readers ages 10 – 13. I provide additional data for evaluating the claim of activation of speech-based phonology during online reading in DHH child signers.

Research questions

1: Do eye-movement patterns in young DHH signers and hearing non-signers demonstrate similar patterns of sensitivity to speech-based phonology in text?

2: Do eye-movement patterns in young DHH signers and hearing readers demonstrate similarly efficient reading patterns?

I expect to see an impact of homophonic error words on reading patterns in hearing readers (Ehri, 2014; Jared et al., 2016). Specifically, I expect to see longer fixation durations on non-homophonic error words for hearing readers as well as increased probability of hearing readers to fixate on or deploy a regression back to non-homophonic error words as compared to homophonic error words. I further expect that while non-homophonic error words will be more disruptive to hearing readers than homophonic error words, such readers will still demonstrate increased fixation durations and regression deployment to homophonic errors than correct target words. This would suggest that some homophonic errors are not noticed when read in context, providing evidence that hearing children of this age are still engaging in some degree of phonological recoding when reading.

I suggest that DHH signers might not demonstrate the same impact of speech-based phonology on reading as hearing readers. I do expect to see increased fixation and regression probability, as well as lower rereading time when encountering errors as compared to correct targets. I do not, however, expect to see differences in these measures when encountering both homophonic and non-homophonic error words. This pattern would suggest that DHH signers are treating homophonic and non-homophonic error words the same way and are thus sensitive to the spelling (and meaning) of the target word, not its phonological representation (Belanger et al., 2012; Costello et al., 2021; Emmorey & Lee, 2021; Glezer et al., 2018; Guitierrez-Sigut et al., 2019). Alternatively, if I do see the same pattern of increased fixation/regression probability and fixation duration on non-homophonic errors as homophonic errors, DHH signers may treat error conditions differently.

I expect to see evidence of increased reading efficiency in DHH signers in comparison with hearing non-signers. Adult signers of ASL demonstrate a greater perceptual span than hearing readers, benefitting their reading efficiency, and increasing the amount of information gained by a single fixation. Further, adult DHH readers have been shown to perform more word-skipping as well as fewer regressions without impacting comprehension (Belanger et al., 2012; Belanger et al., 2018). Though this pattern may not be as robust for young DHH readers, studies have shown fewer regressions and more instances of word-skipping in DHH readers (Bélanger et al., 2012; Bélanger & Rayner, 2015; Bélanger et al., 2018; Yan et al., 2015).

Methods

Participants

Participants are the same as reported in Chapter 2. Seventeen hearing children (3 female; mean age 11;3, 10-12;9) and 10 DHH children (9 female; mean age 11;6; 10-13) participated in the study. DHH participants all attended a bimodal bilingual residential school for the deaf at the time of data collection and throughout early childhood. Exclusion criteria for DHH participants required that they either have acquired ASL from Deaf parents or report using ASL only at school and at home with family. Though I did not exclude participants based on hearing aids, none of the DHH participants use cochlear implants. Exclusion criteria for hearing participants required that they be monolingual speakers of English at home and at school. Exclusion criteria regardless of hearing status required all participants to be typically developing with no report of learning delay or disability and have normal or corrected-to-normal vision. More detail about the participants in this sample can be found in Chapter 2, section 2.3.1.

Eye-tracking and the homophone foil paradigm

Participants completed a version of the homophone foil paradigm described in the first section of the introduction on an eye-tracker. All eye-tracking data were collected via EyeLink 1000 or Portable EyeLink Duo, at 1000 Hz sampling rate. Viewing of the sentences was binocular, but only data from the right eye were analyzed and reported. Prior to the calibration process, participants were instructed to read each sentence naturally and for meaning and to place their chin on a chin and forehead rest such that their eyes were approximately 60cm from the center of the display monitor. Text was presented in 12-point Courier New (0º, 100’, 275”). A horizontal 3-point calibration was continually checked and repeated to ensure accurate data capture. Any time a participant moved their head substantially, calibration was completed again.

Trials were initiated by the participant's fixation on a gaze-contingent trigger, prompting a sentence to appear. Stimuli were presented such that the first character of the sentence appeared in the exact spot as the trigger to ensure the reader began reading the sentence at the first word of the sentence. Sentences contain target words in one of three experimental conditions: correct, homophonic error, and non-homophonic error (from Experiment Three, Jared et al. (2016); Table 3.1). Correct targets and both homophonic and non-homophonic errors were initially controlled for high vs. low frequency such that all pairs were equally distributed between 1.) High frequency correct target vs high frequency error foils; 2.) High frequency correct target vs low frequency foils; 3.) Low frequency correct targets vs. high frequency error foils; and 4.) Low frequency correct targets vs. low frequency error foils. Participants read the same sentence frames, with three possible conditions of target words for each sentence. Each child read up to a total of 108 experimental sentences, broken down into three blocks of 36 sentences, randomized to each condition with filler control sentences throughout. Due to the degree of fatigue associated with the task, four DHH participants and nine hearing participants only completed two scripts, and an additional two DHH participants only completed one of the three possible blocks. Participants were randomly assigned to start with one of the three possible blocks to ensure counterbalancing of stimuli. In addition, following approximately every fourth sentences, YES or NO comprehension questions were asked about the previous sentence to ensure participants read sentences for meaning.

Eye-movement measurements chosen for analysis

I analyzed four specific eye-movement measurements: two measurements that represent the reader's first encounter with the word, and two measurements that represent the reader's second encounter with the word if reassessment or clarification is required. I report the likelihood that a reader fixates on the target word (first fixation probability), as well as the duration of the first fixation (first single fixation duration), if it occurs. Readers do not fixate on all words when reading, but perform saccadic jumps from word to word, skipping expected words, high frequency words, and function words. Increased fixation probability indicates that the reader requires attention on that word due to an error or increased word length (Rayner, 1998; Rayner et al., 2006; Traxler et al., 2021). First single fixation duration provides a metric of how much time the reader requires to activate the word meaning before moving on from the word. Increased time spent reading a word can indicate phonological recoding (Costello et al., 2021) or the need to resolve an error (Rayner et al., 2006; Rayner, 1998). I expected to see increased fixation probability and increased first fixation duration on error words compared to correct words for all readers. I further expected increased fixation probability and duration on non-homophonic error words than homophonic error words for hearing readers, indicating phonological recoding.

I also analyzed the likelihood of a reader to regress back to the target word (regression probability), as well as the amount of time the reader spends fixating on the target during the triggered regression (rereading time). Readers often need to move back in text to resolve errors or misunderstood text and regress to the issue to resolve it (Rayner, 1998; Rayner et al., 2006). If a regression is indeed deployed, the amount of time spent rereading the word can indicate phonological recoding if the fixation is long (Costello et al., 2021) or the amount of time needed to resolve an error (Rayner, 1998; Rayner et al., 2006). I predicted that all participants would demonstrate increased regression probability for error words. Hearing readers will likely regress more often to non-homophonic errors than homophonic errors, indicating an effect of homophony. I further expected DHH readers will perform fewer regressions overall (Belanger et al., 2018; Yan et al., 2015), as well as no difference in regression deployment for homophonic and non-homophonic errors. Finally, I expected increased rereading time for non-homophonic errors than homophonic errors for hearing readers, indicating that the error is resolved with the activation of correct word phonology (Jared et al., 2016). I do not expect the same pattern in DHH signers (Li & Lim, 2020).

Data processing

Eye-movement behaviors were recorded, cleaned, and analyzed via the eye-tracking software suite from the University of Massachusetts, Amherst Eye-Tracking Lab. Eye-movements are recorded by EyeTrack and exported as EyeLink data files (EDFs). EDFs were cleaned and compiled for analysis using Robodoc, and EyeDry was employed to extract reports regarding specific measurements for analysis.

To begin, all within-subject outliers (e.g., data points that fall beyond +/- 3 SD from each participant's mean) for single fixation duration and rereading time measurements were filtered out, resulting in 3.44% of single fixation duration data points being removed and 5.43% of rereading time data points being removed. I report the raw means (*SD*) of each measurement by group.

Statistical analysis

All data were analyzed via "lmer" for continuous outcome and "glmer" for categorical outcome mixed-effects models from the lme4 package in R (Bates, Mächler, Bolker, and Walker, 2015) with a Tukey p-value adjustment to account for the issue of multiple analyses conducted. To test fixed effects, I employed mixed-effect models to understand the degree to which DHH and hearing readers were impacted by sentence conditions in probability of fixating on the target (i.e., "FIX"; categorial variable), first single fixation duration (i.e., "SFD", continuous variable), rereading time (i.e., “RRD”, continuous variable), and probability of regressing back to target (i.e., “REG”, categorial variable). Considering the issue of multiple samples per participant and the violation of the assumption of independence, the random effect of subject is included in all models. Fixed effects models for each group were created and model equations were as follows:

outcome ~ sentence type (reference level = ‘correct’) + (1|subject ID) + (1|trial)

In addition to fixed effects, I employed Helmert contrasts, a sum-to-zero contrast that compares the mean of each level to the mean of the subsequent level (Sundstrom, 2010). Sentence condition factors were ordered (1) homophonic error, (2) non-homophonic error, and (3) correct target. As such, contrast 1 in my sentence condition model reports the impact of error conditions compared to the correct condition target words (factor one compared to two and three) and indicates whether error conditions are noticed by the readers, while contrast 2 reports the contrasts between homophonic and non-homophonic error words and indicates the impact of homophony on noticing errors (factor two compared to factor three). Helmert model equations were as follows:

*outcome ~ group*contrasts 1 & 2 + (1|subject ID) + (1|trial)*

For the purposes of the dissertation, I report significant fixed effects as well as significant effects with Helmert contrasts.[6]

Analysis of comprehension question responses varied between groups. Considering both groups together, participants’ responses were 84.92% correct, with DHH signers’ responses 75.80% (*SD* = 0.44) correct and hearing participants’ responses 88.94% (*SD* = 0.31) correct. Hearing readers responded to comprehension questions correctly more often than DHH readers did (t (404.91) = -5.2198, $p < 0.0001$).

[6] All model statistics can be found in Appendix D.

Results

Homophone foil passive reading paradigm results

See Table 3.2 for means (*SD*) for reported measurements by group and word condition.

Table 3.2

Eye-movement measurements on target words by group and sentence condition

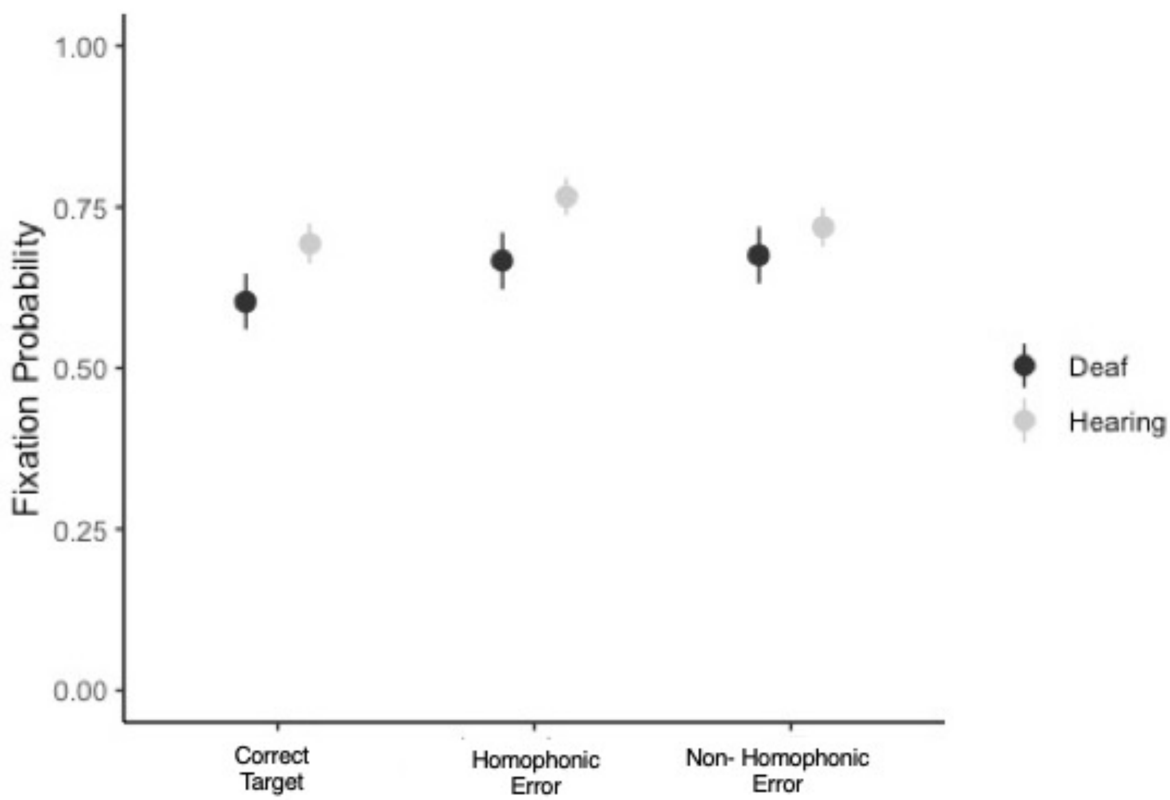
Single fixation duration (ms)	Correct	Homophone error	Spelling control
DHH	229.15 (65)	247.95 (65)	225.14 (59)
Hearing	232.1 (75)	246.39 (76)	233.19 (66)
First Fixation Probability	**Correct**	**Homophone error**	**Spelling control**
DHH	0.60 (0.49)	0.67 (0.47)	0.68 (0.46)
Hearing	0.69 (0.46)	0.77 (0.42)	0.72 (0.45)
Rereading time (ms)	**Correct**	**Homophone error**	**Spelling control**
DHH	348.48 (229)	509.86 (404)	506.68 (603)
Hearing	372.46 (258)	472.62 (472)	569.41 (376)
Regression Probability	**Correct**	**Homophone error**	**Spelling control**
DHH	0.19 (0.39)	0.32 (0.47	0.33 (0.47)
Hearing	0.24 (0.43)	0.43 (0.5)	0.55 (0.5)

Probability of fixating on target during first pass

Groups did not differ overall when first fixating on target words. Hearing readers did not demonstrate any significant fixed effects of sentence condition on their first fixation probability. DHH readers, however, were more likely to fixate on non-homophonic errors than both correct and homophonic errors ($z = 2.01$, $p = 0.044$; $R^2 = 0.52$, 95% CI: [0.01, 1.03]). No significant contrasts emerged when Helmert contrasts were employed. See Figure 3.1.

Figure 3.1

Probability of fixating on target word

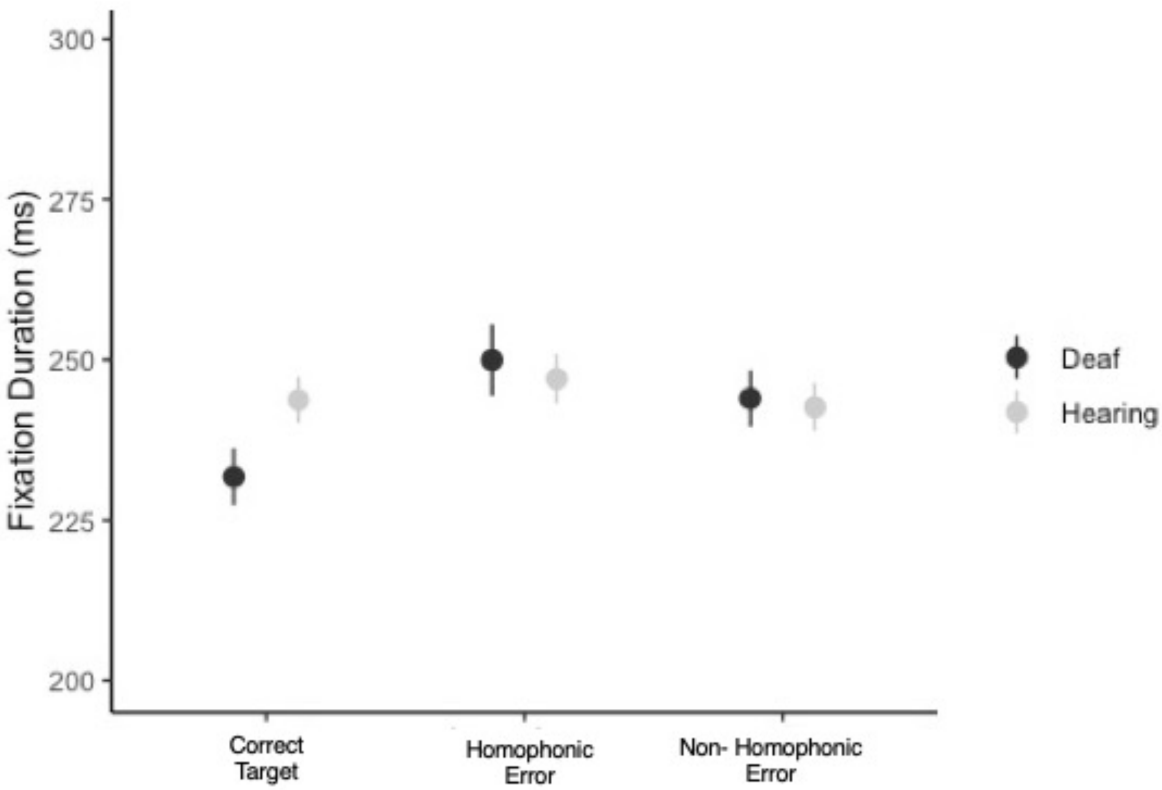


First single fixation duration

No fixed effects emerged DHH or hearing readers in the model predicting first single fixation duration. Models with Helmert contrasts did not yield significant results and groups did not differ. See Figure 3.2.

Figure 3.2

First single fixation duration



Note: Significance: p < 0.05 = *; p < 0.01 = **; p < 0.001 = ***

Probability of regressing back to target

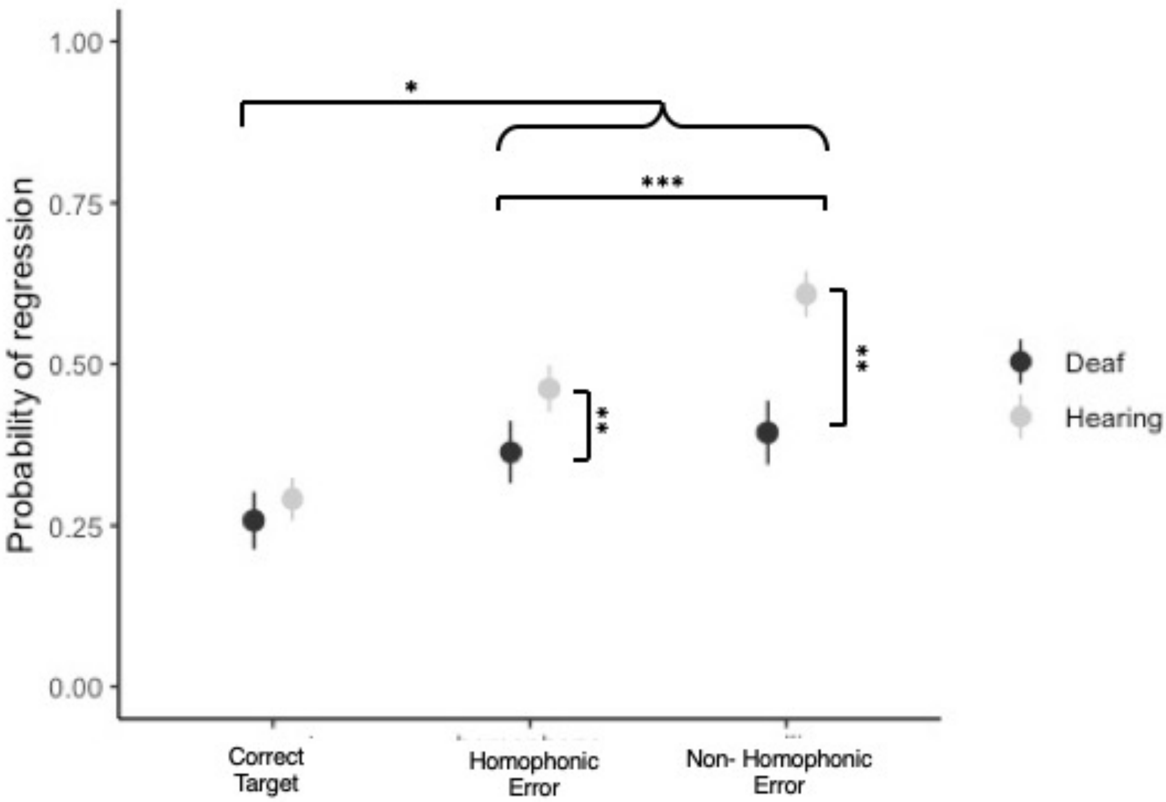
A significant main effect of group emerged (z = -2.42, $p < 0.05$; R^2 = -0.27, 95% CI: [-0.49, -0.05]). Both groups were more likely to regress back to both homophonic (z = 4.56, $p <$ 0.0001; R^2 = 0.79, 95% CI: [0.44, 1.13]) and non-homophonic error targets (z = 6.7, $p < 0.0001$; R^2 = 1.14, 95% CI: [0.8, 1.49])

Both contrasts of sentence type emerged as significant regarding probability of performing a regression back to target for hearing readers (Contrast 1: z = -5.84, $p < 0.0001$; R^2 = -1.09; 95% CI: [-1.45, -0.72]); Contrast 2: z = 2.51, $p < 0.05$; R^2 = 0.5, 95% CI: [0.11, 0.89]).

Contrast 1 emerged as significant for DHH readers (z = -5.84, $p < 0.0001$; R^2 = -0.74, 95% CI: [-1.28, -0.21]), but contrast 2 did not.

Figure 3.3

Probability of performing a regression back to trial



Note: Significance; p < 0.08 = †; p < 0.05 = *; p < 0.01 = **; p < 0.001 = ***

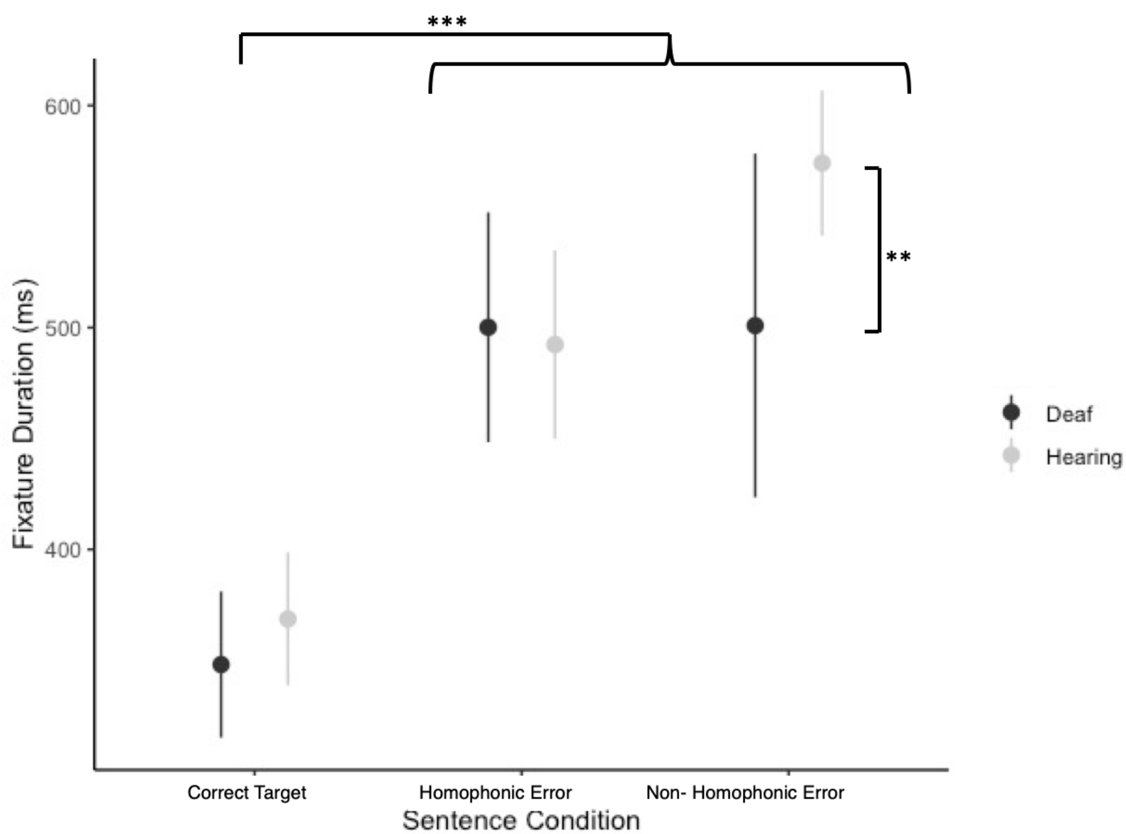
Target word rereading time

Groups did not differ overall regarding rereading time. DHH readers did not demonstrate any significant fixed effects. Hearing readers did demonstrate significant differences in rereading time when encountering homophonic (t (326.78) = 2.04, $p < 0.05$; R^2 = 0.3, 95% CI: [0.01, 0.58]) and non-homophonic error targets (t (324.43) = 3.68, $p < 0.01$; $R2$ = 0.51, 95% CI: [0.24, -0.78]) compared to correct targets.

DHH readers did not demonstrate significant Helmert contrasts regarding rereading time. Hearing readers demonstrated a significant effect of Contrast 1 (t (325.54) = -3.15, $p < 0.001$; R^2 = -0.4, 95% CI = [-0.65, -0.15]) but not Contrast 2.

Figure 3.4

Target word rereading tim



Note: Significance; p < 0.05 = *; p < 0.01 = **; p < 0.0001 = ***

Discussion

This study examined whether DHH adolescent signers of ASL leverage spoken English phonology during silent reading. I reported data from nine DHH signers who attend an ASL-English school, as well as fourteen hearing monolingual students, ages 10-13. An eye-tracking protocol was adopted along with a homophone foil paradigm to test the degree to which the participants engage in speech-based phonological activation when reading. The homophone foil paradigm I used is a silent reading task that manipulates target words in sentences to examine phonological recoding of text. Previous studies have shown that young hearing readers are less disrupted in reading by homophonic errors than by non-homophonic errors (Doctor & Coltheart, 1980; Jared et al., 2016; Johnston et al., 1995). Skilled adult readers, however, do not demonstrate differences in reading patterns between homophonic and non-homophonic errors, suggesting that hearing readers begin reading by engaging in phonological recoding of print to speech, which is later replaced by faster, sight-word reading (Ehri, 2014; Jared et al., 2016; Pennington et al., 1987; Share, 2005).

First fixation probability and single fixation duration data, which describe a reader's first encounter with the target, did not follow predictions regarding differences in activation of speech-based phonology between groups. Results from regression models do not suggest significant differences between DHH and hearing readers' first fixation probability or first single fixation duration. However, when considering mean differences, hearing readers are more likely to fixate on homophonic errors than either correct or non-homophonic error targets, while DHH readers demonstrate similar, increased fixation probability on error words as compared to correct words. This suggests that hearing readers are treating homophonic errors differently than non-homophonic errors when deploying initial fixations, while DHH readers do not. When considering first single fixation duration, both hearing and DHH readers spend more time fixating on homophonic error targets than correct or non-homophonic targets.

Second pass measurements of regression probability and rereading time follow predictions regarding group differences in activation of speech-based codes as well as reading efficiency. I reported a main effect of group in regression probability, demonstrating that DHH signers regress less frequently than hearing readers. I suggest this finding supports the WPE as

DHH signers depend less on regressions as a reading strategy than hearing readers (Bélanger & Rayner, 2015; Bélanger et al., 2018; Traxler et al., 2021). Further, main effects of both sentence type contrasts were found, suggesting that participants are more likely to regress back to the target word if it has an error. The second contrast further indicates that readers treat homophonic and non-homophonic error targets differently when deploying regressions. When considering both the main effect of group as well as significant differences for both contrasts 1 and 2, DHH signers *do not* have a difference in probability of regressing back to both error targets while hearing readers *do*.

Rereading time further suggests that hearing readers are influenced by homophony while DHH readers are not. I found a significant effect of contrast 2 on rereading time on target words, suggesting that all readers spend different amounts of time re-fixating homophonic and non-homophonic error words. DHH readers spend less time rereading non-homophonic errors than hearing readers. In addition, hearing readers spend more time rereading non-homophonic errors than homophonic errors, while DHH readers do not differ in the amount of time rereading error types. These results suggest that hearing readers are engaging in phonological recoding as they spend longer rereading non-homophonic errors than homophonic errors. DHH signers, however, do not demonstrate an influence of homophony in rereading time.

Considered together, there were ways in which DHH and hearing readers performed similarly and ways that they differed. Neither group demonstrated an effect of homophony nor evidence of error detection during their first encounter with a word. Further, the groups did not differ overall for first-pass measures as there was no significant effect of group in first fixation duration and probability of first fixation. However, results suggest that both groups were sensitive to errors in text during their second encounter with target words, including measures for rereading time and regression deployment. Further, a main effect of group indicates that DHH readers performed fewer regressions overall compared to hearing readers.

Regression data suggest that the two groups treat error words differently in second-pass measures. Both contrasts were significant for hearing readers indicating that homophonic error words caused less disruption than non-homophonic error words. Only contrast one (correct targets vs. error-word targets) was significant indicating that homophonic and non-homophonic error words were treated similarly by DHH readers.

Taken together, the current results are mixed. DHH readers in this study deployed fewer regressions than hearing readers when resolving errors in text, which supports findings by Bélanger et al. (2018). The two groups did not differ in measurements of their first encounter with target words, but they did differ on their second encounter. This pattern aligns with two of the handful of previous eye-tracking studies with young, signing DHH readers. Yan and colleagues (2020) reported that DHH and hearing readers performed similarly in first-pass measurements, but the same could not be said for second-pass measurements. These studies also found that neither group demonstrated phonological influences in first pass measurements. Previous studies of reading have shown that child DHH signers fixate for less time and deploy fewer regressions than hearing non-signers (Bélanger et al., 2018). I suggest that further investigations into the relationship between first- and second-pass eye-movement behaviors when detecting errors in text is warranted, for both DHH and hearing readers.

In addition to eye-tracking measures, I reported the results of comprehension questions across group. Groups differed on this result, though the effect size was relatively low (R^2 = -0.15). This result deviates from Bélanger et al. (2018), as their data did not reflect comprehension differences between DHH and hearing groups. It is important to note that

Bélanger's work tested parafoveal processing using a moving window paradigm while the current study leverages a homophone foil paradigm to test error detection and homophony without a moving window. In the homophone foil paradigm, measurements of target words that are correct or incorrect are the focus, whereas in the moving window paradigm, no error words were introduced. I wonder whether the difference in comprehension question performance across the two studies may be due, at least in part, to the existence of error words in sentences and their effect on comprehension question responses. Perhaps DHH readers are not resolving errors in text in the same way that hearing readers do. This warrants further investigation.

Another factor that I speculate had an impact on comprehension scores is differences in SES metrics across group. The overall SES of the families of hearing readers was greater than that of DHH signers as it relates to the highest degrees attained by parent(s) as well as household income. Children who come from higher SES backgrounds are often stronger readers than lower SES peers, particularly maternal education level (Reardon, Valentino, & Shores, 2012; Korat, 2009). Unfortunately, I was unable to match DHH and hearing families in this study for SES.

Overall, the results from the current study do not provide strong evidence for phonological recoding of print to speech by DHH readers. Further, groups demonstrated differences in reading strategies when resolving errors in text, particularly considering regression deployment. I suggest that these findings in conjunction with age-appropriate reading levels for DHH signers do not provide evidence in support of the QSH (Paul, 2001, 2008; Paul & Lee, 2010; Wang et al., 2008).

A notable result is that the DHH readers in this study, who were all primary users of sign language and who grew up in signing households, were not age-delayed in reading fluency. Despite previous data suggesting that DHH signing children are likely to be age-delayed in reading acquisition and achieve overall lower reading success (Easterbrooks & Beal-Alvarez, 2012; Paul, 2001), many scholars and educators suggest that early and robust exposure of a signed language for young deaf children is optimal for literacy development (Allen et al., 2009; Hrastinski & Wilbur, 2016; McQuarrie & Parrila, 2009; Petitto et al., 2016; Stone et al., 2015). Though I do not directly test language ability in this study, I speculate that age-appropriate reading levels in this group are due, at least in part to the fact that DHH participants are first-language users of ASL, having acquired the language in signing households and at ASL-English schools. The relationship between sign language ability and reading proficiency requires additional investigation.

Limitations

There are various limitations of this study that I would like to highlight, which could help to contextualize my results and provide important information to colleagues who wish to replicate this work. First, I acknowledge that statistical power is low due to a small number of participants. This is an unfortunate but common trend in behavioral studies with DHH populations. Future studies with greater resources should include a larger sample size. I was unable to match DHH and hearing readers for reading level or socioeconomic status. I did not control for degree of hearing loss, only everyday language of participants. This is an important covariate that should be considered in future studies. A larger sample size of hearing and DHH families might allow for more matching of groups. Finally, I did not control for the variability in the number of items completed per participant, and several participants were unable to complete all eye-tracking stimuli. The task may have been overall too fatiguing for this group and a shorter paradigm may have resulted in more participants completing all items for all tasks.

Conclusion

I leveraged a homophone foil paradigm to examine the degree to which DHH and hearing readers ages 10-13 engage in phonological recoding of print to speech. All DHH participants were exposed to ASL from birth, grew up in signing households, and attended an ASL-English bilingual school. Signers in this group were not age-delayed in their expected reading levels. While sample sizes are small, my results suggest that DHH readers who are ASL-English bilinguals employ second pass reading strategies that are different than those of hearing readers. DHH signers performed fewer regressions than hearing readers and did not demonstrate evidence of phonological recoding of print to speech. These results align with several recent publications that suggest differences in how DHH signers engage with print. To my knowledge, this is the first eye-tracking investigation of child DHH signers in the US involving the homophone foil paradigm to target phonological activation of spoken English. I hope that additional studies in this area will continue to provide insights about reading behaviors and reading development in DHH children who use a signed language for everyday communication.

Chapter 4: Phonological and orthographic processing during single-word reading

Introduction

In Chapter 4, I discuss the role of spelling and orthographic knowledge on reading in DHH signers ages 10 – 13. Due to the COVID19 pandemic, all methods were adapted to a fully remote, online format. I utilize lexical decision tasks and self-paced reading (SPR) paradigms as a proxy for traditional eye-tracking to test the impact of sound-based errors on lexical retrieval and reading in DHH signers. This chapter begins with an outline several studies that have leveraged lexical decision tasks to understand the role of speech-based phonology on lexical retrieval in DHH readers. Before explaining my research questions and hypotheses, I briefly explain SPR paradigms and how they differ from traditional eye-tracking. Finally, I explain the methods, results, and analyses for this study.

Lexical decision tasks with hearing readers

Lexical decision tasks (LDTs) are commonly employed to test lexical access (Costello et al. 2021; Fariña et al. 2017; Ratcliff, Gomez, & McKoon, 2004; Yap, Balota, & Tan, 2013). For such tasks, participants are presented with individual words and asked to respond as quickly as possible if each word is a real word in the target language. Stimuli lists typically comprise of real words as well non-words. Nonwords can be manipulated to target several linguistic and visual processing factors that underly reading. I focus on three categories of nonwords in this chapter: pseudohomophones, transposed letter (TL) words, and replaced letter (RL) words. Pseudohomophones are nonwords that follow the orthotactic constraints of the target language but sound like real words when pronounced (eg. '*work' - 'work'; 'mean' - 'meen'*). TL words are real words in the target language in which two consonants have been transposed, which results in nonwords (eg. '*medicine' – 'mecidine'; 'comedy' – 'codemy'*). RL words are real words in which one consonant is replaced with a visually-similar consonant to create a nonword (e.g. '*gravity'* – *'gravify'; 'prestige'* – *'presfige'*). Here, visually similar means same height regarding the mid-line (e.g., *t, f, l* vs. *n, m, s*) and whether or not the letter dips below the bottom-line (I.e. *g, j, y* vs. *r, v, k*).

One effect commonly reported by LDT data is the pseudohomophone effect. Hearing readers who encounter pseudohomophones commonly take longer to respond when correctly rejecting pseudohomophones, as well as a higher tendency to incorrectly accept pseudohomophones as real words. This is reported to be one of the strongest indicators of phonological processing in word recognition (Briesemeister et al., 2009; Ferrand & Grainger, 1994; Rubenstein, Lewis, & Rubenstein, 1971; Ziegler, Jacobs, & Klüppel, 2001). Briesemeister and colleagues (2009) used a multi-method approach to understanding the pseudohomophone effect by recording ERP data of adult readers during an LDT. Nonwords comprised of pseudohomophones and non-homophonic non-words. Results demonstrated less accuracy when responding to pseudohomophones compared to non-homophonic non-words and real words, as well as increased response time when responding to pseudohomophones. Further, ERP data revealed some degree of semantic mediation when processing pseudohomophones, providing further evidence that these nonwords activate lexical retrieval in hearing readers.

The presence of active phonological codes in tasks of word-processing is often considered an important step to lexical access for hearing readers of shallow orthographies. Indeed, studies have demonstrated that visual word recognition depends primarily on phonology, not spelling (Coltheart et al., 2001; Frost, 1998; Van Orden, Johnston, & Hale, 1988). Shallow orthographies allow for faster word recognition processes that involve phonological coding as phonological codes are automatically accessed during reading. Scholars have speculated that efficient phonological processing may be an obligatory step for word identification by hearing readers of shallow orthographic languages (Carreiras et al., 2009; Pollatsek, Perea, & Carreiras, 2005).

Another effect that is commonly reported in the literature is the TL effect, which is considered a robust indicator of orthographic processing. Readers demonstrate slower reaction times and more errors when rejecting TL nonwords compared to RL nonwords (Fariña et al., 2017; Perea & Carreiras, 2006; Perea & Lupker, 2004). TL effects can be seen very early in visual word processing at the orthographic level of representation and before phonological processing reportedly begins (Davis, 1999; Gómez et al., 2003; Forster & Davis, 1984; Grainger & Segui, 1990; Lukatela & Turvey, 1996; Perea & Gotor, 1997; Perea & Carreiras 2006; Rajaram & Neely, 1992; Sereno, 1991). Perea and Carreiras (2006) tested the degree to which the TL effect involves phonological processing by comparing Spanish readers' responses to the TL effect specifically for phonologically similar sounds, /b/ and /v/ realized as [β] and unrelated consonants. Results demonstrated that while a small impact of phonological similarity was found for related TL words, this effect-size was far smaller than that of the orthographic TL effect. The authors concluded that this pattern is further evidence that TL words elicit orthographic processing more so than phonological processing (Perea & Carreiras 2006).

Lexical decision tasks with DHH readers

LDTs have been used to target phonological and orthographic processing during lexical retrieval in DHH signers in several studies and languages. Bélanger and colleagues (2012) tested the role of phonological and orthographic codes during reading of French in adult DHH signers and hearing readers. In the first of two tasks, researchers used masked-priming and LDTs to target the time-course of phonological and orthographic processing. Masked priming experiments present words or nonwords very quickly before target words to activate orthographic or phonological processing before target words (Forster & Davis, 1984; Grainger & Segui, 1990; Lukatela & Turvey, 1996; Perea & Gotor, 1997; Rajaram & Neely, 1992; Sereno, 1991). Such tasks have demonstrated that orthographic codes activate 20-30 ms before phonological codes (Gainger & Holcomb, 2008). Experimenters manipulated orthographic and phonological primes to be presented at durations of 40 ms or 60 ms to target differences in priming effects. In a second task, participants completed a serial recall task with orthographic and phonological overlap between words. Participants were instructed to remember lists of words, which contained targets that were either orthographically and phonologically similar (O+P+) or orthographically dissimilar and phonologically similar (O-P+). Serial recall tasks have repeatedly demonstrated that phonologically similar words are more difficult to remember in serial recall tasks for hearing readers than phonologically unrelated words (Baddeley & Logie, 1999; Conrad & Hull, 1964). Experimenters predicted that phonologically related lists would be more difficult for hearing readers to remember and that orthographically and phonologically related words would be easier to remember due to orthographic codes. In contrast, DHH readers were predicted to use orthographic codes primarily, but more skilled DHH readers would show phonological similarity effects (Hanson et al. 1984).

Results on the first task showed that hearing readers activated orthographic information slightly before phonological information (Grainger & Holcomb, 2008) and DHH readers demonstrated use of orthographic information during word processing at both prime durations (Burden & Campbell, 1994; Chamberlain, 2002; Daigle et al., 2009; Harris & Moreno, 2004; Miller, 2006, 2007). DHH signers were not, however, impacted by phonological information during target processing regardless of more- or less-skilled reading. The authors suggest that this finding aligns with previous studies that found no evidence of phonological code activation during English written word recognition (Chamberlain, 2002; Cripps et al., 2005; Waters & Doehring, 1990). The second task results indicated that both hearing and DHH readers used orthographic codes to maintain words in working memory as expected (Chincotta et al., 1999; Logie et al., 2000), and hearing readers were affected by phonological similarity between words during recall (Baddeley & Logie, 1999). DHH readers, however, were not impacted by phonological priming during serial recall and instead depended solely on orthographic codes.

In a study with adult readers, Fariña and colleagues (2017) developed two Spanish LDTs to differentiate between the influence of orthography and speech-based phonology on lexical access of a shallow orthography in DHH and hearing adults: a phonological coding task and an orthographic coding task. The phonological coding task involved 80 real words, 40 pseudohomophones, and 40 non-homophonic nonwords, all 4-6 letters long. For the orthographic coding task, 80 real words were chosen. Additionally, 40 of the chosen real words were manipulated as a transposed letter (TL; i.e. *mecidina* instead of *medicina*), and the remaining 40 were manipulated with a replaced letter (RL; i.e. *meficina* instead of *medicina*). LDT data from 15 adult severely-to-profoundly Deaf readers and 15 hearing adult Spanish monolinguals. Results showed that Deaf signers did not demonstrate a latency effect when correctly rejecting pseudohomophones compared to non-homophonic nonwords and were similarly accurate when categorizing real and non-words. The authors concluded that DHH signers did not demonstrate a pseudohomophony effect to the same degree as hearing readers on the phonological processing LDT. Results from the orthographic processing LDT indicated that DHH signers were significantly faster in response times than hearing readers. Further, no difference between accuracy was found between groups, suggesting that both groups are sensitive to orthographic manipulations. The authors concluded that Deaf signers are not sensitive to speech-based cues, unlike their hearing peers. Instead, considering evidence from the orthographic processing LDT, skilled adult Deaf readers of Spanish primarily depend on orthographic cues.

In another study from Spain, Costello and colleagues (2021) provided neural and behavioral evidence regarding the sensitivity of DHH signers of LSE (the signed language of Spain) to pseudohomophony when engaging in the LDT tasks described in Fariña et al. (2017; above). Participants were all adult, skilled readers. Data from 20 Deaf readers (14 females; mean age = 33, range of 23 – 45 years) and 20 hearing readers (10 females; mean age = 29; range of 20 – 42 years). Behavioral and neural evidence suggested that skilled DHH readers were not sensitive to pseudohomophony, unlike hearing readers. Further, DHH signers responded faster to LDT items compared to hearing readers. The authors suggest this finding indicates that DHH signers are not engaging in phonological activation of text and instead engage in orthographic chunking when reading. Readers who engage in orthographic chunking, in contrast to phonological recoding, recognize frequently co-occurring letter combinations particularly in suffixes and affixes, reducing the amount of time required to recognize the word (Costello et al., 2021; Grainger & Ziegler, 2011; Joseph et al., 2009). The authors further reported no evidence of Spanish phonology activation in DHH signers during single word reading considering that they were not sensitive to pseudohomophony.

Self-paced reading

Self-paced reading (SPR) paradigms differ from traditional eye-tracking tasks in multiple ways. They do not require any eye-tracking technology, making them easier to implement in a remote setting. For such paradigms, individual words are presented on the screen sequentially, and the participant advances the sentence word by word via button press. Reading rate, which is calculated by the speed with which participants advance individual words, is the primary outcome variable of these paradigms. These paradigms have been implemented for a variety of linguistic tasks. One study targeted the use of lexical bundles on reading speed by measuring reaction time (RT) to words that are congruous to common lexical "bundles" (e.g., "in the middle of") instead of less common bundles (e.g., "in the front of"). Results indicated that reading speed is significantly faster when words are within the context of highly predictable lexical bundles (Gibbs, Bogdanovich et al., 1997; Ortony et al., 1978; Schmitt & Underwood, 2004; Tremblay et al., 2011). Additionally, we have learned the effects of word frequency on reading speed and lexical access as higher frequency and function words are read faster than low frequency content words (Schuster et al., 2015).

One interesting aspect of SPR paradigms is that each individual word is seen by the reader. Because words are displayed sequentially and participants are unable to return to previous words, dependence on rechecking and regressive saccades as a reading strategy for resolving errors in text cannot be utilized. Further, words cannot be skipped and must be viewed, ensuring that all participants fixate on each individual word.

I developed two LDTs in conjunction with the homophone foil paradigm as a SPR task as an approach to targeting phonological and orthographic processing during single-word reading and lexical retrieval. I report data from DHH and hearing readers ages 10 – 13, all collected remotely online. I adapted the homophone foil paradigm to an SPR format, measuring the time it takes a reader to advance from target words of all three conditions ('advance time') as well as accuracy and response time when verifying the validity of each sentence. I also adapted the LDT design described in Fariña et al. (2017), leveraging the pseudohomophone and TL effect in two separate LDTs to target phonological and orthographic processing during lexical retrieval, respectively.

Research questions

1. Do DHH and hearing readers engage in speech-based phonological recoding during single word reading, demonstrated by longer reading times for homophonic error targets?
2. Are DHH and hearing readers similarly sensitive to non-homophonic spelling-based errors when engaging in single word reading?
3. Do DHH and hearing readers demonstrate similar response times?

I expect to see a significant impact of speech-based phonological recoding when hearing readers encounter homophonic and pseudo-homophonic errors, resulting in higher instances of incorrectly accepting sound-based error words when completing the phonological processing LDT (Briesemeister et al., 2009; Fariña et al., 2017; Ferrand & Grainger, 1994; Ziegler, Jacobs, & Klüppel, 2001). Further, hearing readers are expected miss homophone error targets more often than non-homophonic error targets (Jared et al., 2016; Cooley & Quinto-Pozos, Resubmitted). DHH readers, however, are not expected to demonstrate sensitivity to speech-based errors when engaging in lexical decision tasks as well as reading within the SPR paradigm (Bélanger et al., 2012; Costello et al., 2021; Cooley & Quinto-Pozos, Resubmitted; Fariña et al., 2017).

DHH readers are likely to demonstrate little to no latency effect in responding to pseudohomophones (Bélanger et al., 2012; Costello et al., 2021; Fariña et al., 2017). Hearing readers, in contrast, likely will demonstrate a latency effect in response time to pseudohomophones due to phonological conflict with real homophone pairs (Briesemeister et al., 2009; Costello et al., 2021; Fariña et al., 2017; Ferrand & Grainger, 1994; Ziegler et al., 2001).

Similarly, hearing readers are likely to incorrectly accept more pseudohomophones than DHH due to a lack of conflict with spoken language phonology (ostello et al. 2021; Fariña et al., 2017C). Finally overall lower RTs for DHH than hearing readers are expected, as has been found in previous single-word reading and response time tasks involving DHH signers (Bélanger et al., 2012; Bélanger et al., 2018; Costello et al., 2021; Fariña et al., 2017).

All participants are expected to demonstrate increased errors and response time on TL words than RL words considering the robust transposed-letter effect which is a robust indicator of orthographic processing (Fariña et al., 2017; Perea & Carreiras, 2006; Perea & Lupker, 2004). DHH participants are likely to have lower response times than hearing readers, as has been found in previous single-word reading and response time tasks (Bélanger et al., 2012; Bélanger et al., 2018; Costello et al., 2021; Fariña et al., 2017). Finally, all participants to perform similarly in response accuracy (Fariña et al., 2017)

It is important to note that Fariña et al. (2017), Costello et al., (2021), and Bélanger et al. (2012) reported data from skilled, adult readers. It may be the case that participants in the current study perform differently due to their age. Additionally, I did not separate groups into more- and less-skilled readers. While I expect to find meaningful differences in how DHH and hearing readers engage with sound-based errors, I do not expect groups to differ significantly on errors that are not manipulated for speech-based phonology. Both groups are likely to be disrupted by non-homophonic errors during single-word reading (Bélanger et al., 2012; Cooley & Quinto-Pozos, Resubmitted; Costello et al., 2021; Fariña et al., 2017).

Finally, DHH participants are likely to demonstrate overall lower RTs compared to hearing readers. Skilled DHH readers have been reported to have lower response times without negatively impacting their reading comprehension (Bélanger et al. 2012; Costello et al., 2021; Fariña et al., 2017).

Methods

Participants

DHH participants were recruited by emails sent to parents of DHH signing children at two residential ASL-English bilingual schools for the deaf. Hearing participants were recruited by flyer and email distribution to parents of previous participants who indicated interest in participating in additional studies with the department. Participants were also recruited via snowball recruitment methods and leveraging participant parent networks.

A total of twenty-two DHH (10 female; average age- 11 years 10 months, range- 10;3 – 14) and twenty-nine hearing participants (13 female; average age- 11 years 8 months, range- 9;3 – 14;4) completed study tasks. DHH participants were reported to have acquired ASL from at home from Deaf parents and primarily use ASL at home. All signers attended ASL-English bilingual schools or ASL-English programs for Deaf and Hard of Hearing students in mainstream schools at the time of data collection and throughout early childhood. Only one participant reported moderate hearing loss (45 – 70 dB loss) while the remaining were severely- to profoundly-deaf (>70 dB loss).

Criteria for DHH participants required that they acquired ASL from Deaf parents and report using ASL as a primary language, at school and at home with family. Though participants were not excluded based on the use of hearing aids or use of cochlear implants, no participants in the DHH group reported amplification via hearing aids or cochlear implantation. Criteria required hearing participants to be monolingual English speakers with no reported hearing loss and normal or corrected-to-normal vision. Participants were all typically developing with no report of learning delay or disability. No participants were homeschooled.

The final analysis included a subset of 11 DHH and 13 hearing participants matched for reading age based on the PIAT-R Reading Comprehension (Markwardt, 1989). This task comprises of 100 sentences ordered from primer to adult. After each sentence, an array of 4 photos was presented and participants indicated with picture matched the previous sentence. Raw scores from task performance correspond to reading age. Matched DHH readers had an average chronological age of 12 years, 5 months (range 10;6 – 14) and average reading age of 11 years (range 8;5 – 15;6), and matched hearing readers had an average chronological age of 11 years, 1 month (range 9;3 – 13;8) and reading age of 11 years, 6 months (range 8;1 – 14). Final groups did not differ in reading age ($p = 0.64$). All participants in the final group read at or above expected reading levels.

Procedure

Data collection was conducted online via Zoom. Prior to sessions, paper consent documents and demographic forms were sent to participant families along with prepaid return envelopes. At the beginning of each session, participants and their parents were provided with consent documents and a description of the study in the participant's preferred language (English or ASL). Once the consent process was completed, participants completed the study battery, beginning with the PIAT-R and followed by the experimental tasks. Participants completed tasks in following order: 1.) A first block of SPR sentences, randomly assigned to A, B, or C; 2.) One LDT, randomly assigned to Spelling or Sounds; 3.) A second block of SPR, randomly assigned to one of the remaining two blocks; 4.) The second LDT; 5.) The final SPR block. Due to fatigue, 12 participants did not complete the final block of SPR sentences.

Experimental tasks were presented on Pavlovia.org, which generates URL links to run PsychoPy tasks and compiles data remotely. Sessions lasted between 45 – 60 minutes, and participant families were reimbursed $40 upon completion of study tasks ($10 for parent time, $30 as a thank you for child participants) via Venmo, PayPal, Zelle, or other app-based payment systems.

Experimental Tasks

Homophone foil SPR paradigm

Sixty sentences from the original homophone foil paradigm (outlined in Chapter 3) were converted to SPR format. 30 sentences contained correct target words (i.e. *see* in "Barbara peered out the window to *see* if you were home"), 15 contained homophonic error targets (i.e. *sea* instead of *see* in "Barbara peered out the window to *sea* if you were home"), and 15 contained non-homophonic spelling control errors (i.e. *set* instead of *see* in "Barbara peered out the window to *set* if you were home"). Sentences were randomly assigned to either be correct in version A, homophonic error in version B, or non-homophonic error in version C. Table 1 provides examples of sentences that will be presented to three sample participants who each read one of the three versions of the homophone foil paradigm (see Appendix D full stimuli list).

Table 4.1

Example sentences for homophone foil SPR task by version

	Version A	Version B	Version C
Participant 1	Barbara peered out the window to **see** if you were home.	Mrs. Baker warned us not to **waist** the art supplies.	Craig's face turned **palm** when he heard the bad news.
Participant 2	Barbara peered out the window to **sea** if you were home.	Mrs. Baker warned us not to **worst** the art supplies.	Craig's face turned **pale** when he heard the bad news.
Participant 3	Barbara peered out the window to **set** if you were home.	Mrs. Baker warned us not to **waste** the art supplies.	Craig's face turned **pail** when he heard the bad news.

Participants were instructed to read sentences for meaning, advancing each word one-by-one by pressing the spacebar. This version of the homophone foil paradigm was a sentence verification task, so participants indicated whether they noticed an error in the previous sentence. Data were analyzed for proportion of correct responses to verification questions, reaction time (RT) on correct trials, and the amount of time it took to advance from target words to subsequent words in the SPR paradigm.

Phonological processing lexical decision task

The "Sounds" lexical decision task was developed to target the impact of speech-based phonology on lexical access following those designed by Fariña and colleagues (2017). Stimuli included 50 real English words and 50 non-words (full word lists can be found in the Appendix). Real words were chosen based on expected vocabulary knowledge for typically developing 3rd – 5th graders and were a mix of high- and low-frequency. Non-words consisted of 25 pseudohomophones, which follow English orthotactic constraints and sound like real English words and 25 non-homophonic nonwords. See Table 4.2 for examples (full word list can be found in Appendix D).

Table 4.2

LDT Sounds examples

Condition	Example
Correct words:	*'thrown', 'boy', 'flaw'*
Pseudohomophones:	*'rhite', 'phays', 'phaught'*
Non-homophonic non-words	*'werd', ' whepes', 'whanx'*

Nonwords were confirmed by students in two sections of undergraduate introduction to linguistics classes (30 students). Students were requested to indicate whether they believed a given word to be a real English word. If they rejected the word, they were requested indicate whether the nonword sounded like an existing English word. Words were included if they received 90% agreement from all 30 students.

This task was presented by pavlovia.org, which compiled datasets. Task instructions were provided in the participant's preferred language as well as in writing at the beginning of the task. Participants were instructed to decide whether each word presented is a real word or not and told to respond as quickly as possible. Tasks were coded such that participants pressed the left arrow key if the word was a real word or right arrow key if the word was not a real word. Participants completed five practice trials and given the opportunity to ask questions before completing the entire task.

LDTs were designed such that if a participant took more than three seconds to respond, the trial would be removed and a brief reminder to respond as fast as they can was presented. Words were randomized to one of two blocks to allow participants to take a brief break during the task. Participant data were analyzed for proportion of errors by group and word type. Only response times (RT) from correct trials were analyzed.

Orthographic processing lexical decision task

To create the Spelling task, a list of 100 English words 5 – 8 characters in length were chosen. Half of the chosen words were then manipulated to be one of two categories: replaced letter (RL) or transposed letter (TL). For RL targets, correct words have one consonant replaced by a similarly shaped but incorrect letter. For TL targets, two salient consonants were transposed such that all letters in the word are correct, but two have been swapped. See Table 4.3 for examples (full word lists in Appendix D3). Data presentation and collection was the same as the LDT: Sounds task. Participant data were analyzed for proportion of errors by group and word type. RT from correct trials were also analyzed.

Table 4.3

LDT Spelling examples

Condition	Example
Correct words:	*'habitat', 'custody', 'variant', 'scratch'*
Transposed letter:	*'hostile – holtise'* *'habitat – hatibat'* *'medicine' – 'mecidine'*
Replaced letter:	*'humanity' – 'humanify'* *'majority' – 'magority'* *'mature' – 'malure'*

Statistical analysis

The SPR paradigm was analyzed for the time participants take before advancing to a subsequent word following targets words (i.e., correct, homophonic errors, and non-homophonic errors). Additionally, the proportion of errors in the verification task and correct trial RTs were analyzed. The lexical decision tasks were analyzed for proportion of errors and correct trial RTs.

All data were analyzed via "lmer" (for continuous RT data) and "glmer" (for categorical proportion of error data) mixed-effects models from the lme4 package in R (Bates, Mächler, Bolker, and Walker, 2015). I employed mixed-effect models to understand the relative contribution of the main effects of group status (hearing vs. DHH) and sentence condition (correct, homophonic error, non-homophonic error) on variations in probability of fixating on the target, rereading time, and probability of regressing back to target. Considering the issue of multiple samples per participant and the violation of the assumption of independence, the random effect of subject is included in all models. A random effect of item is also included in all models. Fixed effects models for each group were created and model equations were as follows:

outcome ~ word type (reference level = 'real word) + (1|subject ID) + (1|trial)

Further, when testing the impact of target word condition (correct, pseudohomophone or TL, non-word or RL), Helmert contrasts were employed, a sum-to-zero contrast that compares the mean of each level to the mean of the subsequent level (Sundstrom, 2010). Sentence condition factors are ordered such that the first contrast is the average of levels one and two compared to level three, and the second contrast is level two compared to level one. As such, contrast 1 in all models reports error conditions vs. correct condition target words and indicates whether error conditions are noticed by the readers. Contrast 2 reports the contrast between error condition types. As such, contrast 2 targets the impact of (pseudo)homophony on measurements for homophone foil and Sounds data. Helmert model equations were as follows:

*outcome ~ group*contrasts 1 & 2 + (1|subject ID) + (1|trial)*

Results

Homophone foil SPR paradigm

Table 4.4 reports the performance of groups on the verification portion of the homophone foil SPR paradigm by word condition. Table 4.5 reports participant advance time on target words by condition.

Table 4.4

SPR verification task results

	DHH		Hearing	
	Prop. Errors	Correct RT: mean (SD)	Prop. errors	Correct RT: mean (SD)
Correct	0.18	138 (61) ms	0.47	148 (63) ms
Homophonic	0.24	134 (129) ms	0.24	145 (76) ms
Non-homophonic	0.24	130 (68) ms	0.1	145 (64) ms

Table 4.5

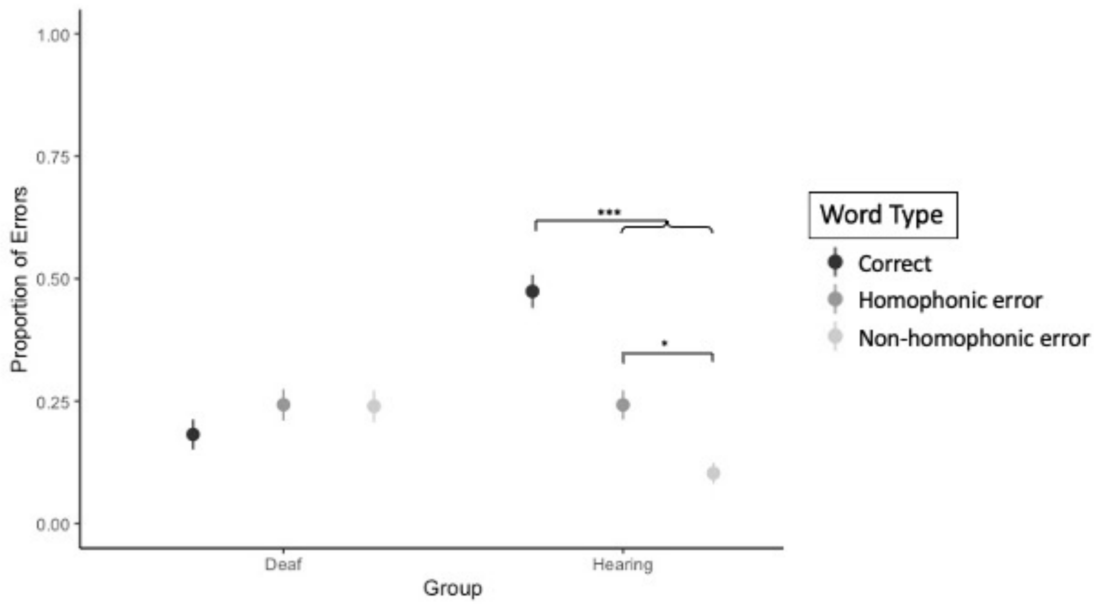
SPR advance time results

Advance Time: Mean (SD)	DHH	Hearing
Correct	53 (27) ms	59.52 (24) ms
Homophonic	58.01 (30) ms	65.83 (35) ms
Non-homophonic	59.27 (33) ms	66.95 (31) ms

DHH readers performed overall more accurately on the homophone foil SPR verification task. Significant interactions emerged between group and both contrasts (contrast 1= correct vs. errors: z (1002) = -4.48, p < 0.0001, R^2 = -1.16 [95% CI: -1.66, -0.65]; contrast 2 = homophonic vs. non-homophonic: z (1002) = -3.91, p = 0.002, R^2 = -0.89 [95% CI: -1.46, -0.33). As for main effects, group (z (1004) = -2.16, p = 0.31; R^2 = -0.53 [95% CI: -1.02, -0.05] and contrast 1 (z (1004) = 3.05, p = 0.0023; R^2 = 1.23 [95% CI: 0.44, 2.02]) (Figure 4.1). No significant contrasts emerged for correct trial RT (Figure 4.2).

Figure 4.1

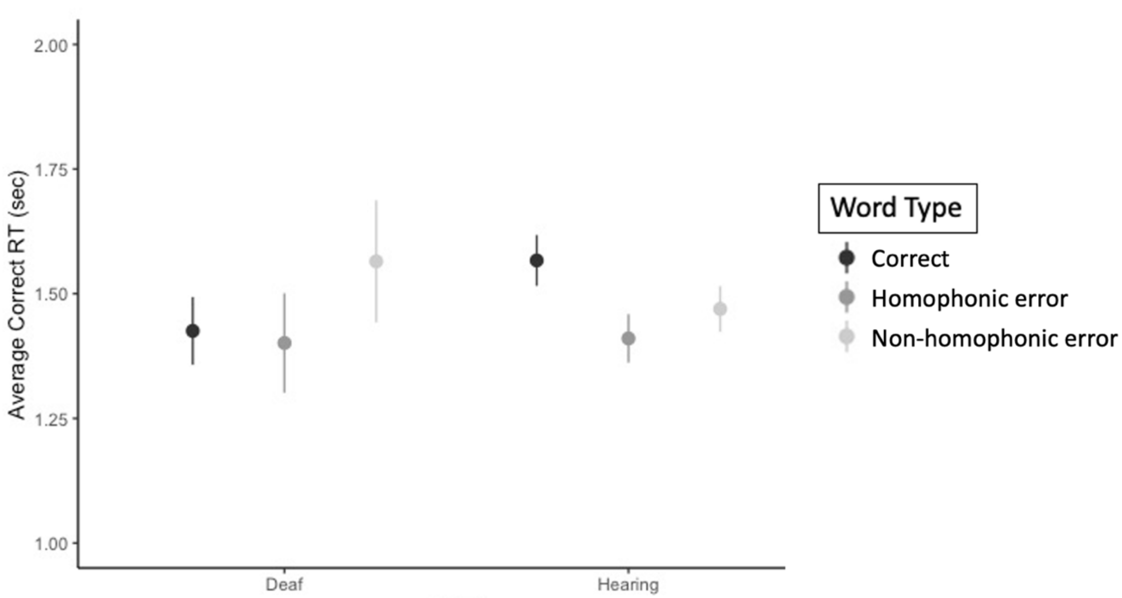
SPR proportion of errors on verification task



Note: Error bars reflect standard deviation; * = p < 0.05; ** = p <0.001; *** = p <0.0001

Figure 4.2

SPR verification task correct trial RT

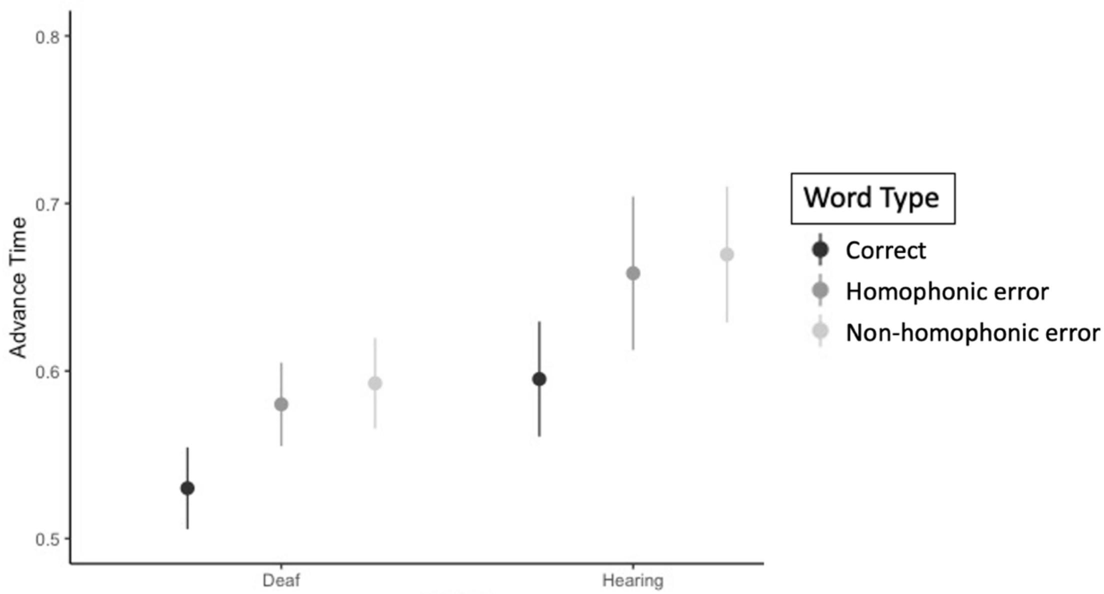


Note: Error bars reflect standard deviation

No significant contrasts emerged regarding advance time (Figure 4.3).

Figure 4.3

SPR target word advance time



Note: Error bars reflect standard deviation

Phonological processing LDT results

Table 4.6 reports the proportion of errors and correct trial RT by groups on the Sounds LDT.

Table 4.6

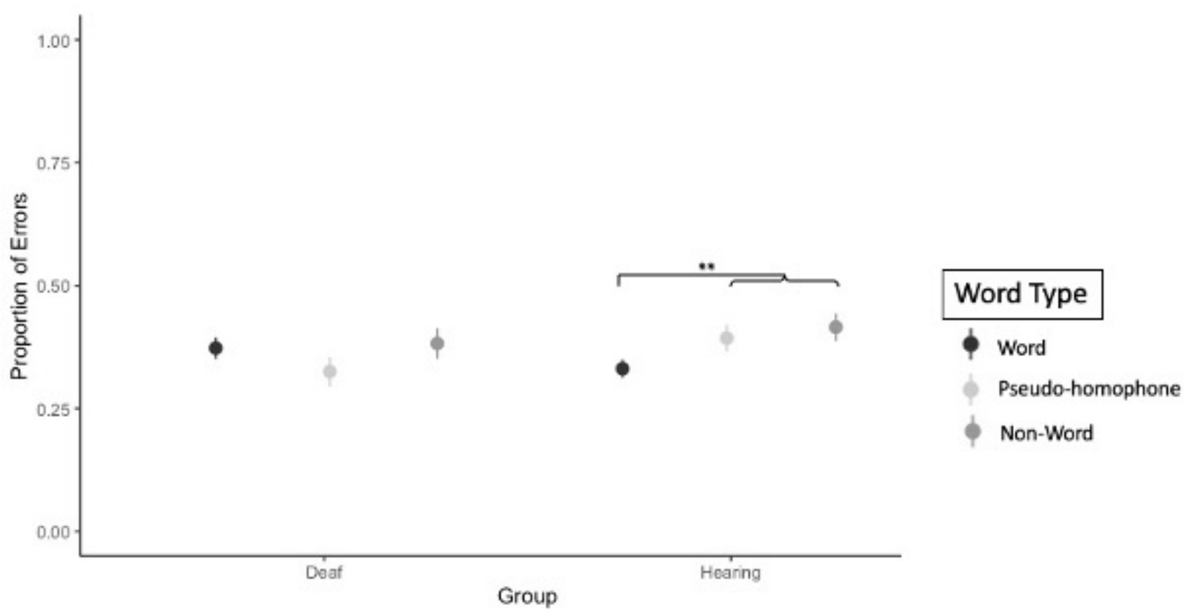
Sounds LDT results

	DHH		Hearing	
	Prop. Errors	Correct RT: mean (SD)	Prop. errors	Correct RT: mean (SD)
Word	0.37	84.52 (40) ms	0.33	81.11 (39) ms
Pseudo-homophones	0.33	92.18 (36) ms	0.39	96.23 (46) ms
Non-words	0.39	94.07 (40) ms	0.42	105.4 (40) ms

A significant interaction between group and contrast 1 emerged (*z* (2232) = 2.71; *p* = 0.0067; R^2 = 0.31 [95% CI: 0.8, 0.53]; Figure 4). DHH readers' accuracy did not differ across word types, while hearing readers performed more accurately on real words than non-words (*z* (1253) = -3.21, *p* = 0.0013, R^2 = -0.48 [95% CI: -0.77, -0.19]). Overall accuracy between groups does not differ (Figure 4.5).

Figure 4.4

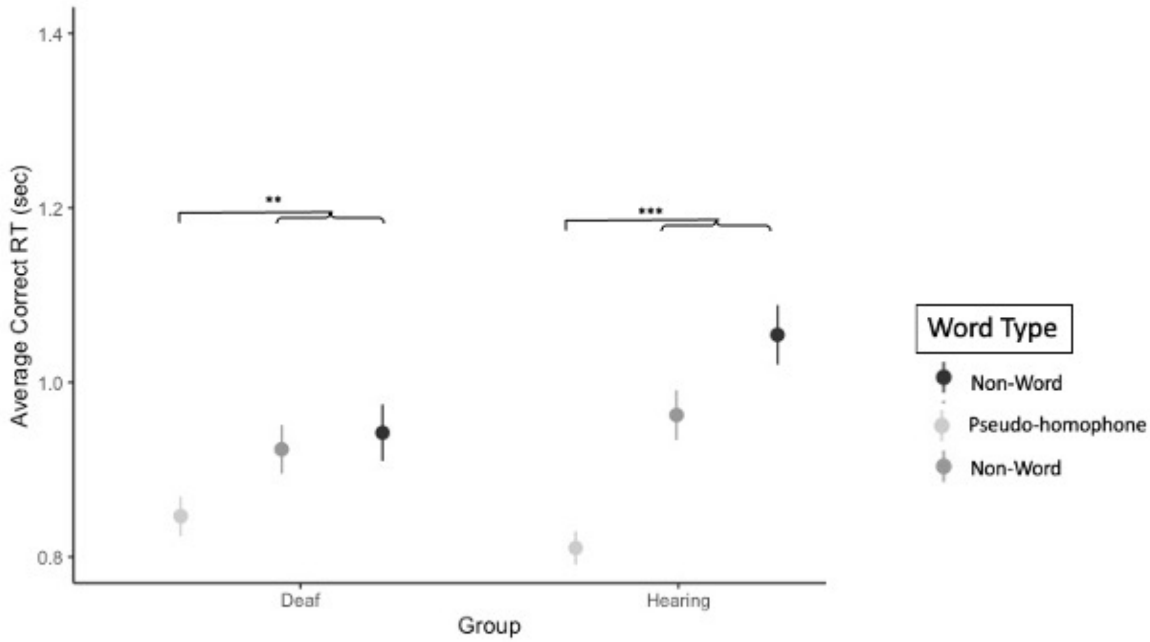
Proportion of errors of Sounds LDT



Note: Error bars reflect standard deviation; ** = p < 0.01

Figure 4.5

Response time for correct trials on Sounds LDT



Note: Error bars reflect standard deviation; ** = p < 0.001; *** = p < 0.0001

Orthographic processing LDT results

Table 4.7 reports the proportion of errors and correct trial RT by groups on the Spelling LDT.

Table 4.7

Spelling LDT results

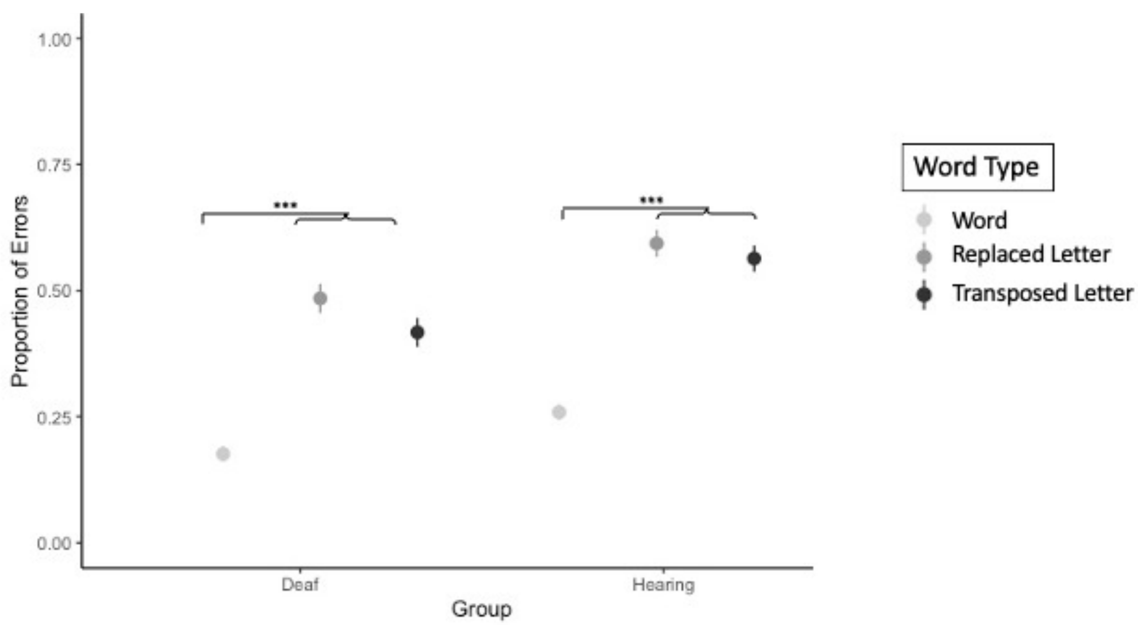
	DHH		Hearing	
	Prop. Errors	Correct RT: mean (SD)	Prop. errors	Correct RT: mean (SD)
Word	0.17	86.19 (25) ms	0.26	115.42 (46) ms
RL	0.42	95.84 (26) ms	0.56	134.34 (57) ms
TL	0.48	92.68 (26) ms	0.6	134.23 (49) ms

Contrast 1 for proportion of errors emerged as a significant main effect for DHH (*z* (1208) = -10.6, $p < 0.0001$; $R^2 = -1.58$ [95% CI: -1.87, -1.28]) and hearing readers (*z* (1401) = -9.42, $p < 0.0001$; $R^2 = -1.71$ [95% CI: -2.06, -1.35]; Figure 4.6).

Regarding correct trial RT, a significant interaction between group both contrast 1 (*z* (1619.13) = 3.09; $p = 0.002$; $R^2 = 0.24$ [95% CI: 0.09, 0.39]) and contrast 2 (*z* (1619.13) = -3.97; $p < 0.0001$; $R^2 = -0.48$ [95% CI: -0.71, -0.24]). DHH readers demonstrated an effect of error on correct trial RT (*t* (94.49) = -6.24, $p < 0.0001$; $R^2 = -0.29$ [95% CI: -0.34, -0.2]). Hearing readers demonstrated an effect of error (*t* (105.46) = -3.19, $p = 0.0019$; $R^2 = -0.27$ [95% CI: -0.44, -0.11]) as well as significant differences between error types (*t* (123.82) = 2.92, $p = 0.0041$; $R^2 = 0.37$ [95% CI: 0.12, 0.62]; Figure 4.7).

Figure 4.6

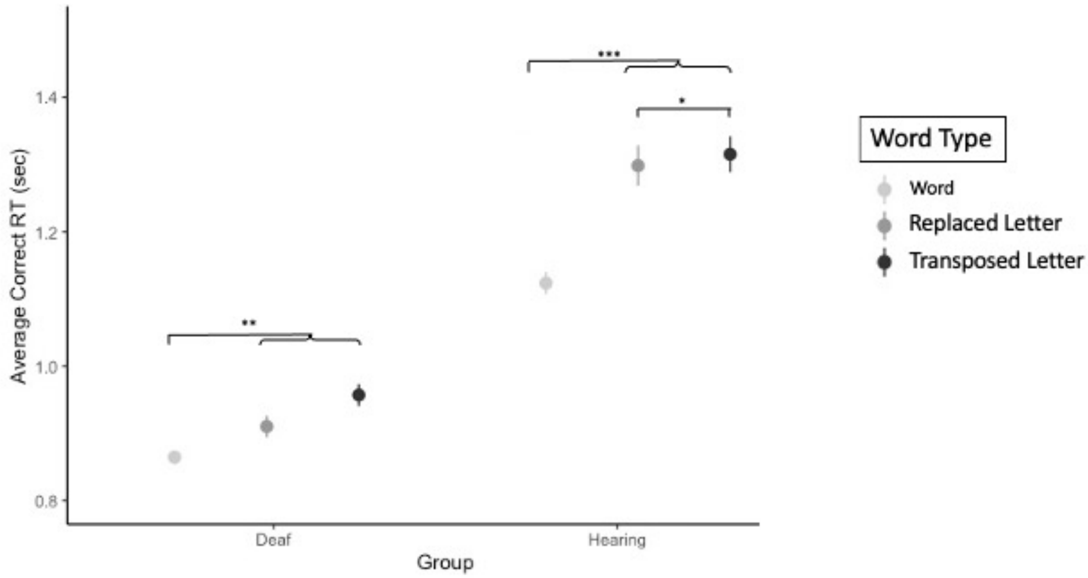
Proportion of errors on Spelling LDT



Note: Error bars reflect standard deviation; *** = p < 0.0001

Figure 4.7

Response time for correct trials on Spelling RT



Note: Error bars reflect standard deviation; * = p < 0.05; ** = p < 0.01; *** = p < 0.0001;

Discussion

Before providing a discussion of results in prose, I provide a table of measures and what the findings suggest about phonological and orthographic coding (Table 4.8). In the upcoming discussion sections, I these findings in more detail.

Table 4.8

Summary of tasks and what they suggested

		Phonology?	Orthography?	Mixed	Inconclusive
SPR verification:					
	DHH:		✓		
	Hearing:	✓			
SPR advance					
	DHH:				✓
	Hearing:				✓
LDT: Sounds					
	DHH:		✓		
	Hearing:			✓	
LDT: Spelling					
	DHH:		✓		
	Hearing:			✓	

The current study used single-word reading paradigms to target orthographic and speech-based phonological processing in reading-age matched native signing DHH and hearing readers ages 10 – 13. On the homophone foil SPR task, participants read homophone foil sentences word-by-word and then indicated whether an error was detected. Participants also completed two lexical decision tasks with non-words manipulated to target the pseudohomophony effect and transposed letter effect.

Results regarding speech-based phonological recoding are mixed for hearing readers. Homophone SPR paradigm data suggests that hearing readers demonstrated evidence of speech-based phonological recoding, as has been previous reported (Cooley & Quinto-Pozos, Resubmitted; Jared et al., 2016). Hearing readers' proportions of errors indicate a significant effect of error and homophony, as homophonic and non-homophonic error sentences were different from one another and the correct sentences. DHH readers did not perform differently across error conditions on the homophone foil SPR regarding proportions of errors and correct trial response time, indicating that they did not depend on speech-based codes when engaging in this task. Against expectations, hearing readers were less accurate on correct condition sentences than error sentences. This may be due to an error bias, considering the instructions primed participants to expect an error. This warrants further investigation, particularly considering that DHH readers were not sensitive to this priming effect.

In addition, neither group reflected a significant pseudohomophone effect on the Sounds LDT. The DHH group did not demonstrate an effect of pseudohomophony when rejecting pseudohomophones (contrast 2: $p = 0.52$). This suggests that DHH signers were not engaging in phonological recoding during lexical retrieval on this task, which aligns with previous studies with DHH signers on tasks with speech-based pseuodhomophony (Bélanger et al., 2012; Costello et al., 2021; Fariña et al., 2017). Interestingly, though they trended towards an effect of pseudohomophony on this task (contrast 2: $p = 0.084$), the hearing group did not demonstrate the pseudohomophone effect. I expected to find increased errors when hearing readers categorized pseudohomophones compared to correct and non-homophonic nonwords, as well as a latency when correctly rejecting pseudohomophones (Briesemeister et al., 2009; Costello et al. 2021; Fariña et al. 2017; Ferrand & Grainger, 1994; Rubenstein, Lewis, & Rubenstein, 1971; Ziegler, Jacobs, & Klüppel, 2001).

DHH and hearing readers performed similarly on non-word categories on the Spelling LDT. Both groups were significantly more inaccurate when rejecting nonwords than accepting correct words, and neither group reflected significant differences between error target conditions. The correct trial RT data similarly did not reflect a TL effect in the DHH group, though hearing readers took longer to reject RL targets than TL targets. The results from both groups did not reflect the TL effect, which would be evidenced by increased proportion of errors on TL targets compared to RL and correct words as well as increased response time when accurately rejecting them (Fariña et al., 2017; Perea & Carreiras, 2006; Perea & Lupker, 2004). This finding does not follow predictions considering that previous investigations with DHH signers and hearing readers have reported the TL effect (Costello et al., 2021; Fariña et al., 2017).

Additionally, the finding that DHH readers performed overall as accurately as hearing readers in conjunction with overall lower correct trial response time provides further support for the hypothesis that DHH readers depend on orthographic codes. Orthographic processing is active 20 – 30 ms earlier than phonological processing when reading (Davis, 1999; Forster & Davis, 1984; Gómez et al. 2003; Grainger & Segui, 1990; Lukatela & Turvey, 1996; Perea & Carreiras 2006; Perea & Gotor, 1997; Rajaram & Neely, 1992; Sereno, 1991). I suggest that DHH readers depended on orthographic codes when completing this task (Bélanger et al., 2012; Fariña et al., 2017; Costello et al., 2021), while hearing readers likely engaged in lexical retrieval at both the orthographic and phonological level (Bélanger et al., 2012; David, 1999; Gómez et al. 2003; Perea & Carreiras 2006).

DHH readers responded significantly faster on the orthographic processing task than hearing readers, as has been found in previous studies with DHH signing adults (Bélanger et al., 2012; Costello et al., 2021; Fariña et al., 2017). Lower RT when engaging in orthographic processing compared to hearing readers may be due to the absence of phonological encoding by DHH readers resulting in overall faster lexical retrieval (Fariña et al., 2017; Mordford et al., 2015). Additionally, in conjunction with overall faster response times, DHH readers were similarly accurate on this task. This suggests that DHH readers were not engaging in a riskier reading strategy because accuracy was not negatively impacted by faster response time (Bélanger et al., 2015; Bélanger et al., 2018). I also report significantly more errors on the SPR verification task by hearing readers than DHH readers. It may be the case that hearing readers were primed to detect errors, resulting in incorrect responses to correct trials. Despite this, there does appear to be some degree of phonological impact resulting in the overall pattern of homophonic errors lying somewhere between correct and non-homophonic errors (Cooley & Quinto-Pozos, Resubmitted; Jared et al., 2016). DHH readers did not appear impacted by condition type considering they were similarly accurate on correct, homophonic, and non-homophonic error sentences. I suggest that this reflects a difference in strategies for groups when engaging in error detection tasks such as the homophone foil SPR paradigm and provides some degree of evidence in support of orthographic processing as a primary reading strategy.

Finally, it is important to note that I did not find pseudohomophony or TL effects in LDT tasks for the hearing group, which does not follow predictions. I suggest that the differences between the current LDT results and those reported in previous studies may be attributed to two factors. Firstly, most of the studies of both the pseudohomophone and TL effects in hearing readers include adult readers (Briesemeister et al., 2009; Ferrand & Grainger, 1994; Rubenstein, Lewis, & Rubenstein, 1971; Ziegler, Jacobs, & Klüppel, 2001). Regarding similar studies comparing the phonological and orthographic processing in deaf and hearing readers, only skilled adult readers were included as well. This current study reports data from child readers ages 10 – 13. In contrast, Fariña and colleagues (2017) and Costello and colleagues (2021) report the mean age of deaf readers to be 34 years old and 29 for hearing readers. Bélanger et al. (2012) report the mean age of DHH participants to be 36 years old and 31 for hearing participants. It may be the case that younger hearing readers are not advance in sight-word reading to demonstrate effects between types of errors and instead treat all errors similarly.

Secondly, both tasks were difficult for participants regardless of hearing status. Of the original 51 participants who completed this task, nine readers performed below chance (mean score < 0.5) on both the Sounds and Spelling tasks. Even after the removal of below-chance performers and reading-age matching groups, error proportions were high as compared to previous reports with similar tasks. On the Sounds task, the average proportion of errors for the DHH group was 36%, and 37% for the hearing group. In contrast, Fariña et al. 2017 report average proportion of errors for Deaf readers to be 5.03% and 9.6% for hearing readers. Similarly, while i report Spelling task proportions of errors to be 31.16% for the DHH group and 41.4% for the hearing group compared to 8.55% for Deaf readers and 9.47% for hearing readers reported by Fariña and colleagues. Taken together, age of participants and difficulty of task may have an impact on both the pseudohomophone effect for hearing readers and TL effect for all readers on LDT performance.

Limitations

The current study was conducted entirely remotely. Previous online studies have not reported a negative impact of online studies on study validity (Goodman et al., 2013; Hauser & Shwarz, 2015; Paolacci et al., 2010). However, this study involved young children and took place during the pandemic. These two factors may have had an adverse impact on data collection. Further, sample sizes are low due to recruitment issues, task difficulty resulting in participant data removal, and reading age matching of groups. As such, trends that emerged in the current data require verification. Finally, the tasks developed may have been too difficult for the target age range. To verify wordlists, participants at the target age range (10 – 13) should have been recruited instead of college-level readers.

Conclusion

The current chapter reports data from the second study that informed my dissertation. I targeted orthographic and phonological processing by DHH and hearing readers during single word reading tasks. I reported evidence that DHH signers ages 10- 13 were not sensitive to homophony on the SPR verification tasks and pseudohomophony in LDTs. Reading-age matched hearing readers did, in contrast, demonstrate an effect of homophony and phonological processing on the homophone foil verification task. Both groups demonstrated effects of error on the orthographic processing task, but only hearing readers demonstrated significant effects of error condition on self-paced reading verification and Sounds lexical decision task responses. This suggests that DHH readers engage in orthographic processing when reading, at least more so than phonological processing (Bélanger et al., 2012; Costello et al. 2021; Fariña et al. 2017).

Chapter 5: Discussion, future directions, and conclusions

Introduction

The first part of this chapter is a summary of results from all studies considered together and a reflection on the components of print literacy targeted here: phonological awareness of speech and sign on reading, the impact of orthographic processing on reading behaviors and the Simple View of Reading, and proposed reading efficiency and visual processing. Finally, I introduce several limitations, conclusions, and possible lines of future research.

Phonological awareness and reading

The primary goal of this line of research was to target the degree to which DHH and hearing readers ages 10 – 13 demonstrate evidence of speech sound activation during online reading. This age range was chosen considering that hearing readers usually transition during this time from phonological decoding as a primary reading strategy to sight-word reading (Ehri, 2014; Jared et al., 2016; Pennington et al., 1987; Rayner et al., 2006; Share, 2005). If DHH readers do read in the same way as hearing readers but are delayed due to a lack of auditory access to speech, they would likely demonstrate similar if not increased levels of phonological decoding compared to hearing readers (Paul 2001, 2008; Paul & Lee, 2010; Wang et al., 2008). If processes underlying reading in DHH signers are different and not primarily dependent on speech-based codes, they would likely pattern differently than hearing readers during tasks that elicit activation of speech-based phonology (Allen et al., 2009; Costello et al., 2021; Fariña et al., 2017).

Chapter 2 reported phonological awareness data from the first empirical study that forms this dissertation. DHH signers performed above chance on measures of English phonological awareness. Although they were outperformed by hearing readers, this finding suggests that the

DHH signers in the first study have some speech-based phonological awareness (King & Quigley, 1985; Leybaert, 1993; Mayer, 2007; Paul, 1998, 2003; Schirmer & McGough, 2005). Hearing readers similarly performed above chance on measures of ASL phonological awareness but were outperformed by DHH readers on one of those tasks. Performance on English and ASL tasks were not correlated. English rhyme judgement scores did predict performance on the WCJ-SRF, but ASL rhyme judgement performance did not. Further, DHH signers performed at their expected age range on the WCJ-SRF, despite overall lower English phonological awareness. All considered, these findings do not support a reciprocal relationship between ASL and English phonology as has been theorized (McQuarrie & Abbott, 2013; Petitto et al., 2016). Further, DHH readers were not age-delayed on the Woodcock-Johnson III Test of Silent Reading Fluency. I suggest that age-expected reading levels indicates that reading in DHH readers may be primarily dependent on processes other than phonology.

Chapter 3 reported eye-tracking data from DHH and hearing readers when encountering homophonic and non-homophonic error words in text. The groups did not demonstrate differences in eye-movement behavior during their first encounter with target words and did not demonstrate any effects of error, but they did have significant differences in eye-movements during their second encounter with target words. Hearing readers showed evidence of phonological activation and an impact of homophony during their second encounter with target words. This result is considered evidence that these readers were less likely to notice a homophonic error than a non-homophonic error (Doctor & Coltheart, 1980; Jared et al, 2016). They were more likely to regress to non-homophonic than homophonic errors and spent more time rereading non-homophonic errors, which suggests that error words that differed from correct targets in spelling, meaning, and phonology were always noticed, whereas some errors with congruous phonology were not noticed. DHH readers, in contrast, did not demonstrate an effect of homophony during their second encounter with targets. Though they were more likely to regress to and spent more time rereading error targets compared to correct targets, regression probability and rereading time did not differ between error conditions for the DHH readers. Regression data suggests that while the hearing readers were impacted by homophonic errors during reading (Ehri, 2014; Jared et al., 2016; Share, 2005), DHH readers were not, aligning with previous investigations of DHH signers that did not report evidence of active speech-based codes during reading (Bélanger et al., 2012; Campbell & Wright, 1988; Chamberlain, 2002; Harris & Beech, 1998; Izzo, 2002; Leybaert & Alegria, 1993; Miller, 2007a).

Chapter 4 reported homophone foil self-paced reading paradigm (SPR) data and lexical decision task data. SPR data was reported by the time it took participants to advance to subsequent words from target words as well as via verification task. Advance time data did not reflect differences between groups or conditions, indicating that both groups were not impacted by error conditions or homophony when advancing to subsequent words from target words. The verification task data is reported by proportion of errors by condition when participants were asked if the previous sentence had an error, as well as the reaction time on correct trials. Correct trials response time did not differ across groups or conditions. Though the overall pattern of SPR proportions of error for hearing readers did not follow expectations regarding accuracy, an impact of homophony can still be detected considering that non-homophonic errors resulted in fewest errors and correct trials resulted in most errors. Homophonic errors resulted in a proportion of errors between correct and non-homophonic targets, which suggests that they are less impacted by homophonic errors than non-homophonic errors and are engaging in some degree of phonological decoding during reading (Ehri, 2014; Jared et al., 2016; Share et al., 2005). DHH readers outperformed hearing readers on this task with overall fewer errors and did not demonstrate any differences in accuracy across conditions, which suggests that DHH readers were not significantly impacted by speech-based phonology.

Interestingly, phonological processing was not detected in hearing readers on the phonological processing task in the SPR and lexical decision tasks. Though they did show an effect of error considering decreased accuracy when categorizing words and nonwords as well as increased response time when correctly categorizing words and non-words, the pseudohomophone effect was not found. This may be due to the task being too difficult, resulting in processing beyond the level of phonological activation. DHH readers performed similarly on SPR and phonological processing LDT tasks. They did not demonstrate any effect of error conditions when accurately categorizing words and nonwords, though they did take longer to correctly reject nonwords than to accept words. DHH signers did not demonstrate an effect of error condition when categorizing words on response accuracy on this task, but they did take longer to correctly accept words and correctly reject nonwords. Considered together, this task does not provide strong evidence in support of phonological decoding of print to speech for either group.

There was no strong evidence for DHH children's phonological decoding of print to speech from the results reported in this dissertation. The findings aligned with theories that suggest that DHH children read via processes different than those of hearing readers, particularly considering phonological decoding. All DHH signers included in the analysis read at age-expected levels and did not appear negatively impacted by a lack of activation of speech-based codes (Allen et al., 2009; Izzo 2002; Kyle & Harris, 2006; Leybaert & Alegria, 1993; Miller, 1997). Hearing readers, however, did engage in phonological decoding of print to speech to at least some degree, and were impacted by homophony during error detection (Ehri, 2014; Jared et al., 2016; Rayner et al., 2006; Share, 2005). Additionally, I suggest that the current dissertation did not provide support for the qualitative similarity hypothesis (QSH; Paul & Lee, 2010; Paul 2001, 2008). According to this hypothesis, DHH children are likely to be delayed in reading development due to a lack of access to speech sounds, though knowledge of speech sounds is ultimately necessary for successful reading in all readers regardless of hearing status. This model further suggests that early strategies employed by DHH readers are likely to depend on phonological decoding of print to speech sounds, like hearing readers. The results presented here did not suggest reading delays in DHH signing children who are ASL-English bilinguals ages 10 – 13. Further, they did not engage in phonological decoding when encountering homophonic errors in sentences or to pseudohomophony during lexical retrieval.

Finally, these results did not necessarily support the VSP model, which suggests that phonological awareness is a meta-linguistic skill that surpasses the level of modality and that the transference of phonological processing ability from sign results in sensitivity to linguistic units beyond sign language (Petitto et al., 2016). Results from Chapter 2 did not show a relationship between ASL phonological awareness and speech-based phonological awareness and reading. Scholars have similarly suggested that phonological awareness of English and reading ability are reciprocal for DHH students and that as reading skill develops, sensitivity to speech-based phonology develops as well (McQuarrie & Abbott, 2013). The current results do not strongly support this theory either, considering that although DHH readers performed above chance on measures of English phonological awareness as reported in Chapter 2, they did not demonstrate an impact of speech-based codes when reading in the studies reported in Chapters 3 and 4.

Orthographic processing and the Simple View of Reading

Regardless of orthographic depth, writing system, and hearing status, all readers engage in orthographic processing and decoding when reading. In Chapter 2, I employed methods that avoided orthographic processing by using picture-based stimuli to test speech-based phonological awareness. Chapter 3 provides some evidence of orthographic processing in DHH signers considering that both homophonic- and non-homophonic error words were treated similarly. While this finding suggests DHH readers do not primarily depend on phonological processing, the mechanism underlying that similarity remains unclear. It may be vocabulary knowledge and meaning activation, orthographic processing and knowledge of spelling, or it may be factors not tested here. Considering evidence from DHH students learning to read Mandarin Chinese, it could be the case that DHH signers would find greater success in literacy development with emphasis on the connection between morphological components of written words and signs (Jones, 2013).

Chapter 4 similarly provided some evidence that DHH readers depend on orthographic knowledge when reading. Hearing readers demonstrated effects of homophony on both versions of the homophone foil paradigm, but DHH readers performed similarly across error conditions. This finding alone, taken with the result that DHH readers performed below hearing readers on English phonological awareness tasks reported in Chapter 2, provides further support that reading may not be primarily dependent on speech for DHH readers, particularly when resolving errors in text. Considering previous evidence of orthographic processing during similar tasks and similar performance on both LDT tasks as reported in Chapter 4, I suggest that DHH readers attended to the spelling of words more so than corresponding speech sounds (Bélanger et al., 2012; Costello et al., 2021; Emmorey & Lee, 2021; Fariña et al., 2017).

The Simple View of Reading (SVR) suggests that there are two primary and equally important factors underlying reading ability: linguistic competence and decoding ability (Chamberlain & Mayberry, 2000; Gough & Tunmer, 1986; Hoover & Gough, 1990; Juel, 1988; Juel, Griffith, & Gough, 1986; Stone et al., 2015; Tunmer & Hoover, 1992). Although I did not explicitly measure language ability of ASL or English of DHH signers in these studies, I speculate that the early and robust access to sign language at home and at school resulted in enough linguistic competence to support reading acquisition. Further, considering evidence presented here that DHH signers were more dependent on orthographic codes than phonological codes, I speculate that they have developed sufficient orthographic decoding skills to further support reading. All considered, I suggest that the results presented in the current dissertation fall most in line with the SVR for DHH child signers. This warrants future investigation.

Proposed reading efficiency and visual processing

I suggest that some of the findings reported in this dissertation support the Word Processing Efficiency Hypothesis (Bélanger & Rayner, 2015) for DHH readers with early and robust exposure to sign language. The word processing efficiency posits that DHH signers have increased visual perceptual sensitivity to linguistic and non-linguistic information (Dye, Hauser, & Bavelier, 2008) which allows them to take greater advantage of information in the periphery when reading and whole-word visual processing than hearing readers. As a result, DHH signers are reportedly more efficient in certain aspects of their reading processes evidenced by increased reading rates (Bélanger et al., 2015), increased rates of word-skipping (Traxler et al., 2021), decreased rates of regression deployment (Bélanger et al., 2012), and faster response times (Bélanger et al., 2012; Costello et al., 2021; Fariña et al., 2017). Importantly, these patterns are reported in conjunction with overall comparable response accuracy compared to hearing readers (Bélanger et al., 2012; Costello et al., 2021; Fariña et al., 2017; Traxler et al., 2021).

The study discussed in Chapter 3 reported fewer instances of regressions for DHH signers than hearing readers. Though evidence of fewer regressions is reported in conjunction with overall lower comprehension scores on the eye-tracking homophone foil paradigm, I suggest there may be factors involved other than phonology, such as the clarity of the comprehension questions, the overall reading ability of groups, and SES factors. As reported in Chapter 4, perhaps most strongly in support of increased reading efficiency, DHH readers responded significantly faster when correctly rejecting nonwords and correctly accepting real words than hearing readers on the orthographic processing LDT, while performing similarly in proportion of errors, which suggests that DHH readers were faster in orthographically manipulated lexical retrieval.

Finally, Chapter 4 provided additional support for increased word processing efficiency in DHH readers, especially on the spelling task. DHH readers responded significantly faster to stimuli on the orthographic processing LDT but were overall similarly accurate compared to hearing readers. Similar accuracy is an important finding when considering efficiency, as increased reading speed in conjunction with decreased accuracy may suggest riskier reading behaviors. Instead, DHH readers were not negatively impacted by their decreased response times. This also supports orthographic processing in DHH readers due to the earlier activation of orthographic codes during reading (Davis, 1999; Forster & Davis, 1984; Gómez et al. 2003; Grainger & Segui, 1990; Lukatela & Turvey, 1996; Perea & Carreiras, 2006; Perea & Gotor, 1997; Rajaram & Neely, 1992; Sereno, 1991).

General discussion, implications, and future directions

The DHH readers included in the analyses that were reported in this dissertation overall read at or above age-expected levels. This is an important finding considering historical reports of lower reading success and delays in DHH readers (Easterbrooks & Beal-Alvarez ,2012; Traxler et al. 2000). All participants had early and robust access to ASL from birth from at least one Deaf, signing parent and all attended ASL-English schools and programs. Though ASL ability was not explicitly targeted in this dissertation, I speculate that the amount of daily exposure to and use of ASL at home and at school contributed to age-appropriate reading levels in these groups (Chamberlain & Mayberry, 2000; Hrastinksi & Wilbur, 2016; Mayberry & Lock, 2003).

I further reported that DHH signers were less sensitive to speech-based codes during reading compared to hearing readers and that DHH students are likely to read by different processes due to comparatively less experience with speech sounds. As such, they are likely to depend on more visually salient cues such as orthography and spelling.

Understanding DHH children as developing bilinguals

It is important to consider DHH children who grow up using a signed language are second language learners of the written form of a spoken language. Studies of children exposed to two spoken languages often identify differences between bilingual children and monolingual control groups. In some cases, the bilingual children perform below monolingual norms in various aspects of linguistic structure, such as vocabulary knowledge and reading. Children who use a minority language at home may arrive at school with no knowledge of the language spoken among classmates and teachers. These students often lag monolingual peers in their oral skills in the at-school language and should not be expected to achieve the same at-school language ability as their monolingual peers (Goldberg, Paradis, & Crago, 2008; Hoff et al., 2012; Paradis, Schneider, & Sorenson Duncan, 2013; Paradis & Kirova, 2014). Studies have demonstrated that second language students are particularly delayed in vocabulary knowledge, grammatical complexity, and narrative skill compared to monolingual students, though ultimately they can catch up with monolingual peers (Paradis, Genesee, & Crago, 2011; Paradis et al., 2013; Pearson, 2002; Paradis & Kirova, 2014).

Children who grow up in signing households acquire a signed language as their first language, regardless of their hearing status. Until they arrive at school, child signers who are severely to profoundly deaf have relatively little exposure to English compared to hearing children. On the other hand, DHH signers who have robust access to signed language early in life typically arrive at school with a first language upon which a second language (i.e., the written form of a spoken language) can be learned. As such, it is important to consider second language learning effects when evaluating reading ability in DHH signers. Profoundly DHH signers who grow up in signing households and attend bimodal-bilingual schools use their signed language vocabulary and grammar skills to acquire a written second language (Mayberry & Lock, 2003; Villwock et al., 2021).

Perhaps DHH are more likely to perform similarly to hearing second language learners, not hearing monolinguals. DHH signers are tasked with learning a second language, namely the written form of the dominant spoken language in the area, at the same time as developing print literacy. As such, some delays in reading achievement in DHH signers as compared to hearing monolingual children of the same age might be expected. Further, it may be the case that hearing monolingual readers are not an accurate comparison group and that norms for DHH signing bilinguals need to be established.

Future directions

The current dissertation provides a small snapshot into the reading development of DHH signing children ages 10 – 13. From here, I hope to take this line of research in two primary directions. First, a more in-depth analyses of reading processes via eye-tracking and neuroimaging. Secondly, expansion of current online and remote data collection methods to target a wide range of DHH and hearing students across the country to further our understanding of language experience on a variety of students.

One line of research focuses on lab-based studies. Future research would benefit from increased sample sizes and more sophisticated eye-tracking and neuroimaging techniques to fully unpack the role of phonological awareness of speech and ASL skill on reading in DHH signers. Specifically, combining eye-tracking and ERP techniques can provide additional insight into the processes underlying error detection and passive reading in DHH readers. Several studies use eye-tracking and LDT tasks in conjunction with neuroimaging (Bélanger, Lee, & Schotter, 2018; Costello et al., 2021; Emmorey & Lee, 2021; Fariña et al., 2021). I suggest that the use of both methodologies together will provide additional insight into the degree to which phonological and orthographic processing is involved in reading for DHH signers.

Another line of research would broaden language testing to an online format to make research more accessible to a variety of students. To better understand the role of language experience on reading development in DHH signing students, I hope to adapt and expand the current methodology to a large-scale, cross-sectional design. The methods for Chapter 4 were easily adapted to an online format to account for issues with in-person data collection due to the COVID19 pandemic. I suggest that such a format creates a more cost-effective way of large-scale recruitment by depending on social media channels, email distributions, within school recruitment, and snowball recruitment methods. Online data collection saves time and money for both researchers and participants, thereby increasing recruitment pools and including subjects for whom scientific research participation would not be possible. The creation of online tasks is simple and easy to implement, which I hope will ultimately result in a wide variety of behavioral tasks, surveys, and other measures of educational and academic success, and the creation of a national database for language and academic outcomes for all students. From there, several approaches such as hierarchical linear mixed-effects modeling could be employed to describe the relationship between outcomes and specific schools, instructional methods, and regional influences.

I also hope to translate this work into a reading intervention study to test the impact of orthographic decoding and general language comprehension training on reading for DHH signers in accordance with the SVR (Chamberlain & Mayberry, 2000; Juel & Gough, 1986; Stone et al., 2015). Such a study would provide more concrete evidence regarding how the SVR can be extended to DHH readers, particularly considering evidence that orthographic depth impacts the contribution of these two components (Kendeou et al., 2009).

I place great emphasis on the homophone foil paradigm and its historical use to target speech-based phonological activation. I also employed this paradigm in two ways: with traditional eye-tracking in Chapter 3, and self-paced reading paradigm in Chapter 4. This paradigm has been repeatedly reported in the literature (Colheart et al., 1986; Coltheart et al., 1988; Doctor & Coltheart, 1980; Jared et al., 2016; Johnston, Rugg, & Scott, 1987; Johnston et al., 1995). However, other eye-tracking paradigms may be more powerful in targeting cognitive processing underlying reading for DHH readers. Bélanger and colleagues (2012, 2015, 2018) employed moving window paradigms and priming effects to understand the impact of parafoveal processing on reading speed. Perhaps the combination of a homophone foil paradigm with a hidden boundary prime would allow us to understand how phonological information is processed parafoveally for DHH signing children. Further, it may be the case that other mechanisms are involved with encountering homophonic and non-homophonic errors in text beyond phonological and orthographic processing. The use of the foil paradigm with other linguistic features (such as word class, grammatical structure, etc.) may provide further insight into error processing and the degree to which phonological processing is truly being tapped.

Finally, future studies should include hearing bilingual controls as well as hearing monolinguals. Traxler and colleagues (2021) report data from the first such study, comparing data from hearing bilingual and monolingual controls and DHH signers, all of whom were college-aged and skilled readers. The authors reported that DHH signers performed similarly to, or outperformed, hearing bilingual readers on measures of text comprehension (Traxler et al. 2021). I hope to test this further in my later work beyond graduate school, leveraging eye-tracking and psycholinguistic methods to target phonological and orthographic processing in DHH signing students, hearing monolingual students, and hearing bilingual students. This will allow for a more careful comparison of groups by considering language experience and bilingualism and its role in language development (Ameel et al., 2005; Paradis & Kirova, 2014; Paradis et al., 2011; Paradis et al., 2013; Traxler et al., 2021; Van Assche et al., 2009; Villwock et al., 2021).

While there are many other factors that are involved in the reading process that warrant future study, I suggest that a more sophisticated look at the relationship between vocabulary knowledge of sign and DHH children's target written language is necessary. Such studies will help unpack the question of orthographic and semantic processing during reading in DHH signers. The relationship between vocabulary knowledge and reading is robust for hearing and DHH students alike (Cain, Oakhill, & Lemmon, 2014; Mann, Roy, & Morgan, 2015; Reynolds, 2020). Unfortunately, at the time of the development of these studies, no measures of ASL or English vocabulary have been published. One task, the ASL-VT (Mann, Roy, & Morgan, 2015), targets ASL and English vocabulary knowledge at four levels in DHH signers up to the age of 10. Hopefully future lines of research include newly developed vocabulary tasks for older DHH students. Otherwise, future research may include younger students so that the ASL-VT is sensitive enough to use or similar tests need to be created for older groups.

One important methodological distinction between the eye-tracking study and SPR study was the ability to reading-age match DHH and hearing readers in the SPR study. Future lines of research will benefit from performing reading and language testing on participants prior to the completion of experimental tasks to ensure a certain level of reading ability necessary to answer questions of phonological and orthographic processing. Similarly, I hope future lines of work will allow for the recruitment of large numbers of participants from a variety of backgrounds and language skill to allow for a more sophisticated view of the factors underlying skilled and less-skilled reading in DHH children.

Limitations

I acknowledge that there are several limitations to the methods reported and described in this dissertation. Here I describe some of these limitations in no particular order.

Firstly, I speculate on the role of language ability provided by early and robust access to sign language experienced by DHH signers who completed reported studies. I did not, however, explicitly test ASL or English language ability. Such measures might include narrative comprehension tests, vocabulary tests of both ASL and English, and bilingual ability. Such tasks might include the ASL-Sentence Repetition Task (ASL-SRT; Hauser et al., 2008), the VL2 Fingerspelling test (Morere, 2012), the ASL- and English VTs (Mann & Marshall, 2012). Future studies would benefit from performing language testing prior to completion of study tasks for participants to ensure a certain level of linguistic ability and comprehension before completing study tasks.

Another major limitation is reported sample sizes. Unfortunately, children within minority groups are difficult to recruit to laboratory settings. Recruitment for studies requiring special lab-based equipment is particularly difficult due to the distance from target populations. As a result, I was unfortunately unable to recruit enough participants for reading-age matching of groups for the study that informed Chapters 2 and 3. The online format of the study that informed Chapter 4 allowed for more participants to enroll in the study, and I was able to report reading age matched groups. Future studies will benefit greatly from higher numbers of participants. This will allow for more appropriate matching of groups by reading and chronological age, as well as providing the degrees of freedom necessary to control for other factors that underly reading, such as socioeconomic status (SES), language backgrounds, and schooling.

Conclusions

This dissertation aimed to fill a small gap in our understanding of the processes by which DHH children learn to read. I used psycholinguistic methods and mixed-effects modeling to understand the impact of speech-based phonological decoding and orthographic processing on reading strategies in DHH signers and hearing monolinguals, ages 10 –13. I used eye-tracking, lexical decision tasks, and behavioral language testing in three separate studies. Considered together, I suggest that the data reported here do not support claims that DHH and hearing readers are similar in reading strategies as it relates to speech-based phonological decoding.

Chapter 2 tested phonological awareness of English and ASL in DHH signing and hearing readers ages 10 –13. DHH outperformed hearing participants on one measure of ASL phonological awareness which targeted sublexical structure at the rhyme level. Hearing readers outperformed DHH participants on measures of English phonological awareness at the rhyme and syllable levels, though they performed above chance on these measures. DHH readers were not age-delayed in their reading skill as measured by one measure of English reading fluency, and hearing readers read beyond expected reading levels. English rhyme scores predicted reading fluency, but no other measures of phonological awareness were related. Chapter 3 reported eye-tracking data from the same participants reported in Chapter 2 when encountering homophonic and non-homophonic errors when reading. Results indicated that DHH and hearing readers were not impacted by errors when first encountering words and patterned overall similarly on first-pass measures. Second pass measurements of regression deployment and rereading time, however, demonstrated an effect of homophony for hearing readers indicating that non-homophonic errors were more likely to be detected than homophonic errors. The DHH group noticed errors and were more likely to regress back to and reread error conditions, but they treated homophonic and non-homophonic error words similarly. This finding suggests that DHH readers did not engage in phonological decoding during this task to the same extent as hearing readers, if at all.

Chapter 4 reported single-word reading data from a new group of reading-age matched DHH and hearing participants ages 10 – 13. SPR data revealed some impact of homophony for hearing readers, but not for DHH readers. In addition, DHH readers were more accurate on homophone foil SPR verification questions and did not have meaningful differences in accuracy on sentence conditions. The phonological processing LDT results demonstrated that both groups were less accuracy on error conditions, but neither were impacted by pseudohomophony. The orthographic processing LDT results showed that DHH and hearing readers were similarly accurate, but DHH readers responded faster to all word types than hearing readers did. This finding provides some support for increased reading efficiency in DHH signers and reflects orthographic processing due to process timing (Bélanger et al., 2012). However, LDTs may have been difficult for these participants, considering a high proportion of errors.

In contrast to theories that DHH signers are delayed in their acquisition of print literacy due to overall lower phonological awareness of English compared to hearing readers (Paul & Lee, 2010; Wang et al., 2008), the results reported in this dissertation appear to support claims that DHH readers primarily rely on different mechanisms such as general linguistic and ASL ability (Allen, 2015; Hrastinski & Wilbur, 2016; Mayberry et al., 2011; Mayberry & Lock, 2003; Petitto et al., 2016; Stone et al., 2015), visual processing skills (Bélanger et al., 2012, 2015, 2018; Dye, Bavelier, & Hauser, 2008), and orthographic decoding ability (Bélanger et al., 2012, 2015, 2018; Chamberlain & Mayberry, 2000; Costello et al., 2021; Fariña et al., 2017; Stone et al., 2015). I suggest that these results reflect a difference in reading strategies by young DHH signers and hearing readers. Hearing readers at this age still engaged in phonological decoding of print to speech while DHH readers appeared to depend on other cues when reading, particularly orthography. I suggest that findings presented here have implications for educational practices for DHH children, particularly as they relate to language choice at home and at school. Perhaps most notably, all DHH participants reported in the analyses had early and robust access to ASL at home and throughout school and were not age delayed in their reading ability.

Appendix A

Additional factors underlying reading

While the current dissertation focuses on the role of phonological awareness of speech and the use of sound-based codes during online reading, this is just one of the myriad factors that could influence reading acquisition in hearing and DHH children. Table A1 provides a list of a few other factors underlying reading skill as well as several citations that discuss each factor in more detail, though this list is not exhaustive.

Table A1: Additional factors that influence reading

Factor	Claim	Articles
Hearing Levels	The more residual hearing a DHH child has, the better their reading ability will be.	Harris & Terlektsi 2010 Trezek & Wang 2006 Hirshorn et al. 2014
Oral Ability	DHH children with better oral abilities (i.e. clear speech) will be better readers.	Burden & Campbell 1994 Leybaert & Alegria 1995
Language Exposure	Age of exposure to a first or second language impacts how the language is acquired.	Mayberry & Lock 2003 Fitzgerald et al. 2015 Kovelman et al. 2015 Allen 2015
Vocabulary Skill	Better vocabulary knowledge (sign or written) relates to stronger reading ability.	Mann & Marshall 2012 Cain, Oakhill, & Lemmon 2014 Reynolds 2020
Home Literacy Practices	Children who engage in home literacy practices with parents (in ASL or spoken language) will become stronger readers.	Sénéchal & Le Fevre 2002 Hood, Conlon, & Andrews 2008 Swanick & Watson 2005
Socio-economic Status	Higher socioeconomic status correlates with stronger academic achievement for children, particularly maternal education.	Twitchell, Morford, & Hauser 2015 Korat 2009 Reardon, Valentino, & Shores, 2012
Cognitive Ability/IQ	DHH children with overall higher IQs and short-term memory skill will become strong readers.	Daneman et al. 1995 Harris & Moreno 2004 MacSweeney 1998 Waters & Doehring 1990
Bi/multi-lingualism	Readers who are bi/multilingual engage with language differently, particularly when considering modality (spoken, signed, written).	Ameel et al. 2005 Van Assche et al. 2009 Villwock et al. 2021 Traxler et al. 2021

These factors can be broadly grouped as individual-level factors and family/environment level factors. At the individual level, a child's oral ability and hearing levels impact the amount of the spoken language ability they have. Children with more auditory access to speech from residual hearing tend to better oral ability and command of the spoken language (Burden & Campbell 1994; Leybaert & Alegria 1995) and have higher reading levels than profoundly deaf individuals (Harris & Terlektsi 2010; Trezek & Wang 2006; Hirshorn et al. 2014). Reading ability for all children regardless of hearing status is also highly related to cognitive ability and IQ (Daneman et al. 1995; Harris & Moreno 2004; MacSweeney 1998; Waters & Doehring 1990). Finally, individual readers who have superior vocabulary knowledge of the written language are more successful readers (Mann & Marshall 2012; Cain et al. 2014; Reynolds 2020). While scholars still continually debate the role of speech-based phonological awareness and phonological decoding, there seems to be a consensus in the field that vocabulary development is essential for reading success. Indeed, many reports intent upon understanding the predictive power of sign language use or speechreading skills on reading fluency have also implicated vocabulary development as most predictive of later reading skill (Allen et al., 2008; Harris & Beech, 1998; Hermans et al., 2008; Kyle & Harris, 2008). However, DHH children's acquisition of both signed and written vocabulary has been minimally studied in the past.

Family and environment level factors also contribute significantly to variability seen in all readers regardless of hearing status. The more exposure a child has to a target language, the more successful their literacy acquistion is likely to be (Fitzgerald et al. 2015; Kovelman et al. 2015). Specifically as it relates to DHH children, the amount of exposure to any appropriate language has a major impact on literacy development, for both spoken, written, and signed language (Mayberry & Lock 2003; Allen 2015). Exposure to multiple languages impacts how each is acquired and used (Ameel et al. 2005; Van Assche et al. 2009; Villwock et al. 2021; Traxler et al. 2021). Finally, home literacy practices and family socioeconomic status can impact literacy development. Children who come from higher socioeconomic backgrounds tend to have overall better academic achievement (Twitchell, Morford, & Hauser 2015; Korat 2009; Reardon, Valentino, & Shores, 2012). Moreover, maternal education level and home literacy practices such as reading together and reading aloud have a significant impact on language and literacy development (Korat 2009; Sénéchal & Le Fevre 2002; Hood, Conlon, & Andrews 2008; Swanick & Watson 2005)

Appendix B

Participant questionnaire: **University of Texas at Austin Research Study**
Investigators: **David Quinto-Pozos, PhD; Frances Cooley**

Title: *The role of phonological awareness on reading in deaf children*

General information

1. If you are not the participant, indicate your relationship with the participant
    ____Parent or legal guardian
    ____School Psychologist
    ____Speech Language Pathologist
    ____ASL Specialist
    ____Teacher
    ____Other ____

2. Sex of participant
    ____Male
    ____Female

3. Participant's Date of Birth (month/day/year):___________

4. Hearing Status
    ____Deaf (with or without use of hearing aids/cochlear implants)
    ____Hearing

5. Was the participant born prematurely?
    ____Yes (if yes, please indicate number of weeks preterm):_________
    ____No

6. Did the participant's mother have any complications during the participant's birth?
    ____Yes
    ____No
    ____Unknown
    ____Decline to Answer

7. If there were complications, please describe here:

8. Participant's handedness.
    ____Left
    ____Right
    ____Both (ambidextrous)

Participant's Vision and Hearing:

Vision:

9. Participant's status of vision.
    ____No correction needed
    ____Vision correction to normal (i.e., with use of glasses or contact lenses)
    ____Vision corrected but remains impaired

10. If glasses or contact lenses are used by participant, please indicate type of correction:
    ____Far-sighted (needs glasses or contact lenses for reading & focusing on close distances)
    ____Near-sighted (needs glasses or contact lenses for focusing on objects at far distances)
    ____Needs glasses or contact lenses for close and far distances
    ____Needs glasses or contact lenses for astigmatism

Hearing: If the participant is a hearing child, please skip to question 19.

11. Participant's unaided hearing status in the left ear
    ____25-40dB or Mild loss
    ____0-55dB or Moderate
    ____55-70dB or Moderately Severe
    ____70-90dB or Profound
    ____No reported loss

12. Participant's unaided hearing status in the right ear
    ____25-40dB or Mild loss
    ____40-55dB or Moderate
    ____55-70dB or Moderately Severe
    ____70-90dB or Profound
    ____No reported loss

13. If applicable, age of onset of participant's hearing loss.

    ____
    ____Unknown

14. Does the participant have a cochlear implant?
    ____Yes
    ____No

15. If yes, which side?
    ____Left
    ____Right
    ____Both

16. Participant's age at time of implantation
    ____Left
    ____Right
    ____Both
    ____Does not apply

17. Does the participant use a hearing aid, FM system, T-coil loop or other Assistive Listening Device on a regular basis?
    ____Yes
    ____No
    ____Unknown

18. If yes, please indicate which Assistive Listening Device the participant uses.
    ____Hearing Aid
    ____FM System
    ____T-coil loop
    ____Other ____
    ____Does not apply

19. Does the participant have any deaf relatives?
    ____Yes
    ____No
    ____Unknown

20. If yes, select all that apply:
    ____Parent
    ____Sibling
    ____Grandparent
    ____Aunt/uncle
    ____Cousin

General Health Information:

21. Cause of participant's hearing loss, if known.
    ____Genetic/Hereditary
    ____Illness
    ____Syndromic Condition (Ushers, Downs, etc.)
    ____Unknown
    ____Other ________________

22. If known, which if any of the following diagnoses have been made for the participant?
    ____Autism Spectrum Disorder
    ____Attention Deficit Disorder
    ____Auditory Processing Spectrum Disorder
    ____Other cognitive/learning disability
    ____None

____Unknown

23. Indicate if the participant's hearing loss is accompanied by any of the following syndromes.
    ____C.H.A.R.G.E.
    ____Down
    ____Usher
    ____Pierre Robin
    ____Treacher Collins
    ____Other ________________________
    ____Unsure

Language and school information:

23. Indicate the languages that the participant was exposed to before they entered school.
    ____English
    ____Spanish
    ____ASL
    ____Other ________________
    ____Unknown

24. Indicate the languages the participant was exposed to during school.
    ____English
    ____Spanish
    ____ASL
    ____Other ________________
    ____Unknown

25. Types of schools attended (select all)
    ____Residential or Day school for the Deaf
    ____Mainstream (public or private school)
    ____Deaf program in a public school
    ____Homeschool
    ____Other______________________
    ____Unknown

26. Did the participant participate in at-home reading activities (ie. computer-based reading games, learn-to-read games, reading with parents) at home or daycare before entering school?
    ____Yes ____No ____Unknown

27. If the response to #26 was "Yes", please estimate the number of hours per week for each of the ages listed below:
    ____Age 1 ____Age 2 ____Age 3 ____Age 4 ____Age 5

28. Did the participant participate in book reading activities at home or daycare before entering school?

____Yes ____No ____Unknown

29. If the response to #28 was "Yes", please estimate the number of hours per week for each of the ages listed below:

____Age 1 ____Age 2 ____Age 3 ____Age 4 ____Age 5

30. Has the participant participated in speech and language therapy sessions?

____Yes ____No ____Unknown

31. If the response to #30 was "Yes", please estimate the number of hours per week for each of the grades listed below (as appropriate and applicable):

____Grade 1 ____Grade 2 ____Grade 3 ____Grade 4 ____Grade 5 ____Grade 6
____Grade 7 ____Grade 8 ____Grade 9 ____Grade 10 ____Grade 11

Family Background information

32.) What is the highest level of education received by primary caregiver #1?

____12th grade or less
____High school/GED
____Some college/AA degree/tech degree
____College graduate (BA or BS)
____Masters or graduate degree (MA; PhD; MD; JD)

32.) What is the highest level of education received by primary caregiver #2 (if applicable)?

____12th grade or less
____High school/GED
____Some college/AA degree/tech degree
____College graduate (BA or BS)
____Masters or graduate degree (MA; PhD; MD; JD)

33.) Employment of primary caregiver #1 (write YES or NO for each question)

____Working full time
____Working part-time
____Not working and not looking for work
____Unemployed and looking for word
____Disabled or retired
____Currently in school

34.) Employment of primary caregiver #2 (if applicable; write YES or NO for each question)

____Working full time
____Working part-time
____Not working and not looking for work
____Unemployed and looking for word
____Disabled or retired
____Currently in school

35.) Total household income (before taxes from all sources; if unsure, please estimate)

____Less than $5,000
____$5,000-$19,999
____$20,000-$49,999
____$50,000-$99,999
____$100,000-$149,999
____More than $150,000
____Don't know
____Choose not to answer

Future contact information:

32. Would you be willing to be contacted for other research opportunities?
____Yes
____No

33. Preferred contact information
____Email____
____Phone/Text____
____Mail____

Note: Developed for another project in the sign language lab at UT Austin (Quinto-Pozos & Cooley, 2021).

Table B1: English rhyme awareness word list

O+ : orthographic rhyme pairs; O− : nonorthographic rhyme pairs.

Word set 1—dissimilar distracter items to the target							
Type	Cue	Rhyme	Distracter	Type	Cue	Rhyme	Distracter
O+	sock	clock	bed	O−	fly	eye	hat
O+	snail	tail	bridge	O−	four	saw	car
O+	spoon	moon	feet	O−	light	kite	bag
O+	pear	bear	glove	O−	plane	rain	key
O+	ship	zip	heart	O−	drum	thumb	leaf
Word set 2—similar lip-shape distracter items to target							
Type	Cue	Rhyme	Distracter	Type	Cue	Rhyme	Distracter
O+	boat	coat	moon	O−	whale	snail	stairs
O+	house	mouse	owl	O−	rope	soap	comb
O+	book	hook	man	O−	box	socks	pig
O+	king	ring	cheese	O−	ghost	toast	cloud
O+	phone	bone	van	O−	bear	hair	pie
Word set 3—similar initial consonant distracter items to target							
Type	Cue	Rhyme	Distracter	Type	Cue	Rhyme	Distracter
O+	wall	ball	witch	O−	goal	bowl	gate
O+	tap	map	ten	O−	bed	head	boat
O+	run	gun	ring	O−	kite	light	key
O+	bag	flag	book	O−	door	saw	dog
O+	fan	van	fox	O−	fruit	boot	fish
Word set 4—similar initial consonant cluster distracter items to target							
Type	Cue	Rhyme	Distracter	Type	Cue	Rhyme	Distracter
O+	snake	cake	snowman	O−	plane	rain	plug
O+	train	chain	tree	O−	shoe	blue	ship
O+	star	car	stool	O−	chair	pear	church
O+	fridge	bridge	frog	O−	three	key	thumb
O+	sweet	feet	swing	O−	cry	tie	cross
Word set 5—similar onset-vowel distracter items to target							
Type	Cue	Rhyme	Distracter	Type	Cue	Rhyme	Distracter
O+	bridge	fridge	bricks	O−	bed	head	belt
O+	clown	brown	clock	O−	chair	pear	chain
O+	star	car	stamp	O−	shoe	blue	shorts
O+	bat	cat	bag	O−	goal	bowl	goat
O+	cake	snake	camel	O−	boot	suit	book

Note: from Sterne & Goswami 2000

Table B2: English syllable awareness word list

Word 1	U	Word 2	U
Category 1			
4 letters, 1 syllable		4 letters, 2 syllables	
cake	42.62	lion	44.02
hair	144.02	baby	132.97
door	290.25	body	295.73
Category 2			
5 letters, 1 syllable		5 letters, 2 syllables	
chair	73.82	lorry	73.65
snake	34.49	ruler	39.34
light	413.06	money	307.57
Category 3			
6 letters, 1 syllable		6 letters, 2 syllables	
church	70.92	finger	64.36
cheese	34.45	rocket	37.65
bridge	54.85	pencil	49.39
Category 4			
5 letters, 1 syllable		5 letters, 3 syllables	
swing	32.57	piano	32.60
fence	57.18	radio	59.80
fruit	66.23	video[a]	72.26
Category 5			
6 letters, 1 syllable		6 letters, 3 syllables	
switch	16.52	potato	21.18
shorts	2.14	tomato	4.14
fridge	11.32	banana	9.30
Category 6			
3 syllables		3 syllables	
piano	32.60	elephant	32.90
tomato	4.14	kangaroo	6.64
camera	24.69	chocolate	21.54
Average U	78.10	Average U	72.50
Long-short word pairs			
helicopter	10.94	stamp	12.58
telephone	52.30	bowl	51.75
volcano	15.47	bath	14.77
television	72.26	wheel	72.94
dinosaur	15.13	hook	18.21
caterpillar	7.29	toast	7.61
crocodile	9.21	comb	10.17
butterfly	11.92	fork	15.53
computer[a]	72.26	fruit	66.23
dog	231.49	box	207.12
boat	162.11	rain	168.02
leaf	36.07	bone	42.47
wall	116.20	tail	109.64
mouse	32.78	chain	35.08
hat	83.20	key	78.95
train	97.92	cross	88.73
moon	185.69	blue	193.67
star	65.64	coat	63.58
Average U	70.99	Average U	69.84

U-frequencies taken from Carroll et al. (1971).
[a] Frequency score taken from television as computers are as common now as televisions were in 1971.

Note: from Sterne & Goswami 2000

Appendix C

Table C1: Homophone foil sentences: High frequency correct, high frequency error

Sandra asked to **hear/here/hair** her favorite song.
The crowd wanted to **hear/here/hair** the president speak.
It is hard to **hear/here/hair** the words of the song.
Bill's dream is to **meet/meat/mean** his hockey hero.
At school you get to **meet/meat/mean** new friends.
Laurie and Kate decided to **meet/meat/mean** after school.
Brian walked **by/buy/boy** the new house.
Your lunch is on the counter **by/buy/boy** the stove.
I just finished another book **by/buy/boy** my favorite author.
Ellen knows a lot of words **for/four/form** her age.
The class collected fifty dollars **for/four/form** poor families.
Tom wants hockey posters **for/four/form** his room.
The doctor examined Peter to **see/sea/set** if he had the flu.
The teacher checked to **see/sea/set** if the homework was done.
Barbara peered through the window to **see/sea/set** if you were home.
The teacher **would/wood/wild** like someone to hand out the tests.
Jim wanted to know if Susan **would/wood/wild** dance with him.
She thought that she **would/wood/wild** win the game.
The farmer and his cute **son/sun/six** sold carrots at the market.
Mrs. Green put her baby **son/sun/six** to bed for a nap.
Mr. Brown is proud of his only **son/sun/six** who is a soldier.
Please put the book back **where/wear/wire** you got it.
Sam couldn't think **where/wear/wire** he put his keys.
Tim knows **where/wear/wire** his mother hides the cookies.
The coach wasn't sure **whether/weather/winter** his team could win.
The little girl asked **whether/weather/winter** she could stay up late.
The doctor will tell you **whether/weather/winter** you have the flu.

Table C2: Homophone foil sentences: High frequency correct, low frequency error

The team captains decided **which/witch/whirl** players they wanted.
David didn't know **which/witch/whirl** chocolate bar he wanted.
The janitor showed us **which/witch/whirl** recycling box is for paper.
The fireworks **made/maid/male** a very loud noise.
Last night Janice **made/maid/male** supper for her family.
The student really **made/maid/male** a big mistake when she told a lie.
The doctor wanted to **do/due/doe** something about the injury fast.
Jason hoped to **do/due/doe** something fun on his holiday.
The teacher told him to **do/due/doe** the math problems again.
Sara wants a sweater **or/oar/oat** a video for her birthday.
You can have an apple **or/oar/oat** an orange for lunch today.
Use a pencil **or/oar/oat** pen to write your story.
Kevin ripped his new **pair/pear/pain** of jeans when he fell.
Linda tried on a **pair/pear/pain** of running shoes.
Nancy's mom knit her a **pair/pear/pain** of mittens.
Her cousin Maria has **been/bin/bun** taking swimming lessons.
Alice and Sam have **been/bin/bun** to Detroit twice this month.
The Miller's dog has **been/bin/bun** found wandering downtown.
Michael was **so/sew/sin** tired after walking all day.
The lake was **so/sew/sin** cold that nobody wanted to swim.
The movie was **so/sew/sin** sad that we all cried.
The new hockey sticks **break/brake/brick** too easily.
The cups will **break/brake/brick** if they are dropped.
Lisa's new radio will **break/brake/brick** if she isn't careful.
At school we learned how **steel/steal/stall** is produced.
We drove over the **steel/steal/stall** railway bridge.
Max tends the furnace at the **steel/steal/stall** mill in town.

Table C3: Homophone foil sentences: Low frequency correct, high frequency error

Diana likes to go around in **bare/bear/barn** feet at home.
Josh formed a snowball with his **bare/bear/barn** hands today.
The room looked **bare/bear/barn** when all the furniture was gone.
Mrs. Watts gave us **plain/plane/plant** brown paper for our poster.
The ice cream served at the picnic was **plain/plane/plant** vanilla.
Greg ate two bags of **plain/plane/plant** potato chips.
Joey started to stomp and **bawl/ball/bowl** when Rob took his toy.
A baby will **bawl/ball/bowl** if it is hungry.
My grandmother will **bawl/ball/bowl** if I trample her flowers.
Mr. Webb told a funny **tale/tail/tall** about his camping trip.
Yesterday we read a scary **tale/tail/tall** about pirates.
The prisoner told his **tale/tail/tall** to the police.
Dad asked for **peace/piece/place** and quiet during his nap.
The generals hoped for lasting **peace/piece/place** after the war.
The people prayed for **peace/piece/place** in the world.
The swing has a **weak/week/work** link in the chain that holds it up.
Frank felt very **weak/week/work** when he had the flu.
Glen is too **weak/week/work** to lift the heavy box.
The students **blew/blue/black** up lots of balloons for the party.
Alanna quickly **blew/blue/black** out all the candles on her birthday cake.
The storm **blew/blue/black** the snow into huge drifts.
The bags of apples will **weigh/way/wet** five pounds each.
Danny learned what kinds of rockets **weigh/way/wet** the most.
Racing bicycles don't **weigh/way/wet** as much as ordinary bicycles.
The cheerleaders were very **hoarse/horse/hours** by the end of the game.
Pam had a bad cold and a **hoarse/horse/hours** voice.
The old man spoke in a **hoarse/horse/hours** whisper.

Table C4: Homophone foil sentences: Low frequency correct, low frequency error

Mrs. Baker warned us not to **waste/waist/worst** the art supplies.
If you leave the lights on you will **waste/waist/worst** electricity.
The class decided to prevent **waste/waist/worst** at their school.
Ann’s elbow will **heal/heel/heap** if she stops playing tennis.
Jill stayed in bed to help **heal/heel/heap** her sprained knee.
The cuts and bruises will **heal/heel/heap** in a few days.
Scott tried not to **stare/stair/stale** at Amy’s swollen eye.
I don’t like it when people **stare/stair/stale** at me.
People will **stare/stair/stale** if you act silly.
Eric tried to **flee/flea/flaw** when the bull started chasing him.
Many people want to **flee/flea/flaw** from wars in their country.
The family tried to **flee/flea/flaw** their burning house.
Craig’s face turned **pale/pail/palm** when he heard the bad news.
Carol’s new dress is **pale/pail/palm** yellow and pink.
Wendy was quite **pale/pail/palm** when she was sick.
They jogged for two miles without a **pause/paws/pose** to rest.
Alan put the movie on **pause/paws/pose** while he got a snack.
The chatter will **pause/paws/pose** when the president arrives.
The rock was **thrown/throne/throat** at someone in the crowd.
Marco’s homework was **thrown/throne/throat** in the garbage by mistake.
Dick has never **thrown/throne/throat** a good pitch to Henry.
The repairman had to **tow/toe/ton** the car to the garage.
Julia planned to **tow/toe/ton** her boat home on a trailer.
Don’s job is to **tow/toe/ton** large ships into the harbor.
The huge waves nearly tipped over the **ferry/fairy/fancy** to the island.
Cars must travel by **ferry/fairy/fancy** to get across the river.
The captain steered the **ferry/fairy/fancy** towards the dock.

Table C5: Probability of fixating on target: Fixed effects

	Estimate (beta)	Std. error	z-value	p-value
Group	0.007	0.21	0.033	0.97
Corr vs. hom	0.1	0.16	0.64	0.52
Corr vs. spell	0.09	0.16	0.58	0.56
Group*corrvhom	0.083	0.33	0.26	0.8
Group*corrvspell	0.66	0.33	2.02	0.044*
D: corrvhom	0.16	0.26	0.62	0.53
D: corrvspel	0.52	0.26	2.01	0.044*
H: corrvhom	0.07	0.2	0.34	0.73
H: corrvspell	-0.15	0.2	-0.76	0.45

Table C6: Probability of fixating on target: Helmert contrasts

	Estimate	Std. error	z-value	p-value
Contrast 1	-0.096	0.13	-0.71	0.48
Contrast 2	-0.009	0.16	-0.056	0.96
Group*contrast1	-0.37	0.28	-1.33	0.18
Group*contrast2	0.58	0.34	1.72	0.086
D: contrast1	-0.34	0.22	-1.54	0.12
D: contrast2	0.36	0.27	1.35	0.18
H: contrast1	0.04	0.17	0.24	0.81
H: contrast2	-0.22	0.2	-1.08	0.28

Table C7: First single fixation duration: Fixed effects

	Estimate	Std. error	df	t-value	p-value
Group	-7.25	13.95	24.79	-0.52	0.61
Corr vs. hom	14.68	7.12	500.53	2.063	0.040*
Corr vs. spell	7.093	7.09	499.04	0.15	0.88
Group*corrvhom	9.47	15.04	498.45	0.63	0.53
Group*corrvspell	0.54	14.69	497.34	0.037	0.97
D: corrvhom	20.95	11.68	179.92	1.79	0.075
D: corrvspel	2.02	11.12	180.04	0.18	0.86
H: corrvhom	11.51	8.98	318.34	1.28	0.2
H: corrvspell	1.19	9.21	316.02	0.13	0.9

Table C8: First single fixation duration: Helmert contrasts

	Estimate	Std. error	df	t-value	p-value
Contrast 1	-7.88	6.12	498.14	-1.29	0.2
Contrast 2	-13.6	7.23	504.15	-1.88	0.061
Group*contrast1	-5	12.84	496.5	-0.39	0.7
Group*contrast2	-8.93	15	501.74	-0.6	0.55
D: contrast1	-11.48	9.88	179.51	-1.16	0.25
D: contrast2	-18.94	11.38	181.28	-1.66	0.098
H: contrast1	-6.35	7.8	316.14	-0.82	0.42
H: contrast2	-10.32	9.36	319.83	-1.1	0.27

Table C9: Regression probability: Fixed effects

	Estimate	Std. error	z-value	p-value
Group	0.56	0.23	-2.42	0.016*
Corr vs. hom	0.8	0.18	4.56	< 0.0001***
Corr vs. spell	1.17	0.17	6.7	< 0.0001***
Group*corrvhom	-0.15	0.37	-0.41	0.68
Group*corrvspell	-0.57	0.37	-1.54	0.12
D: corrvhom	0.7	0.31	2.25	0.025*
D: corrvspel	0.79	0.31	2.58	0.0099**
H: corrvhom	0.84	0.21	3.97	< 0.0001***
H: corrvspell	1.34	0.22	6.33	< 0.0001***

Table C10: Regression probability: Helmert contrasts

	Estimate	Std. error	z-value	p-value
Contrast 1	-0.98	0.15	-6.34	< 0.0001 ***
Contrast 2	0.37	0.16	2.23	0.026*
Group*contrast1	0.36	0.33	1.11	0.27
Group*contrast2	-0.42	0.35	-1.18	0.24
D: contrast1	-0.74	0.27	-2.74	0.0062**
D: contrast2	0.095	0.29	0.33	0.75
H: contrast1	-1.09	0.19	-5.84	< 0.0001***
H: contrast2	0.5	0.2	2.51	0.012*

Table C11: Rereading time: Fixed effects

	Estimate	Std. error	df	t-value	p-value
Group	-24.8	52.15	28.39	-0.48	0.64
Corr vs. hom	131	49.06	480.24	2.67	0.0078**
Corr vs. spell	189.95	47.51	478.88	4	<0.0001***
Group*corrvhom	39.96	103.05	476.97	0.39	0.7
Group*corrvspell	-44.95	101.59	475.84	-0.44	0.7
D: corrvhom	158.17	92.42	150.65	1.71	0.089
D: corrvspel	157.64	92.42	150.69	1.71	0.09
H: corrvhom	117.6	57.56	326.78	2.043	0.042*
H: corrvspell	202.67	55.01	324.43	3.68	0.0027**

Table C12: Rereading time: Helmert contrasts

	Estimate	Std. error	df	t-value	p-value
Contrast 1	-160.48	43.41	479.62	-3.7	0.00024***
Contrast 2	58.95	42.33	479.49	1.39	0.16
Group*contrast1	2.4	91.39	476.84	0.026	0.98
Group*contrast2	2.4	91.39	476.66	-0.92	0.36
D: contrast1	-157.9	82.09	150.94	-1.92	0.056
D: contrast2	-0.53	84.95	149.53	-0.006	1
H: contrast1	-160.13	50.88	325.54	-3.15	0.0018*
H: contrast2	85.07	48.19	326.48	1.77	0.079

Appendix D

Table D1: Block 1 of homophone foil self-paced reading paradigm sentences

S1	The	new	movie	was	sew	sad	that	we	all	cried
S2	Josh	formed	a	big	snowball	with	his	bear	hands	today
S3	The	generals	hoped	for	lasting	piece	after	the	long	war
S4	My	grandmother	will	bowl	if	I	trample	her	fresh	garden
S5	Ayanna	wants	a	sweater	or	a	scarf	for	her	birthday
S6	Max	tends	the	furance	at	the	steel	mill	in	town
S7	Andres	tried	to	flea	when	the	bull	was	chasing	him
S8	Mrs.	Robinson	told	us	not	to	waist	the	art	supplies
S9	Marco's	homework	was	accidentally	throat	into	the	garbage	by	Henry
S10	It	is	hard	to	hear	the	words	of	the	song
S11	The	teacher	told	him	to	doe	the	math	problems	again
S12	Makia	put	the	movie	on	pose	while	getting	a	snack
S13	Laurie	and	Kate	decided	to	meat	each	other	after	school
S14	The	singers'	voices	were	hoarse	after	they	sang	their	songs
S15	The	doctor	will	tell	you	whether	you	have	the	flu
S16	The	small	bag	of	apples	will	way	only	two	pounds
S17	The	teacher	decided	to	set	if	the	homework	was	done
S18	The	janitor	showed	us	witch	recycling	box	is	for	paper
S19	Cars	must	travel	by	fancy	to	get	on	the	island
S20	Alanna	blew	out	all	the	candles	on	her	birthday	cake
S21	Jerome's	mom	knit	him	a	pear	of	red	mittens	yesterday
S22	Tim	says	he	knows	wire	his	mother	hides	the	cookies
S23	Frank	felt	work	when	he	had	the	flu	last	month
S24	The	Miller's	brown	dog	has	bin	found	wandering	alone	downtown
S25	Lisa's	new	glass	vase	will	break	if	she	isn't	careful
S26	I	just	finished	another	book	boy	my	favorite	mystery	author
S27	Gerard	is	proud	of	his	sun	who	is	who	soldier
S28	She	thought	she	would	win	the	soccer	game	last	Saturday
S29	The	cuts	and	bruises	will	heal	in	a	few	days
S30	Daryl	and	Michael	want	hockey	posters	for	their	dorm	room
S31	The	ice	cream	after	dinner	was	plant	vanilla	with	sprinkles
S32	Other	people	might	stale	if	you	act	silly	in	public
S33	The	teacher	read	a	tale	about	pirates	to	the	class
S34	Wendy	was	quite	pail	when	she	was	sick	last	week
S35	The	young	student	male	a	big	mistake	when	she	lied
S36	Don's	job	is	to	ton	large	ships	into	the	harbor

Table D2: Block 2 of homophone foil self-paced reading paradigm sentences

S1	The	new	movie	was	sin	sad	that	we	all	cried
S2	Josh	formed	a	big	snowball	with	his	barn	hands	today
S3	The	generals	hoped	for	lasting	place	after	the	long	war
S4	My	grandmother	will	bawl	if	I	trample	her	fresh	garden
S5	Ayanna	wants	a	sweater	oar	a	scarf	for	her	birthday
S6	Max	tends	the	furance	at	the	steal	mill	in	town
S7	Andres	tried	to	flaw	when	the	bull	was	chasing	him
S8	Mrs.	Robinson	told	us	not	to	worst	the	art	supplies
S9	Marco's	homework	was	accidentally	thrown	into	the	garbage	by	Henry
S10	It	is	hard	to	here	the	words	of	the	story
S11	The	teacher	told	him	to	do	the	math	problems	again
S12	Makia	put	the	movie	on	pause	while	getting	a	snack
S13	Laurie	and	Kate	decided	to	mean	each	other	after	school
S14	The	actors'	voices	were	horse	after	they	performed	their	play
S15	The	doctor	will	tell	you	weather	you	have	the	flu
S16	The	small	bag	of	apples	will	wet	only	two	pounds
S17	The	teacher	decided	to	see	if	the	homework	was	done
S18	The	janitor	showed	us	whirl	recycling	box	is	for	paper
S19	Cars	must	travel	by	ferry	to	get	on	the	island
S20	Alanna	blue	out	all	the	candles	on	her	birthday	cake
S21	Jerome's	mom	knit	him	a	pain	of	red	mittens	yesterday
S22	Tim	says	he	knows	where	his	mother	hides	the	cookies
S23	Frank	felt	weak	when	he	had	the	flu	last	month
S24	The	Miller's	brown	dog	has	bun	found	wandering	alone	downtown
S25	Lisa's	new	glass	vase	will	brake	if	she	isn't	careful
S26	I	just	finished	another	book	by	my	favorite	mystery	author
S27	Gerard	is	proud	of	his	six	who	is	who	soldier
S28	She	thought	she	wood	win	the	soccer	game	last	Saturday
S29	The	cuts	and	bruises	will	heel	in	a	few	days
S30	Daryl	and	Michael	want	hockey	posters	form	their	dorm	room
S31	The	ice	cream	after	dinner	was	plain	vanilla	with	sprinkles
S32	Other	people	might	stare	if	you	act	silly	in	public
S33	The	teacher	read	a	tail	about	pirates	to	the	class
S34	Wendy	was	quite	palm	when	she	was	sick	last	week
S35	The	young	student	made	a	big	mistake	when	she	lied
S36	Don's	job	is	to	tow	large	ships	into	the	harbor

Table D3: Block 3 of homophone foil self-paced reading paradigm sentences

S1	The	new	movie	was	so	sad	that	we	all	cried
S2	Josh	formed	a	big	snowball	with	his	bare	hands	today
S3	The	generals	hoped	for	lasting	peace	after	the	long	war
S4	My	grandmother	will	ball	if	I	trample	her	fresh	garden
S5	Ayanna	wants	a	sweater	oat	a	scarf	for	her	birthday
S6	Max	tends	the	furance	at	the	stall	mill	in	town
S7	Andres	tried	to	flee	when	the	bull	was	chasing	him
S8	Mrs.	Robinson	told	us	not	to	waste	the	art	supplies
S9	Marco's	homework	was	accidentally	throne	into	the	garbage	by	Henry
S10	It	is	hard	to	hair	the	words	of	the	story
S11	The	teacher	told	him	to	due	the	math	problems	again
S12	Makia	put	the	movie	on	paws	while	getting	a	snack
S13	Laurie	and	Kate	decided	to	meet	each	other	after	school
S14	The	actors'	voices	were	hours	after	they	performed	their	play
S15	The	doctor	will	tell	you	winter	you	have	the	flu
S16	The	small	bag	of	apples	will	weigh	only	two	pounds
S17	The	teacher	decided	to	sea	if	the	homework	was	done
S18	The	janitor	showed	us	which	recycling	box	is	for	paper
S19	Cars	must	travel	by	fairy	to	get	on	the	island
S20	Alanna	black	out	all	the	candles	on	her	birthday	cake
S21	Jerome's	mom	knit	him	a	pair	of	red	mittens	yesterday
S22	Tim	says	he	knows	wire	his	mother	hides	the	cookies
S23	Frank	felt	week	when	he	had	the	flu	last	month
S24	The	Miller's	brown	dog	has	been	found	wandering	alone	downtown
S25	Lisa's	new	glass	vase	will	brick	if	she	isn't	careful
S26	I	just	finished	another	book	by	my	favorite	mystery	author
S27	Gerard	is	proud	of	his	son	who	is	who	soldier
S28	She	thought	she	wild	win	the	soccer	game	last	Saturday
S29	The	cuts	and	bruises	will	heap	in	a	few	days
S30	Daryl	and	Michael	want	hockey	posters	for	their	dorm	room
S31	The	ice	cream	after	dinner	was	plane	vanilla	with	sprinkles
S32	Other	people	might	stair	if	you	act	silly	in	public
S33	The	teacher	read	a	tall	about	pirates	to	the	class
S34	Wendy	was	quite	pale	when	she	was	sick	last	week
S35	The	young	student	maid	a	big	mistake	when	she	lied
S36	Don's	job	is	to	toe	large	ships	into	the	harbor

Table D4: Phonological processing lexical decision task word list

High-frequency	Low-frequency	Pseudohomophones	Nonwords
made	brick	freche	ghound
by	bun	phrost	woled
waste	pain	hure	whuip
pause	flea	heiled	phruds
stare	blue	phaun	menned
meet	ton	traides	croot
so	pose	phaught	skairs
where	heel	fraze	lears
ferry	throne	greized	knome
break	way	poes	wrux
hours	bear	phreeks	bumbs
pear	week	phur	warque
been	horse	wird	gorls
steal	male	kog	buide
hair	tail	knymphs	ploars
winter	worst	phite	marr
wear	heap	taque	whanx
thrown	stall	kude	chyne
steel	flaw	roured	rhusks
which	pail	phays	slieng
pale		glair	whepes
witch		rhite	hude
for		whypes	knosh
meat		scroles	pind
boy		braide	knourt
sew			
hoarse			
hear			
whether			

Table D5: Orthographic processing lexical decision task word list

Words	Words, cont	TL targets	RL targets
cucumber	import	condece	concete
romantic	minister	parcitle	fumeral
habitat	humanity	indicert	indisect
nominate	indirect	nonimate	prosit
please	misery	hatibat	relade
scratch	charge	misinter	magority
humanity	charter	gerenal	limifed
fitness	profit	ciziten	sedarate
expect	castle	marojity	humanify
express	comedy	hunamity	haditat
absorb	general	miresy	mifery
particle	article	litimed	parficle
majority	protest	detupy	cusfody
context	contract	cumucber	gravify
mature	separate	retale	madure
candle	platform	marute	minisfer
deputy	medicine	protif	romanfic
island	insert	grativy	cucunber
warning	relate	cusdoty	nominafe
offender	flavor	furenal	conedy
limited	gravity	mecidine	cifizen
funeral	second	hunamity	genecal
concede	couple	serapate	deduty
citizen	extend	ronamtic	meficine
express	Custody	codemy	humanify

Table D6: SPR resp, correct: Fixed effects

	Estimate	Std. error	z-value	p-value
Group	-0.54	0.53	-1.034	0.3
D: WordvH	-0.36	0.34	-1.06	0.29
D: WordvNH	-0.35	0.34	-1.02	0.31
H: WordvH	1.16	0.52	2.24	0.025*
H: WordvNH	2.46	0.56	4.39	< 0.0001***

H, word vs. homophonic: $R^2 = 1.16$, 95% CI: [0.15, 2.18]
H, word vs. non-homophonic: $R^2 = 2.46$, 95% CI: [1.36, 3.55]

Table D7: SPR resp, correct: Helmert contrasts

	Estimate	Std. error	z-value	p-value
Contrast 1	20.1	0.4	-5.16	< 0.0001***
Contrast 2	-1.06	0.44	-2.38	0.017*
Group* Contrast1	-2.16	0.42	-5.16	< 0.0001***
Group* Contrast2	-1.27	0.47	-2.7	0.0069**
D: Contrast 1	0.36	0.3	1.18	0.24
D: Contrast 2	0.014	0.32	0.043	0.97
H: Contrast 1	-1.7	0.43	-3.96	< 0.0001***
H: Contrast 2	1.15	0.52	2.22	0.027*

Group*contrast 1: $R^2 = -2.16$, 95% CI: [-2.98, -1.34]
Group*contrast 2: $R^2 = -1.27$, 95% CI: [-2.19, -0.35]
Hearing: contrast 1: $R^2 = -1.81$, 95% CI: [-2.71, -0.91]
Hearing: Contrast 2: $R^2 = -1.3$, 95% CI: [-2.39, -0.2]

Table D8: SPR correct RT: Fixed effects

	Estimate	Std. error	df	t-value	p-value
Group	-0.085	0.25	16.2	-0.32	0.75
D: WordvH	0.1	0.11	152.69	0.91	0.36
D: WordvNH	0.011	0.11	158.82	0.099	0.92
H: WordvH	-0.091	0.078	120.14	-1.17	0.24
H: WordvNH	-0.045	0.075	108.39	-0.6	0.55

Table D9: SPR correct RT: Helmert contrasts

	Estimate	Std. error	df	t-value	p-value
Contrast 1	-0.096	0.2	138.61	-0.47	0.64
Contrast 2	0.22	022	123.96	1	0.32
Group* Contrast1	-0.58	0.35	865.12	0.17	0.87
Group* Contrast2	-0.35	0.37	871.7	-0.95	0.35
D: Contrast 1	-0.058	0.1	149.88	-0.58	0.56
D: Contrast 2	0.092	0.1	176.18	0.83	0.41
H: Contrast 1	-0.068	0.69	120.27	0.99	0.32
H: Contrast 2	-0.046	0.068	93.4	-0.68	0.5

Table D10: Advance time: Fixed effects

	Estimate	Std. error	df	t-value	p-value
Group	0.14	0.14	6.98	1.06	0.33
D: WordvH	0.051	0.055	68.54	0.92	0.36
D: WordvNH	0.064	0.055	67.55	1.15	0.25
H: WordvH	0.085	0.048	56.38	1.75	0.085
H: WordvNH	0.088	0.048	56.75	1.82	0.075

Table D11: Advance time: Helmert contrasts

	Estimate	Std. error	df	t-value	p-value
Contrast 1	-0.064	0.044	67.52	-1.45	0.15
Contrast 2	0.012	0.048	64.69	0.24	0.81
Group* Contrast1	-0.027	0.04	489.41	-0.68	0.5
Group* Contrast2	-0.01	0.043	490.37	-0.24	0.81
D: Contrast 1	-0.057	0.049	67.97	-1.18	0.24
D: Contrast 2	0.013	0.053	68.28	0.25	0.81
H: Contrast 1	0.085	0.048	56.38	1.75	0.085
H: Contrast 2	0.088	0.48	56.75	1.82	0.075

Table D12: Sounds, correct: Fixed effects

	Estimate	Std. error	z-value	p-value
Group	0.093	0.73	0.13	0.9
D: wordvNW	0.082	0.21	0.39	0.7
D: wordvPH	-0.35	0.22	-1.61	0.11
H: wordvNW	0.57	0.18	3.13	0.0018**
H: wordvPH	0.39	0.18	2.16	0.031*

R^2 = 0.57, 95% CI: [0.21, 0.93]
R^2 = 0.39, 95% CI: [0.04, 0.75]

Table D13: Sounds, correct: Helmert contrasts

	Estimate	Std. error	z-value	p-value
Group*contrast1	-0.62	0.23	-2.71	0.0067**
Group*contrast2	-0.25	0.32	-0.78	0.43
D: contrast1	0.13	0.17	0.76	0.45
D: contrast2	0.43	0.25	1.73	0.084
H: contrast1	-0.48	0.15	-3.21	0.0013**
H: contrast2	0.18	0.21	0.86	0.39

Group*cont1: R^2 = -0.62, 95% CI: [-1.06, -0.17]
H: contr1: R^2 = -0.48, 95% CI: [-0.23, 0.58]

Table D14: Sounds, correct RT: Fixed effects

	Estimate	Std. error	df	t-value	p-value
Group	0.03	0.089	19.68	0.33	0.74
D: wordvNW	0.11	0.04	94.12	2.68	0.0087**
D: wordvPH	0.078	0.039	83.098	2.01	0.048*
H: wordvNW	0.18	0.35	163.47	3.16	< 0.0001***
H: wordvPH	0.11	0.034	184.6	3.16	0.0019**

Deaf; R^2 = 0.27, 95% CI: [0.07, 0.47]
Deaf: R^2 = 0.2, 95% CI: [0, 0.39]
Hearing: R^2= 0.42, 95% CI: [0.25, 0.58]
Hearing: R^2 = 0.26, 95% CI: [0.1, 0.42]

Table D15: Sounds, correct RT: Helmert contrasts

	Estimate	Std. error	df	t-value	p-value
Contrast 1	-0.12	0.023	143.15	-5.18	< 0.0001***
Contrast 2	0.052	0.033	133.99	1.61	0.11
Group* Contrast1	0.062	0.039	1341.08	1.59	0.11
Group* Contrast2	-0.029	0.055	1335.99	-0.53	0.6
D: Contrast 1	-0.92	0.032	88.59	-2.87	0.0052**
D: Contrast 2	0.03	0.045	88.43	0.65	0.52
H: Contrast 1	-0.14	0.028	178.36	-5.02	< 0.0001***
H: Contrast 2	0.067	0.04	164.02	1.66	0.098

Contrast 1: R^2 = -0.29, 95% CI: [-0.4, -0.18]
D: contrast 1: R^2 = -0.24, 95% CI: [-0.15, 0.3]
H: contrast 1: R^2 = -0.34, 95% CI: [-0.47, -0.21]

Table D16: Spelling, correct: Fixed effects

	Estimate	Std. error	z-value	p-value
Group	0.54	0.44	1.24	0.22
D: word vs. RL	1.57	0.15	10.76	< 0.0001***
D: word vs TL	1.7	0.15	11.5	< 0.000***
H: word vs. RL	-0.027	0.24	-0.11	0.91
H: word vs. TL	-1.72	0.22	-7.9	< 0.0001***

D: word vs. RL: R^2 = 1.42, 95% CI: [1.08, 1.76]
D: word vs. TL: R^2 = 1.74, 95% CI: [1.39, 2.08
H: RL vs. word: R^2 = -1.72, 95% CI: [-2.15, -1.29]

Table D17: Spelling, correct: Helmert contrasts

	Estimate	Std. error	z-value	p-value
Group* Contrast1	0.029	0.2	0.15	0.88
Group* Contrast2	-0.23	0.25	-0.92	0.36
D: Contrast 1	-1.58	0.15	-10.6	< 0.0001***
D: Contrast 2	-0.32	0.18	-1.74	0.082
H: Contrast 1	-1.71	0.18	-9.42	< 0.0001***
H: Contrast 2	0.027	0.24	0.11	0.91

D, contrast 1: R^2 = -1.58, 95% CI: [-1.87, -1.28]
H, contrast 1: R^2 = -1.71, 95% CI: [-2.06, -1.35]

Table D18: Spelling, correct RT: Fixed effects

	Estimate	Std. error	df	t-value	p-value
Group	0.28	0.11	17	2.49	0.023*
D: word vs. RL	0.06	0.022	101.95	2.68	0.0087**
D: word vs. TL	0.049	0.034	116.45	2.15	0.033*
H: word vs. RL	-0.22	0.053	112.09	4.29	< 0.0001***
H: word vs. TL	0.043	0.052	110.97	0.82	0.41

Group: R^2 = 0.66, 95% CI: [0.14, 1.18]
Deaf: word vs. RL: R^2 = 0.23, 95% CI: [0.06, 0.41]
Deaf: word vs. TL: R^2 = 0.19, 95% CI: [0.02, 0.37]
Hearing: word vs. RL: R^2 = 0.45, 95% CI: 0.25, 0.67]

Table D19: Spelling, correct RT: Helmert contrasts

	Estimate	Std. error	df	t-value	p-value
Group* Contrast1	0.1	0.32	1619.13	3.09	0.002**
Group* Contrast2	-0.2	0.05	1624.25	-3.97	< 0.0001***
D: Contrast 1	-0.055	0.018	100.83	-3.02	0.0032**
D: Contrast 2	0.011	0.027	125.91	0.38	0.7
H: Contrast 1	-0.13	0.042	105.46	-3.19	0.0019**
H: Contrast 2	0.18	0.063	123.82	2.92	0.0041**

Group * contrast1: R^2 = -0.24, 95% CI: [-0.39, -0.09]
Group * contrast2: R^2 = -0.48, 95% CI: [-0.71, -0.24]
Deaf, contrast 1: R^2 = -0.21, 95% CI: [-0.35, -0.07]
Hearing, contrast 1: R^2 = -0.27, 95% CI: [-0.44, -0.11]
Hearing, contrast 2: R^2 = -0.37, 95% CI: [-0.62, -0.12]

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