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Word representation and processing in deaf readers: Evidence from ERPs and eye-tracking

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy

in

Language and Communicative Disorders

by

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The dissertation of Brittany Alexandra Lee is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

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DEDICATION

To my family, who taught me the value of hard work and education but kept me grounded and laughing along the way.

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ABSTRACT OF THE DISSERTATION

Word representation and processing in deaf readers: Evidence from ERPs and eye-tracking

by

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Skilled hearing readers activate phonological, orthographic, and semantic representations in order to recognize and comprehend words. However, deaf readers may achieve reading comprehension by different means. More specifically, enhanced visual attention, reduced access to phonology, and bimodal bilingualism may influence how deaf readers represent and process words. In this dissertation, I introduce the topic of deaf readers and review literature describing

the unique sensory and linguistic experiences that shape how they read. I then present data from a set of behavioral, eye tracking, and electrophysiological studies to compare deaf and hearing readers matched on reading skill and identify alternative approaches to achieving reading success. In Chapter 2, I present a pair of eye tracking studies that suggest deaf readers are more efficient at processing words in sentences and more sensitive to letter transpositions compared to hearing readers. In Chapter 3, I present ERP data from a masked lexical decision experiment showing similarities in how deaf and hearing readers process words and nonwords at sublexical and lexical levels. In Chapter 4, I use ERP evidence to demonstrate that deaf readers co-activate English word representations when recognizing ASL signs. Overall, deaf readers are more sensitive to the visual-orthographic structure of words, which makes them more reliant on orthographic representations during word recognition and more efficient at processing visual word forms in sentence reading.

Chapter 1: Introduction

A vast literature on reading and reading disorders is dedicated to understanding how hearing readers integrate orthographic, phonological, and semantic information to recognize and comprehend words. A reader must first decode the visual features of a printed word, which activate the word's orthographic and phonological codes at the sublexical level. These sublexical representations are then mapped onto whole-word representations, which in turn are mapped onto lexical semantic representations. However, less is known about if and how deaf readers carry out the same processes in order to access a word's meaning. In this dissertation, I will address the topic of word representation and processing in deaf readers. I begin by introducing the topic of deaf literacy and highlighting its importance as an educational and public health issue. I then review relevant studies on the unique sensory and linguistic experiences of deaf readers, namely their enhanced visual attention in the periphery, reduced access to speech-based phonology, and bimodal bilingualism. Finally, I present a series of three studies in which I use eye tracking and event-related potentials (ERPs) to examine each of these defining characteristics of deaf readers and how they influence word representation and processing. This comparison of deaf readers and hearing readers with similar reading ability helps identify alternative pathways to reading success.

1.1 Deaf Readers

People read more now than ever before in human history. Global literacy rates have steadily increased over the past 50 years, and 86% of adults and 91% of children were literate in 2016 (UNESCO Institute for Statistics, 2017). The growing number of readers worldwide magnifies the profound impact that literacy has on socioeconomic opportunities and quality of life. Poor reading ability has been linked to negative outcomes in education, employment, income, civic engagement, and even parent-child interactions (Kutner et al., 2007). Given both the prevalence and importance of literacy, it is critical to understand how people read and to address disparities in reading outcomes.

One population that has difficulty achieving high levels of reading skill is deaf readers. Historically, literacy rates have been lower in the deaf population than the general population (Kelly & Barac-Cikoja, 2007), and this achievement gap between deaf and hearing readers has not closed over the past three decades (Qi & Mitchell, 2012). Limited literacy puts deaf individuals at greater risk of marginalization in the contexts of employment (Luft, 2000), the justice system (Morgan, 2001), and healthcare (Kuenburg et al., 2016; Napier & Kidd, 2013; McKee & Paasche-Orlow, 2012). In order to address this disparity, research should inform educational approaches to reading, which have traditionally built on spoken language skills for hearing readers (Perfetti & Sandak, 2000). By better understanding similarities and differences between deaf and hearing readers, educators can tailor instruction to support reading proficiency for deaf individuals and ultimately break down socioeconomic barriers that result from poor literacy in the Deaf community.

Research on deaf readers can also contribute to a better theoretical understanding of reading processes in general. Because of their hearing loss, deaf readers have reduced or altered auditory input and access to English phonology, a central component of most models of reading developed with hearing readers in mind. By refining such theories, research with deaf readers stands to inform reading interventions for deaf and hearing readers alike. In addition, comparing deaf and hearing readers matched on reading skill helps characterize different but equally successful ways of recognizing and comprehending words.

It is important to note that the deaf and hard of hearing population represents varying levels of hearing, signing skill, and spoken language proficiency, and each of these factors may influence reading patterns. However, for the purpose of this dissertation, it is necessary to control for this variability. The research presented here therefore examines reading patterns in a relatively homogeneous group of severely-to-profoundly deaf adults who are early or native users of a signed language. Severely-to-profoundly deaf individuals are likely to have limited access to English phonology and are less likely to access phonology during reading compared to oral deaf individuals or hearing readers (e.g., Koo et al., 2008; Hirshorn et al., 2015). This linguistic profile is crucial for evaluating reading models and practices centered on phonology. In addition, early and native signers are less likely to experience language deprivation, which is known to impact linguistic, cognitive, and psychosocial development (Humphries et al., 2012). Finally, studying adults allows us to determine the end state of successful reading, distinct from changes that occur during development.

1.2 Enhanced Visual Attention in the Periphery

Sentence reading is more naturalistic than single word reading because it allows the reader to view and process multiple words at a time. Both deaf and hearing readers begin processing upcoming words in the parafovea before they are fixated (Bélanger, Slattery, et al., 2012), and so extrafoveal processing may support visual word recognition and comprehension.

The issue of extrafoveal word processing is especially important for deaf readers because deaf individuals have also been shown to have enhanced visual attention in the periphery compared to hearing individuals (e.g., Bavelier et al., 2006). This enhancement extends from low-level visual perceptual tasks (Proksch & Bavelier, 2002; Dye et al., 2008) to more complex tasks like reading. For example, skilled adult hearing readers have a visual span of 3 to 4 characters to the left of fixation and 14 to 15 characters to the left of fixation (McConkie & Rayner, 1975). By comparison, skilled adult deaf readers have a visual span of up to 18 characters to the right of fixation (Bélanger, Slattery, et al., 2012). In short, deaf readers are able to perceive and attend to more letters within a single fixation compared to reading-matched hearing peers.

However, it is unclear whether additional visual information gained from pre-processing words in the parafovea is advantageous to deaf readers. Dye and colleagues (2008) suggested that deaf individuals may find increased access to parafoveal information distracting, causing slower processing in the fovea, longer fixations, and slower reading. Bélanger, Slattery, and colleagues (2012) tested this assertion in an eye tracking experiment that measured common eye movements during reading: regressions (going back in the text to reread), saccade length (how many characters the eyes pass over between fixations), skipped words (words that are passed over during saccades and not fixated), and refixations (multiple fixations on one - usually longer - word). Deaf readers' efficiency at processing visual word forms was seen in their unique eye movement patterns during sentence reading, as skilled deaf readers had fewer regressions, longer forward saccades, more skipped words, and fewer refixations than skilled hearing readers.

These findings led to the Word Processing Efficiency Hypothesis (Bélanger & Rayner, 2015), in which increased access to parafoveal information makes deaf readers more efficient at extracting the orthographic code that supports lexical access. Importantly, this efficiency was attributed to the visual advantage specific to deafness and was not merely a function of reading skill, as less-skilled deaf readers had comparable visual spans to those of skilled hearing readers. An enhanced visual span (Bélanger et al., 2017) and the associated efficient eye movement patterns (Bélanger et al., 2014) were also seen in young deaf readers relative to reading-matched hearing peers. Thus, deafness results in an early change in visual attention, which in turn affects word recognition even for emerging readers.

1.3 Reduced Access to Speech-Based Phonology

Phonological awareness is a strong predictor of reading ability for hearing individuals (Elbro, 1996). Deaf individuals can develop varying degrees of phonological knowledge depending on their language experience (Hirshorn et al., 2015) and may even employ phonological strategies in memory, rhyme-detection, and pronunciation tasks (Perfetti & Sandak, 2000; Sevcikova Sehyr et al., 2016; Hall & Bavelier, 2010). However, it has been hotly debated whether deaf individuals need to access the phonological code in order to become successful readers (Hanson & Fowler, 1987; Perfetti & Sandak, 2000; Wagner & Torgesen, 1987; Ziegler & Goswami, 2005, Easterbrooks et al., 2008; Paul et al., 2009; Wang et al., 2008) or not (Bélanger et al., 2013; Mayberry et al., 2011; Miller & Clark, 2011; Izzo, 2002; Chamberlain, 2002; Bélanger, Baum, et al., 2012; Cripps & McBride, 2005).

One way to test whether phonological codes are accessed during word reading is with pseudohomophone studies. Pseudohomophones are spelled differently from real words but are pronounced the same as an existing real word (e.g., *brane* for *brain*). In lexical decision tasks, hearing readers have slower responses and more false positives to pseudohomophones compared to control non-words (e.g., Ferrand & Grainger, 1994; Ziegler et al., 2001). This classic pseudohomophone effect is thought to reflect phonological processing during visual word recognition, as a shared phonological representation allows the pseudohomophone to activate the real word's meaning. Indeed, ERP studies show that pseudohomophones produce smaller amplitude N400s compared to non-words (Newman & Connolly, 2004) and spelling controls (e.g., *brine*) (Briesemeister et al., 2009), indicating at least partial activation of a word's meaning through the pseudohomophone's shared phonological representation.

Pseudohomophone studies have been used to test whether deaf readers also activate phonological codes during visual word processing. While some studies have found a behavioral pseudohomophone effect for both deaf and hearing readers (Transler & Reitsma, 2005; Gutierrez-Sigut et al., 2017), most have shown the effect in hearing but not deaf readers (Beech & Harris, 1997; Ormel et al., 2010; Fariña et al., 2017). These latter findings bolster the claim that deaf readers do not automatically activate phonological codes during word reading.

Interestingly, Gutierrez-Sigut and colleagues (2017) found similar ERP pseudohomophone effects for both deaf and hearing Spanish readers. Pseudohomophones elicited smaller N250 and N400 amplitudes compared to a control condition for both groups. These ERP components reflect mapping between orthography and phonology and between words and meaning, respectively (Grainger & Holcomb, 2009), and smaller negativities for the pseudohomophones (compared to control words) suggests that deaf readers *do* automatically activate phonology during visual word recognition. However, the amplitude of the ERP pseudohomophone effect did not correlate with reading ability for the deaf readers (in contrast to the hearing readers), and there was a stronger effect of repeated words (the identity condition) for deaf readers than for hearing readers. These results suggest that orthography may be a more significant contributor to reading ability than phonology for deaf readers. It should also be noted that this study had optimal circumstances for eliciting a pseudohomophone effect: Spanish, unlike English, has a transparent orthography, which may allow deaf readers to more easily map orthography to phonology, and the masked priming paradigm is highly sensitive to early, automatic processes involved in word reading. Thus, deaf readers may be capable of accessing phonological code and may even do so to the same extent or in the same automatic way as hearing readers under certain conditions, but activation of phonological representations is not a requisite for successful reading.

1.4 Bimodal Bilingualism

Deaf readers are also sometimes referred to as sign-print bilinguals or bimodal bilinguals because they are fluent users of both a signed language and the written form of a spoken language. Bimodal bilinguals share some but not all of the linguistic and cognitive features of spoken language bilinguals because their languages do not compete for articulation in the same way that two spoken languages do (Emmorey et al., 2016). Bimodal bilinguals allow us to examine how language co-activation between a signed and written language is the same or different from language co-activation between two spoken languages. This question is especially intriguing as it relates to word processing because ASL does not have a written form and its phonology is based on handshape, location, and movement rather than speech sounds.

Language co-activation in bimodal bilinguals also has important implications for reading. Based on theories of spoken language bilingualism that state bilinguals make use of their first language to access meaning in their less proficient second language (e.g., Kroll & Stewart, 1994), one may predict that less-skilled deaf readers may rely more on ASL than skilled deaf readers. In an ERP study of cross-language phonological priming, Meade and colleagues (2017) found that deaf readers *do* co-activate ASL signs when reading English words. They found that implicit co-activation of ASL signs resulted in phonological priming effects, as seen in an attenuated N400 to targets in word pairs whose ASL translations were related in handshape and location (e.g., GORILLA-BATH) compared to targets in words pairs with unrelated ASL translations (e.g., ACCENT-BATH). Behavioral effects showed that the co-activation of ASL phonology interfered with participants' ability to make a semantic decision in English, resulting in longer reaction times to reject English word pairs that were unrelated in meaning but whose ASL translations shared handshape and location (e.g., BATH-GORILLA). This behavioral interference effect was correlated with reading ability, meaning less-skilled readers were more likely to co-activate ASL and were therefore more susceptible to interference from ASL phonology while making a semantic decision. This study replicates the same finding by Morford and colleagues (2014), suggesting that less skilled deaf readers may use their ASL knowledge to support reading.

While ASL may facilitate reading through co-activation, deaf students will not attain literacy through ASL proficiency alone. Transfer of knowledge across languages entails building associations between ASL and English (Padden & Ramsey, 2000; Mayer & Wells, 1996). One proposed method of cultivating stronger cross-language associations and improving English vocabulary for deaf readers is through “chaining” (Humphries & MacDougall, 1997). With this instructional method, a teacher models a sign along with its corresponding fingerspelled word and its English translation in print. These successive multi-modal representations of the same concept strengthen access to meaning from each format as well as associations between them.

Another method of building cross-language associations is through fingerspelling (Padden & Ramsey, 2000). Signers use fingerspelling by producing distinct handshapes that map onto letters of an alphabet. Although based on English orthography, the manual alphabet is an important part of ASL. Fingerspelling accounts for 15% of vocabulary in ASL discourse (Padden, 1998). It is not acquired by oral deaf children who do not sign (Padden & Ramsey, 2000), yet fully productive fingerspelling abilities only emerge in signing deaf children when they begin learning to read (Padden, 2006; Haptonstall-Nykaza & Schick, 2007). Fingerspelling allows deaf readers to produce fine-grained articulations of unfamiliar words (Maxwell, 1984), develop sensitivity to orthotactic patterns in English (Hanson, 1989), develop phonological awareness (Padden & Hanson, 2000; Leybaert, 2000), increase vocabulary and meta-linguistic skills (Hirsh-Pasek, 1987), and mediate reading comprehension (Hanson et al., 1984). It serves an alternative code for orthographic information that can strengthen orthographic representations, facilitate word recognition, and ultimately support reading comprehension (Puente et al., 2006). Thus, fingerspelling and reading provide reciprocal support for one another, and studying cross-language associations is critical to understanding how sign and print interact for bimodal bilinguals.

1.5. Contribution of the Dissertation

The goal of the present dissertation is to shed light on word representation and processing in deaf readers. To achieve this goal, I conducted eye tracking and ERP experiments that compared deaf and hearing readers matched on reading skill. In Chapter 2, I present a pair of eye tracking studies that consider how orthographic and phonological representations are activated in the parafovea during sentence reading for deaf and hearing readers. In Chapter 3, I present a masked lexical decision ERP study in which I examined how deaf and hearing readers activate orthographic and phonological representations at sublexical and lexical levels as indexed by the N250 and N400 ERP components. Finally, in Chapter 4, I consider how word representations are co-activated during sign recognition. Together, these studies help characterize skilled reading in deaf adults.

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Chapter 2: Deaf readers use visual-orthographic information and efficient eye movements to process words in sentences

2.1 Abstract

Deaf people have differences in visual attention and access to phonology that may influence how they recognize words during sentence reading compared to hearing people. Two eye tracking studies used transposed-letter (TL) nonwords to prime target words for deaf and hearing participants matched on reading ability. Primes were presented in the parafovea and changed to the target words once the reader's eye gaze crossed an invisible boundary. Primes in Experiment 1 were TL nonwords (*setak*) or identity primes (*steak*). Both groups of readers had longer gaze durations on targets with TL primes compared to those with identity primes, and deaf readers refixated targets with TL primes more often that those with identity primes. Primes in Experiment 2 were pronounceable TL nonwords (*barve*) and unpronounceable TL nonwords (*brvae*). The initial landing position was earlier for targets with pronounceable compared to unpronounceable TL nonword primes only for deaf readers. In both experiments, deaf readers had faster reading speeds, shorter gaze durations, more skips, fewer regressions, and fewer refixations on target words compared to hearing readers. These findings suggest that deaf readers are more sensitive to the visual-orthographic structure of word forms and support the Word Processing Efficiency Hypothesis, i.e., deaf readers are more efficient at extracting orthographic information for word recognition than hearing readers.

2.2 Experiment 1: Introduction

Successful readers orchestrate many complex perceptual and linguistic processes. A reader must first extract visual information from a printed word to allow for subsequent orthographic, phonological, and semantic processing that supports word recognition and ultimately comprehension. One population that may offer insights into the mechanisms behind word recognition is deaf readers. Because deaf individuals have reduced or altered access to auditory input, they also have reduced access to speech-based phonology. Instead of relying heavily on phonological awareness for word recognition as hearing readers do, it has been suggested that deaf readers are more attuned to the visual-orthographic structure of words and have tighter orthographic-to-semantic connections (e.g., Bélanger & Rayner, 2015).

One way to test this claim and assess the quality of orthographic representations is with transposed-letter (TL) manipulations. In TL studies, nonwords are formed by transposing two letters in a real word (e.g., *barve* from *brave*). The transposition disrupts the orthographic (and phonological) properties of the word and can reveal how letter identities and positions are encoded in word representations. TL interference effects have been well documented in lexical decision tasks. Hearing readers are slower and less accurate at classifying TL nonwords compared to control nonwords (e.g., Chambers, 1979; O'Connor & Forster, 1981). TL nonwords activate the orthographic representations of their base word and are therefore more likely to be mistaken for real words. This activation occurs despite the letter transposition and regardless of whether the transposed letters are adjacent (e.g., *tosat* from *toast*) or non-adjacent (e.g., *caniso* from *casino*) (Perea & Lupker, 2004), suggesting that letter position must be encoded flexibly in order for word recognition to withstand such disruptions. In ERP studies, hearing readers show attenuated N250s for target words (e.g., *brain*) with TL nonword primes (e.g., *barin*) compared to those with control nonword primes (e.g., *bosin*) (Grainger et al., 2006), indicating that TLs facilitate orthographic processing of their base words.

Several studies have shown that TL effects are largely similar for deaf and hearing readers. Both groups were slower and less accurate at rejecting TL nonwords (e.g., *mecidina* from *medicina*) than replaced-letter nonwords (e.g., *mesifina* from *medicina*) in a behavioral lexical decision study in Spanish (Fariña et al., 2017). Both groups also showed greater amplitude N400s to TL nonwords compared to replaced-letter nonwords in an ERP lexical decision study (Fariña et al., 2016) and to target words with TL primes compared to those with substitution primes in an ERP masked priming paradigm (Meade et al., 2020). These ERP studies provide evidence that the TL nonwords activated representations of real words despite the letter transpositions. Both deaf and hearing readers must have orthographic representations that are coarse-grained or flexible enough to allow for lexical access even when a transposition disrupts the word's orthographic properties. Together, these studies show that deaf and hearing readers are similar in their sensitivity to orthographic information during word recognition, despite differences in their phonological awareness.

However, one major limitation of these TL studies with deaf readers is that they were all conducted at the single-word level. Studies with hearing readers demonstrate that letter transpositions are associated with costs not only for recognizing single words (see Grainger, 2008 for a review) but also for recognizing words in the context of sentences. Reading text containing words with letter transpositions results in longer fixation durations, more refixations, and more regressions compared to reading text without transpositions (Blythe et al., 2014; Johnson et al., 2007; Mirault et al., 2019; Rayner et al., 2006; White et al., 2008). Sentence-level studies have the added benefit of being more naturalistic, allowing for more top-down processing and providing greater context to support reading comprehension.

Sentence-level studies are especially important for deaf readers because of differences in another sensory domain that affects how they read: visual attention. By virtue of their deafness and/or sign language experience, deaf individuals are known to have enhanced visual attention in their peripheral visual field compared to hearing individuals (e.g., Dye & Bavalier, 2013, Pavani

& Bottari, 2012). This enhancement extends not just to detecting stimuli in low-level perceptual tasks (Dye et al., 2008) but also to processing visual-linguistic information in more complex tasks like sign comprehension (Schotter et al., 2020). In terms of reading, this enhancement results in a wider perceptual span for deaf readers; skilled adult deaf readers have a reading span of up to 18 characters to the right of fixation (Bélanger, Slattery, et al., 2012), which is several characters more than the 14 to 15 characters skilled adult hearing readers perceive to the right of fixation (McConkie & Rayner, 1975). A wider reading span has also been found for deaf children, who perceive 10 characters to the right of fixation compared to six characters for their hearing counterparts (Bélanger, Lee, et al., 2017). Deaf readers are able to perceive and attend to more letters within a single fixation compared to reading-matched hearing peers.

Because both deaf and hearing readers begin processing upcoming words in the parafovea before they are fixated (Bélanger, Slattery, et al., 2012), this enhancement in visual attention may give deaf readers an advantage in pre-processing upcoming words in a sentence. In an eye tracking experiment comparing skilled deaf and hearing readers, Bélanger, Slattery, et al. (2012) measured detailed eye movement behaviors during sentence reading: regressions, saccade length, skipped words, and refixations. Skilled deaf readers had fewer regressions, longer forward saccades, more skipped words, and fewer refixations than hearing readers matched on reading ability. These unique eye movement patterns show that deaf readers were more efficient at processing visual word forms in the context of sentences. These findings led to the Word Processing Efficiency Hypothesis (WPEH) (Bélanger & Rayner, 2015), in which increased access to parafoveal information makes deaf readers more efficient at extracting the orthographic code that supports word recognition. Crucially, less-skilled deaf readers and skilled hearing readers had comparable reading spans, suggesting that the efficient eye movement patterns were tied to the visual enhancement associated with deafness or sign language experience and not just a product of reading skill. The eye movement patterns of young deaf readers also indicate that they process words in sentences more efficiently than hearing peers with similar reading ability (Bélanger et al., 2014).

Because the TL studies with deaf readers to date were conducted at the single word level and differences in their visual attention affect sentence reading, it is important to see whether visual and orthographic processing interact for deaf readers when processing words in the context of sentences. Therefore, the current eye tracking study sought to address the following research question: Are deaf readers more sensitive to letter transpositions than hearing readers during sentence reading?

To answer this question, we recorded the eye movements of deaf and hearing readers while they read sentences that contained target words primed by either TL or identity parafoveal primes. We used the gaze-contingent boundary paradigm to present primes (previews) in the parafovea. For this paradigm, primes are pre-processed while displayed in the parafovea but are replaced by target words once the reader's gaze moves across an invisible boundary in the sentence (Rayner, 1975). The display change occurs during a saccade, unbeknownst to the reader. The time spent reading a target word reflects the priming effect of the prime, with shorter fixation durations indicating facilitative priming.

We predicted that both deaf and hearing readers would demonstrate transposed-letter effects, as evidenced by (a) shorter fixation durations, (b) fewer refixations, and (c) fewer regressions on target words with identity primes compared to those with TL primes. Furthermore, we predicted a TL x Group interaction in which TL effects would be stronger in the deaf group than in the hearing group, based on the hypothesis that TL effects are related to activation of orthographic representations and deaf readers may be especially attuned to the visual-orthographic information involved in this type of priming.

We also conducted a second experiment in the same testing session that examined whether the pronounceability of the TL nonword primes (e.g., *barve* vs. *brvae* for the target *brave*) impacted eye movement behaviors in deaf or hearing readers. Note that in English, phonology and orthography are confounded such that pronounceable TL nonwords also conform to orthotactic constraints and unpronounceable TL nonwords generally violate them. In Experiment 1, we hypothesized that TL effects are driven by accessing orthographic representations of the target word. If so, then in Experiment 2 we would expect comparable or even larger pronounceability effects for deaf readers compared to hearing readers. On the other hand, if TL effects are driven by accessing phonological representations of the target word (Frankish & Turner, 2007), then we would expect larger pronounceability effects for hearing compared to deaf readers.

A secondary aim of these experiments was to replicate the efficient eye movement patterns that deaf readers demonstrate when processing word forms during sentence reading: (a) shorter fixations durations, (b) more skips, (c) fewer refixations, and (d) fewer regressions on target words compared to hearing readers matched on reading skill. After presenting the results of Experiments 1 and 2, we extend our understanding of these eye movement patterns through correlational analyses between these eye movement measures and reading measures (reading comprehension ability, spelling skill, and phonological awareness). To our knowledge, this study is the first to pair eye tracking data with behavioral data from a battery of reading assessments in order to consider the relationship between word processing efficiency and reading skills. We predicted that more efficient eye movements would be associated with better reading comprehension and spelling for both groups and with better phonological awareness for hearing readers only.

2.3 Experiment 1: Methods

2.3.1 Participants. The participants were 43 severely-to-profoundly deaf adults (22f; mean age = 35.30 years) and 40 hearing adults (19f; mean age = 30.58 years). The minimum number of participants (36 per group) was determined based on the number of stimuli available (see Stimuli for a complete list) and Brysbaert and Stevens' (2018) recommendation of 1,600 data points per condition for sufficient statistical power. Deaf participants were native signers ($n = 18$; born into deaf signing families) or early signers ($n = 25$; exposed to American Sign Language (ASL) before the age of seven). All participants reported ASL as their primary and preferred language. Hearing participants all reported being monolingual speakers of English with no prior exposure to ASL.

Prior to the experiment, participants took behavioral tests for the purposes of group matching and planned correlational analyses. The deaf and hearing groups were matched on nonverbal intelligence as measured by the Kaufman Brief Intelligence Test - 2 (KBIT-2) (Kaufman & Kaufman, 1990), $t(81) = -0.53$, $p = 0.60$, reading level as measured by the comprehension subtest of the Peabody Individual Achievement Test-Revised (PIAT-R) (Markwardt, 1989), $t(81) = -1.84$, $p = 0.07$, and spelling skill as measured by a Spelling Recognition Test (Andrews & Hersch, 2010), $t(81) = 1.01$, $p = 0.31$ (see Table 2.1). The hearing group had significantly better phonological awareness compared to the deaf group as measured by the Phonological Awareness Tests developed by Hirshorn and colleagues (2015), which were specially designed for testing deaf adults, $t(81) = 9.01$, $p < 0.001$. All participants reported having normal or corrected-to-normal vision and provided informed consent in accordance with the Institutional Review Board at San Diego State University. Additional participants were excluded from analyses due to low accuracy on the comprehension questions (< 60% accuracy; one deaf participant; four hearing participants) or to an inability to calibrate due to shaky eyes or glasses with an anti-reflective coating (three deaf participants; three hearing participants).

Table 2.1. Nonverbal intelligence and English language scores for deaf and hearing readers in Experiment 1 (95% confidence intervals and averages based on raw scores)

Group	Nonverbal Intelligence Out of 46	Reading Comprehension Out of 100	Spelling Recognition Out of 88	Phonological Awareness Out of 100
Deaf Readers (N = 43)	[36.51, 39.49] 37.77 (104.28 standard)	[77.11, 84.89] 81.19	[79.31, 84.69] 72.23 (82.08%)	[57.82, 66.18] 62.05
Hearing Readers (N = 40)	[36.76, 39.24] 38.28 (104.90 standard)	[83.21, 88.79] 85.58	[77.21, 82.79] 70.23 (79.81%)	[83.59, 90.41] 86.71

2.3.2 Stimuli. The experiment comprised 92 experimental sentences, each containing a 5-letter target word (all stimuli are available on OSF, https://osf.io/9tuay/). Each target word (e.g., *steak*) had an identity prime (e.g., *steak*) and a TL nonword prime (e.g., *setak*). TL nonwords were created by transposing adjacent letters within the target word (i.e., either the second and third or third and fourth letters). Each of the 92 target words was embedded in a sentence frame between 6-10 words long (e.g., Matthew took the medium steak off the grill). These sentences had simple syntactic structures to ensure comprehension even for less-skilled readers. The word preceding the target word was a high-frequency word between five and seven letters long in order to increase the likelihood that the participant would fixate on the target word (Rayner, 2012). A norming study was conducted using Mechanical Turk in which 20 hearing monolingual speakers of English completed a cloze task in which they were presented with the beginning of each sentence, up to the target word. To ensure that target words were not predictable, sentences for which more than two participants correctly predicted the target word were rewritten until all of the sentences had unpredictable continuations.

For a given participant, half of the sentences were displayed with identity primes (e.g., *steak*), and half were displayed with TL primes (e.g., *setak*). Each sentence appeared only once in each of two lists, with preview conditions counterbalanced across participants with a Latin Square design. In other words, half of the participants saw an identity prime for a given sentence (Matthew took the medium steak...) and half of the participants saw a TL prime for that sentence (Matthew took the medium setak...). Each participant read all 92 sentences, which were displayed in random order.

2.3.3 Procedure. We used OpenSesame 3.1.9 (Mathôt et al., 2012) and PyGaze 0.6.0a24 (Dalmaijer, et al., 2014) to display the stimuli on a ViewSonic 21-inch CRT screen (40x30 cm for 1024x768 pixels at 85Hz). Each sentence was presented on a single line in 22-point monospaced font in black on a light gray background. Participants were seated ~86 cm away from the monitor, so that every 3 characters (1.5 cm) equaled approximately 1° of visual angle (dva). Vision was binocular, but only the position of the participant’s right eye was recorded. Eye movements were recorded with an EyeLink 1000+ (SR Research, Mississauga, ON, Canada), a remote video-based eye tracker sampling at 1000 Hz with a spatial resolution of 0.01°.

Before the experiment began, participants received instructions in their preferred language. Chin and forehead rests stabilized the participant’s head, and the participant's eye position was then calibrated using a 3-point calibration. Each trial began with a drift correction dot located 112 pixels (2.91 dva) from the left edge of the display. Participants focused on this dot to trigger the display of a sentence beginning just to the right of the drift correction dot. Since the sentences had different lengths, the distance between the fixation point and the beginning of the sentence was variable and participants were not able to anticipate how many pixels to the right of the dot each sentence would begin.

Participants read each sentence silently, at a natural rate, and for comprehension. They responded to Yes/No comprehension questions for 20% of trials (e.g., Was the steak well done?). They pressed a button on a gamepad with one hand to give a "Yes" response and a different button on the gamepad with their other hand to give a "No" response. Response hand was counterbalanced across participants. A feedback dot was presented for 500 ms after their response (green = correct, red = incorrect). Participants were given 12 practice sentences (and 2 comprehension questions) before the actual experiment.

2.3.4 Analyses. From the raw recordings of participants' eye movements, we calculated a number of standard eye tracking measures. At the sentence level, we recorded accuracy of responses to comprehension questions and reading speed. At the word level, we calculated several types of durations to measure fixations on target words: first fixation duration, single fixation duration, gaze duration, and total viewing time; we also calculated saccade probabilities to see how often readers skipped, refixated, or regressed onto a target word, and we identified the initial landing position to determine where readers' eyes fell within a target word during their first forward saccade into the word.

We used Linear Mixed Effects models (LMEs) to analyze fixation durations, with items and participants as random effects (including by-item and by-participant random intercepts; Baayen et al., 2008). Durations were inverse transformed. Generalized (logistic) LMEs were used to analyze probabilities of target word skips, regressions, and refixations as well as accuracy for comprehension questions. The models were fitted with the lmer (for LMEs) and glmer (for GLMEs) functions from the lme4 package (Bates et al., 2015) in the R statistical computing environment (REF: R Core Team, 2018). We report regression coefficients (b), standard errors (SE) and |t-values| (for LMEs) or |z-values| (for GLMEs) for all eye tracking measures. Fixed effects were deemed reliable if |t| (or |z|) > 1.96 (Baayen et al, 2008). We used the maximal random structure model that converged (Barr et al., 2013) in the reported analyses. These models included by-participant and by-item random intercepts for all measures, as well as by-item random slopes for reading speed and by-participant random slopes for single fixation duration, first fixation duration, and total viewing time.

2.4 Experiment 1: Results

Trials contaminated by blink artifacts (2% of all trials) were excluded from analyses. The remaining dataset was composed of 7,465 data points. Trials containing outliers with values beyond 2.5 standard deviation from the grand mean for each measure were also excluded for nonbinary data, as were trials in which the target word was skipped on the first pass.

2.4.1 Sentence-Level Analyses

2.4.1.1 Accuracy. Recall that each participant answered yes/no comprehension questions following 20% of trials, or roughly 9 questions per condition. There was no difference in accuracy on comprehension questions for deaf readers (Mean = 0.80, 95% CI [0.77, 0.83]) and hearing readers (Mean = 0.83, 95% CI [0.80, 0.86]), $t(81) = -1.67$, $p = 0.10$.

2.4.1.2 Reading Speed. We calculated reading speed in words per minute by dividing the total reading time for each sentence by the number of words in that sentence. We found a significant effect of Group on reading speed ($b = 78.01$; $SE = 19.75$; $t = 3.95$), with deaf readers reading faster on average (344 words per minute) compared to hearing readers (279 words per minute). There was no effect of TL or Group x TL interaction.

2.4.2 Target Word Analyses

2.4.2.1 Fixation Durations. We calculated several types of durations to measure fixations on target words: *single fixation duration (SFD)*, or the time spent on the target if it was only fixated once (i.e., not refixated); *first fixation duration (FFD)*, or the time spent on the target word immediately following the first forward saccade into the target word; *gaze duration (GD)*, or the sum of all first-pass fixations and refixations on the target word; and *total viewing time (TVT)*, or the sum of all fixations, refixations, and regressions on the target word. We found significant effects of Group for single fixation duration ($b = 0.65$; $SE = 0.24$; $t = 2.73$), gaze duration ($b = 0.80$; $SE = 0.23$; $t = 3.52$), and total viewing time ($b = 0.90$; $SE = 0.25$; $t = 3.54$). Deaf readers had shorter fixations on target words compared to hearing readers (see Figure 2.1).

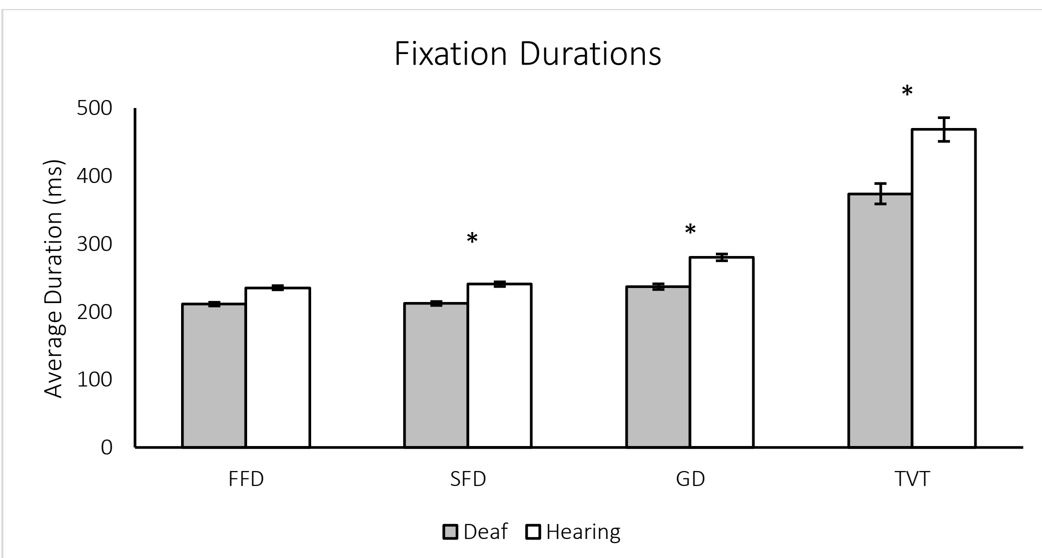

Figure 2.1. Average single fixation duration (SFD), first fixation duration (FFD), gaze duration (GD), and total viewing time (TVT) on target words for deaf and hearing readers for Experiment 1. Error bars reflect 95% confidence intervals, and an asterisk indicates a significant group difference, $p < .05$.

We also found a significant main effect of TL on gaze duration (*b* = 0.24; *SE* = 0.08; *t* = 2.96). Readers had longer fixations on targets with TL primes (M = 263 ms, 95% CI = [258, 267]) compared to those with identity primes (M = 255 ms, 95% CI = [250, 259]).

2.4.2.2 Saccade Probabilities. We also calculated the probabilities of several binary patterns: *skips*: instances when target words that were passed over during a saccade and never fixated; *regressions*: backward movements into the target word after the reader's gaze had already passed the target window; and *refixations*: when the target word is fixated multiple times before the reader's gaze moves out of the target window.

We found significant effects of Group for regression rates (*b* = 0.47; *SE* = 0.20; *z* = 2.33) and refixation rates (*b* = 0.81; *SE* = 0.24; *z* = 3.40). Deaf readers had fewer regressions and fewer refixations on target words compared to hearing readers (see Figure 2.2). There was a marginal effect of Group on skipping rates (*b* = 0.35; *SE* = 0.18; *z* = 1.95), with deaf readers skipping more target words than hearing readers.

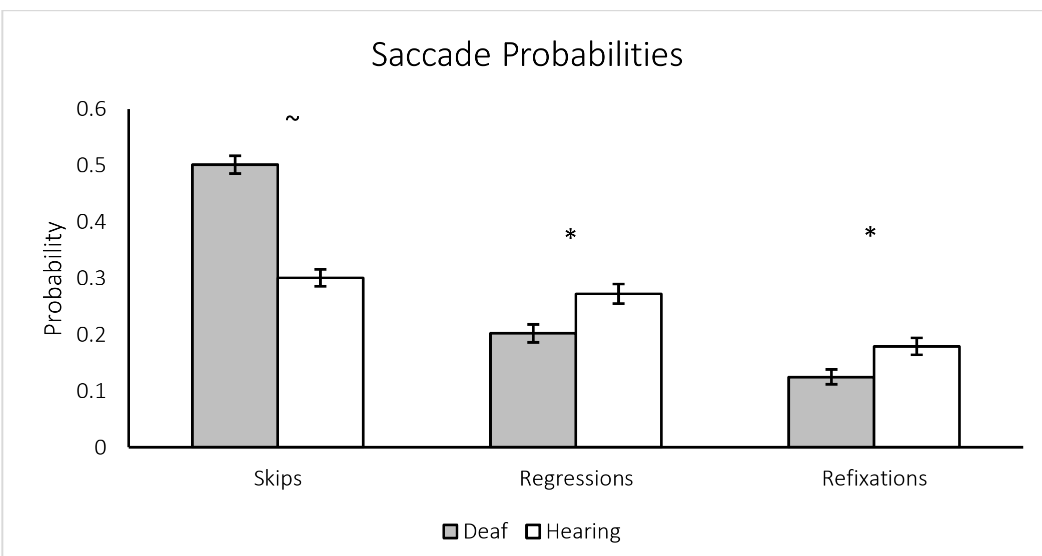

Figure 2.2. Average percent of trials containing skips, regressions, and refixations on target words for deaf and hearing readers in Experiment 1. Error bars reflect 95% confidence intervals, an asterisk indicates a significant group difference, $p < 0.05$, and a tilde indicates a marginal group difference, $0.05 < p < 0.10$.

There were no main effects of TL or Group x TL interactions for skipping or regression rates. However, a significant main effect of TL on refixation rate (*b* = 0.45; *SE* = 0.13; *z* = 3.45) showed that readers refixated targets with TL previews more often than those with identity previews. There was also a Group x TL interaction (*b* = 0.33; *SE* = 0.17; *z* = 2.00); the difference in refixation rates for targets with TL previews versus identity previews was greater for the deaf readers compared to the hearing readers, i.e., there was a bigger TL effect in the deaf group. Follow up analyses confirmed a main effect of TL in the deaf group only (see Figure 2.3).

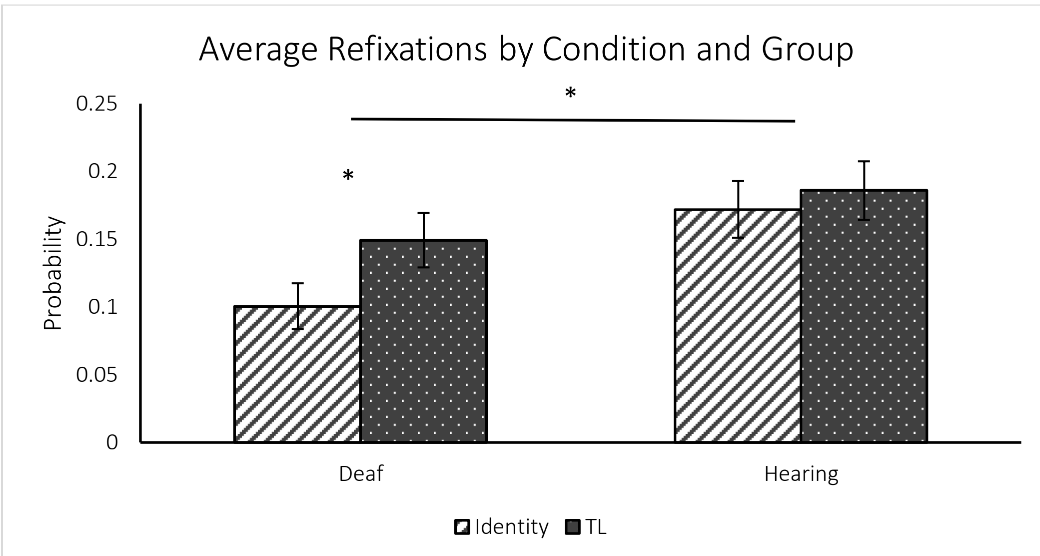

Figure 2.3. Average percent of trials containing refixations on target words with identity primes and TL (transposed-letter) primes for deaf and hearing readers in Experiment 1. Error bars reflect 95% confidence intervals, and an asterisk indicates a significant difference, $p < .05$.

2.4.2.3 Initial Landing Position. Initial landing position was calculated to identify where participants' first fixation fell within the target window, which contained the five letters in the target word and a half space before and after the word to allow for variation in calibration. This measure is reported on a scale from 0 to 1, representing the start and end of the target window. We found no significant effect of Group, TL, or Group x TL interaction on initial landing position.

2.5 Experiment 1: Discussion

This eye tracking study investigated orthographic sensitivity in deaf and hearing readers using parafoveal previews during sentence reading. Participants read sentences containing target words primed by either TL primes or identity primes. As predicted by the Word Processing Efficiency Hypothesis (WPEH), we found that deaf readers had faster reading speeds, shorter fixation durations on target words, fewer regressions, and fewer refixations on target words compared to hearing readers matched on reading ability. These results are consistent with the efficient eye movement patterns previously seen in deaf readers and support the WPEH. We also found evidence of TL effects: readers had longer gaze durations on targets with TL previews compared to those with identity previews, and deaf readers refixated targets with TL previews more often compared to those with identity previews.

The efficient eye movement patterns may point to different strengths of deaf compared to hearing readers. Gordon et al. (2019) found that increased skipping rates and shorter gaze duration were associated with increased scores on a measure of print exposure, while fewer regressions and shorter second-pass reading times were associated with faster times on a Rapid Automatized Naming (RAN) task. They argued that the former measures reflected efficient word recognition while the latter reflected efficient perceptual-motor/attentional processes for reading. Deaf readers showed advantages in both types of measures, representing strengths in both linguistic and perceptual domains of word processing.

Deaf readers were also more sensitive to the letter transpositions. Although it is possible that deaf readers may just be better at detecting visual changes in the parafovea, it seems unlikely that the effect is merely perceptual. We hypothesize that the greater TL effect in the deaf group may be explained by an increased sensitivity to orthographic structure and/or enhanced visual processing, which could provide deaf readers with an advantage in detecting letter transpositions. Although the hearing readers had similar spelling ability, they may not have been as sensitive to visual-orthographic changes to word forms in the parafovea.

Another possibility is that access to phonological structure may have differentially affected deaf and hearing readers in their ability to detect letter transpositions. Hearing readers rely more heavily on phonology for word recognition and may benefit from top-down processing from phonological information at the lexical level to reconcile differences between the target and its TL prime (Perea et al., 2016). This phonological check would act to stabilize the orthographic representation of the target word and help offset the effect of letter transpositions in the primes. Deaf readers may bypass this phonological check and map sublexical orthographic representations (letter identities and positions) directly onto whole word representations. This direct orthographic-to-semantic route may have required more refixations in order to resolve the conflicting orthographic representations for target words and their TL primes. One limitation of Experiment 1 is that it does not allow us to tease apart the unique contributions of phonological and orthographic processing to TL effects. We further explored this topic in Experiment 2 by manipulating the orthotactics/pronounceability of TL nonword primes.

2.6 Experiment 2: Introduction

TL studies that manipulate pronunciation in addition to letter position offer one approach to investigating phonological and orthographic constraints on word recognition. A series of masked lexical decision experiments by Frankish and Turner (2007) found that typical hearing readers were more likely to mistake TL nonwords for real words when the letter string was unpronounceable (e.g., *brvae* for *brave*) compared to pronounceable (e.g., *barve* for *brave*). Since phonology and orthography are conflated in English, the effect could be attributed to either one. Pronounceable nonwords (*barve*) conform to both phonotactics and orthotactics, but they generate phonological representations in conflict with those of their base words (*brave*), making them easier to reject. However, unpronounceable nonwords (*brvae*) violate both phonotactics and orthotactics, so they are mistaken for words that are misspelled and need to be orthographically repaired. Frankish and Turner (2007) favored a phonological basis for this TL effect, in part because no such effect was found for dyslexic hearing readers, who are thought to have a deficit in decoding graphemes to generate phonological representations.

Others argue that TL effects are driven by orthography instead of phonology. Perea and Carreiras (2006) used masked TL priming to show that Spanish target words (*REVOLUCIÓN*) preceded by orthographic TL primes (*relovucion*) resulted in shorter response times compared to targets preceded by pseudohomophones of TL primes (*relobucion*). If the effect were driven by phonology, there would have been no difference in these conditions, as both primes have the same pronunciation. Perea and Carreiras (2008) also compared TL priming effects for Spanish word targets with TL primes that either upheld or disrupted the pronunciation of the target word. There were no significant differences in priming whether transpositions in the primes displaced the letter ‘c’ but retained its sound as /k/ (*cholocate-CHOCOLATE*), altered the phonological context of the ‘c’ and changed its pronunciation to /θ/ (*racidal-RADICAL*), or did not involve the letter ‘c’ at all (*maretial-MATERIAL*). If the effect were driven by phonology, primes with different pronunciation manipulations would have yielded different effects. Finally, Grainger and colleagues (2006) found ERP evidence that TL priming has distinct and earlier-emerging effects on the N250 compared to pseudohomophone priming, reflecting sublexical orthographic and phonological processing, respectively. Together, these studies suggest that TL effects are orthographic, not phonological, in nature.

Studying pronounceability effects in deaf readers could shed light on the role of orthographic and phonological processing in word recognition. While deaf individuals can develop varying degrees of speech-based phonological knowledge depending on their language experience (Hirshorn et al., 2015) and may to use this knowledge to perform memory or phonological judgment tasks (Perfetti & Sandak, 2000; Sevcikova Sehyr et al., 2016; Hall & Bavelier, 2011), there is a long-standing debate about whether or not they engage phonological knowledge during reading. Many have argued that speech-based phonology is a requisite component of reading (Easterbrooks et al., 2008; Hanson & Fowler, 1987; Paul et al., 2009; Perfetti & Sandak, 2000; Wagner & Torgesen, 1987; Wang et al., 2008; Ziegler & Goswami, 2005), while others argue that phonological awareness is not necessary for deaf individuals to become skilled readers. For example, in a parafoveal preview study, Bélanger et al. (2013) found that deaf readers activated orthographic but not phonological codes in parafoveal vision, regardless of their reading skill. This study and others (Bélanger, Baum et al., 2012; Chamberlain, 2002; Costello et al., 2021; Cripps & McBride, 2005; Emmorey et al., 2017; Hirshorn et al., 2015; Izzo, 2002; Mayberry et al., 2011; Miller & Clark, 2011; Sehyr et al., 2017) suggest that speech-based phonological awareness is not a determinant of reading skill in deaf readers.

Because deaf readers do not appear to automatically access the phonological code for word reading (similar to dyslexic readers) but they are sensitive to the orthographic code (like typical hearing readers), they allow us to further examine the basis of TL effects. Experiment 2 sought to address the following research question: Are deaf readers just as sensitive to the pronounceability of TL nonwords as hearing readers during sentence reading? Using the same gaze-contingent boundary paradigm as Experiment 1, we recorded the eye movements of deaf and hearing readers while they read sentences that contained target words primed by either pronounceable or unpronounceable TL nonwords.

We predicted that hearing readers would show a pronounceability effect as evidenced by (a) shorter fixation durations, (b) fewer refixations, and (c) fewer regressions on target words with unpronounceable TL nonword previews compared to pronounceable TL nonword previews. If pronounceability effects are due to phonotactic sensitivity, as suggested by Frankish and Turner (2007), then we would expect only hearing readers to show these effects. On the other hand, if pronounceability effects are due to orthotactic sensitivity, we would expect both groups to show pronounceability effects, with greater priming for unpronounceable primes than pronounceable primes. Pronounceability effects may even be larger for deaf readers, as they are more likely to rely on orthotactics for word recognition.

2.7 Experiment 2: Methods

2.7.1 Participants. The same people participated in Experiment 1 and Experiment 2. However, different individuals were excluded from analyses due to low comprehension accuracy (three deaf participants) or to an inability to calibrate (3 deaf participants; 2 hearing participants). Therefore, Experiment 2 included 41 severely-to-profoundly deaf adults (21f; mean age = 35.59 years; 16 native and 25 early signers) and 43 hearing adults (20f; mean age = 30.21 years). The minimum number of participants for sufficient statistical power was again met. Participant language background, vision, and consenting procedures were the same as described in Experiment 1. Again, the deaf and hearing groups were matched on nonverbal intelligence, $t(82) = 0.03$, $p = 0.98$, reading level, $t(82) = -1.37$, $p = 0.17$, and spelling recognition, $t(82) = 1.11$, $p = 0.27$ (see Table 2). The hearing group had significantly better phonological awareness compared to the deaf group, $t(82) = -9.07$, $p < 0.001$.

Table 2.2. Nonverbal Intelligence and English Language Scores for Deaf and Hearing Readers in Experiment 2 (95% CI and averages based on raw scores)

Group	Nonverbal Intelligence Out of 46	Reading Comprehension Out of 100	Spelling Recognition Out of 88	Phonological Awareness Out of 100
Deaf Readers (N = 41)	[36.78, 39.22] 38.05 (104.93 standard)	[77.02, 84.98] 81.34	[69.25, 74.75] 72.28 (82.14%)	[57.71,66.29] 62.37
Hearing Readers (N = 43)	[36.80, 39.20] 38.02 (104.21 standard)	[82.01, 87.99] 84.70	[67.31, 72.69] 70.12 (79.68%)	[83.71, 90.29] 87.45

2.7.2 Stimuli. The experiment comprised 92 experimental sentences, each containing a 5-letter target word. The procedure for creating TL nonwords was the same as in Experiment 1. A norming study was conducted in which 20 hearing monolingual speakers of English rated the TL nonwords for pronounceability on Mechanical Turk. They rated each nonword on a four-point scale (1 = not at all pronounceable, 4 = totally pronounceable). Only nonwords that were rated as 4 by at least 80% of participants were considered pronounceable, and nonwords that were rated as 1 by at least 80% of participants were deemed unpronounceable. We selected 92 target words (e.g., *brave*) whose transpositions formed one pronounceable TL nonword (e.g., *barve*) and one unpronounceable TL nonword (e.g., *brvae*) to be included in the experiment. The procedure for creating and norming sentence frames for predictability was the same as Experiment 1.

For any given participant, half of the sentences were displayed with pronounceable previews (*barve*), and half were displayed with unpronounceable previews (*brvae*). Each sentence appeared only once in each of two lists, with conditions counterbalanced across participants using a Latin-Square design. In other words, half of the participants saw an unpronounceable prime for a given sentence (e.g., The little girl acted brvae...), and half of the participants saw a pronounceable preview for that sentence (e.g., The little girl acted barve...). An additional 92 sentences were added as fillers without display changes. Each participant read all 184 sentences, which were displayed in random order.

2.7.3 Procedure. The procedure was the same as in Experiment 1. Participants took Experiment 2 on the same day and in the same session as Experiment 1, with a short a break in between experiments. The order of experiments was counterbalanced across participants.

2.7.4 Analyses. The analyses, participant exclusion criteria, trial exclusion criteria, and modeling procedures were the same as in Experiment 1. Again, we used the maximal random structure model that converged (Barr et al., 2013) in the reported analyses. These models included by-participant and by-item random intercepts for all measures, as well as by-item random slopes for single fixation duration and gaze duration and by-participant random slopes for reading speed.

2.8 Experiment 1: Results

Trials contaminated by blink artifacts (2% of all trials) were excluded from analyses. The remaining dataset was composed of 7,546 data points. Trials in which the target word was skipped were also excluded, as were trials containing outliers with values beyond 2.5 standard deviation from the grand mean for each measure were also excluded for nonbinary data.

2.8.1 Sentence-Level Analyses

2.8.1.1 Accuracy. As in Experiment 1, each participant answered yes/no comprehension questions following 20% of trials, or roughly 9 questions per condition. Accuracy on comprehension questions was slightly lower for deaf readers (M = 0.83, 95% CI =

[0.81, 0.85]) than for hearing readers (M = 0.86, SE = 0.08, 95% CI = [0.84, 0.88]), $t(82) = -2.03$, $p = 0.046$.

2.8.1.2. Reading Speed. We found a significant effect of Group ($b = 76.24$ $SE = 16.39$; $t = 4.65$) for reading speed, with deaf readers reading at a faster rate on average (329 words per minute) compared to hearing readers (267 words per minute). There was no effect of Pronounceability or Group × Pronounceability interaction.

2.8.2 Target Word Analyses

2.8.2.1 Fixation Durations. We found significant effects of Group for gaze duration ($b = 0.46$; $SE = 0.23$; $t = 2.05$) and total viewing time ($b = 0.56$; $SE = 0.24$; $t = 2.39$) (see Figure 2.4). Deaf readers had shorter fixations on target words compared to hearing readers. We found no effects of Pronounceability or Group × Pronounceability interactions for fixation durations.

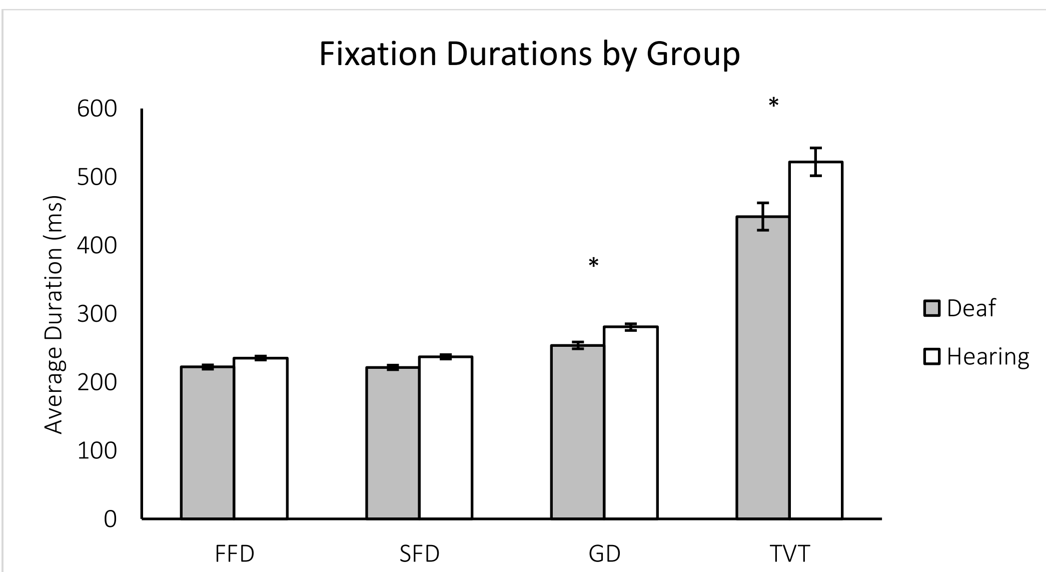

Figure 2.4. Average single fixation duration (SFD), first fixation duration (FFD), gaze duration (GD), and total viewing time (TVT) on target words for deaf and hearing readers in Experiment 2. Error bars reflect 95% confidence intervals, and an asterisk indicates a significant group difference, $p < .05$.

2.8.2.2. Saccade Probabilities. We found significant effects of Group for skipping rate (b = 0.51; SE = 0.17; z = 2.98), regression rate (b = 0.49; SE = 0.19; z = 2.57), and refixation rate (b = 0.63; SE = 0.22; z = 2.93). Deaf readers had more skips, fewer regressions, and fewer refixations on target words compared to hearing readers (see Figure 2.5). We found no effects of Pronounceability or Group × Pronounceability interactions for saccade probabilities.

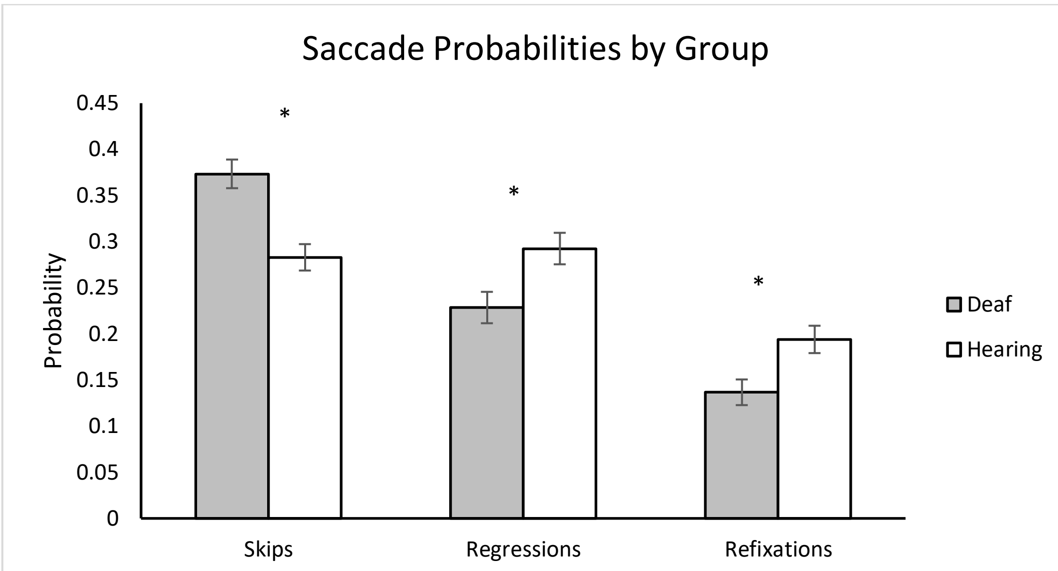

Figure 2.5. Average number of skips, regressions, and refixations on target words for deaf and hearing readers in Experiment 2. Error bars reflect 95% confidence intervals, and an asterisk indicates a significant group difference, $p < .05$.

2.8.3 Initial Landing Position. There was a significant effect of Pronounceability on initial landing position (b = 0.03; SE = 0.01; z = 2.58) and a Group x Pronounceability interaction (b = 0.03; SE = 0.01; z = 2.13). Readers' gaze landed earlier in targets with pronounceable TL nonword primes than in unpronounceable TL nonword primes, and this effect was larger in deaf group than in the hearing group. Follow-up analyses revealed that this TL effect was significant in the deaf group only (see Figure 2.6).

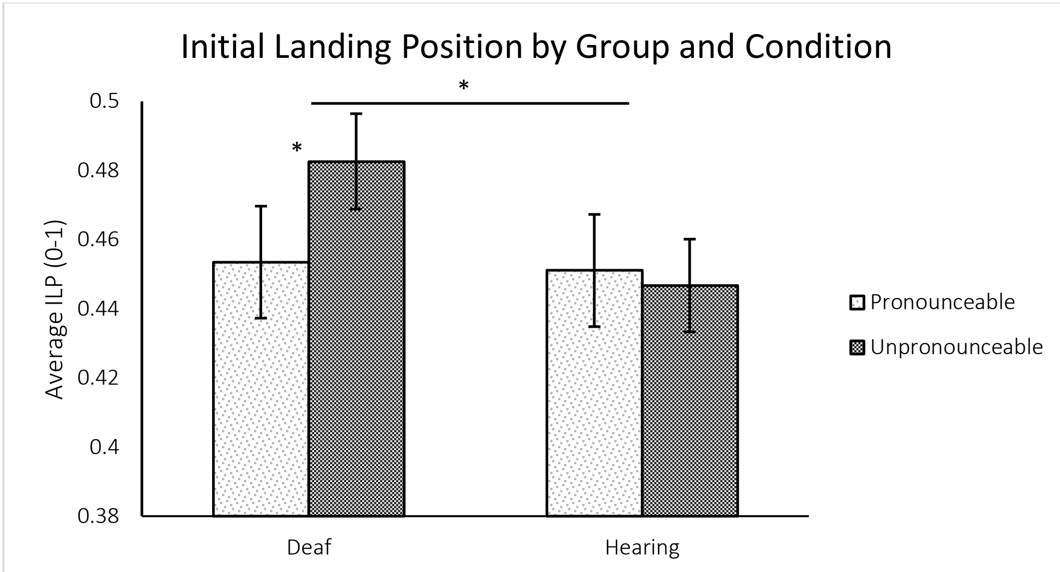

Figure 2.6. Average initial landing position on target words with pronounceable and unpronounceable TL primes for deaf and hearing readers in Experiment 2. Error bars reflect 95% confidence intervals, and an asterisk indicates a significant difference, $p < .05$.

2.9 Experiment 2: Discussion

This experiment investigated orthographic and phonological constraints on word processing in deaf and hearing readers by manipulating the pronounceability of TL nonword primes during sentence reading. Participants read sentences containing target words primed by either pronounceable TL nonwords or unpronounceable TL nonwords. As predicted and similar to findings in Experiment 1, we found that deaf readers had faster reading speeds, shorter fixation durations, more skips, fewer regressions, and fewer refixations on target words compared to hearing readers matched on reading ability. This replication provides further support for the WPEH.

Interestingly, we found an effect of pronounceability for deaf but not hearing readers. Deaf readers' gaze landed earlier in targets with pronounceable TL nonword primes than in unpronounceable TL nonword primes, which corresponds to where most of the letter transpositions took place for each type of prime (letters 2 and 3 were transposed in *barve*, whereas letters 3 and 4 were transposed in *brvae*). It seems deaf participants were able to detect the letter transposition in the parafovea and use that information to direct their eye movements to their initial landing position within the target word. Hearing readers showed no significant differences in initial landing position related to the pronounceability of the prime. This finding suggests that hearing readers do not access orthographic information as precisely as deaf readers in the parafovea or that hearing readers lack the perceptual-motor control to use this information in directing their eye movements toward the target word.

These findings do not support the phonological interpretation of the pronounceability effects proposed by Frankish and Turner (2007). Hearing readers had better phonological awareness than the deaf readers, so we would have expected them to show stronger effects if they were using the phonological properties of the primes for word recognition. This was not the case, and in fact hearing readers showed no effect of pronounceability at all. Methodological differences also may have contributed to the lack of effects for hearing readers in Experiment 2. Specifically, the additional context and top-down processing involved in the sentence reading task used here could have dampened the pronounceability effects previously seen in Frankish and Turner's (2007) word-level study.

The results from Experiment 2 are, however, consistent with the hypothesis that pronounceability effects are due to orthotactic sensitivity (Perea & Carreiras, 2006a, 2008). These results also support the WPEH and its claim that deaf readers are highly attuned to visual-orthographic makeup of words and have an advantage in the extracting this information for word recognition. Furthermore, the fact that deaf readers could clearly detect letter transpositions in the parafovea but showed no difference in fixation durations or saccade probabilities for the two types of primes highlights the flexibility of their orthographic representations. They treated unpronounceable and pronounceable primes similarly, despite the former containing illegal bigrams and the latter conforming to the orthotactic principles of English. The fact that neither group showed pronounceability priming effects supports the notion that deaf and hearing readers use flexible orthographic coding for word recognition (Fariña et al., 2016; Meade et al., 2020), consistent with the open bigram model of orthographic processing in which letter position is not encoded exactly but relative to other letters (Grainger, 2008; Grainger & van Heuven, 2003; Grainger & Whitney, 2004).

We next turn to our analysis of the relationship between reading skills and measures of eye movements to investigate whether and how reading ability is related to the differences in eye movement patterns across deaf and hearing readers.

2.10 Correlations

As a complement to the eye tracking data and an extension of the WPEH, Pearson correlations were used to identify associations between eye movement behaviors and reading ability, spelling skill, and phonological awareness. Eye movement behaviors included trials from all conditions across both experiments to maximize power since there were no significant differences in fixation durations or saccade probabilities between TL pronounceability conditions. Correlations were corrected for multiple comparisons with false discovery rate (FDR) corrections.

Deaf (M = 81.18, 95% CI = [68.33, 93.75]), and hearing (M = 84.70, 95% CI = [71.85, 94.19]) readers were matched on reading comprehension ability (PIAT scores), $t(84) = -1.46$, $p = 0.14$. Overall, hearing readers with better reading comprehension ability had shorter total viewing times, $r = -0.41$, $p = 0.04$, and better spellers had shorter gaze durations, $r = -0.38$, $p =$

0.03; shorter total viewing times, $r = -0.40$, $p = 0.02$; faster reading speeds, $r = 0.47$, $p = 0.01$; and fewer refixations, $r = -0.42$, $p = 0.02$. In addition, hearing readers with better phonological awareness had shorter single fixation durations, $r = -0.46$, $p = 0.02$; shorter first fixation durations, $r = -0.42$, $p = 0.03$; and shorter gaze durations, $r = -0.39$, $p = 0.04$. For deaf readers, none of the eye movement behaviors correlated with any of the language measures, all *ps* > 0.08.

We also ran the correlations with the eye movement behaviors from the subset of identity trials to confirm the patterns in the absence of TL primes. Similar to the findings with the entire data set, hearing readers with better spelling ability had shorter gaze durations, $r = -0.39$, $p = 0.048$, and fewer refixations, $r = -0.41$, $p = 0.048$, and hearing readers with better phonological awareness had shorter single fixation durations, $r = -0.42$, $p = 0.01$; shorter first fixation durations, $r = -0.39$, $p = 0.01$; and shorter gaze durations, $r = -0.47$, $p = 0.002$. Again, for deaf readers, none of the eye movement behaviors correlated with any of the language measures, all *ps* > 0.09. See Appendix A for a complete table of correlations between English language scores and eye tracking measures.

For hearing readers, better reading ability, spelling ability, and phonological awareness all correlated with shorter gaze durations, which are associated with greater print exposure and may be indicative of better word recognition (Gordon et al., 2020). Better spellers had to refixate words less often and spent less time on words that did require a refixation or regression (total viewing time), indicating that orthographic knowledge allowed the readers to recognize words more quickly. The fact that better phonological awareness was associated with shorter durations for the first/only fixation of a word (but not refixations or total viewing time) may indicate that the readers used phonology to facilitate access to easily recognized words but favored orthographic knowledge for recognizing words that required additional fixations or regressions.

Overall, the pattern of correlations suggests that hearing readers use complementary orthotactic and phonotactic information during word recognition.

The lack of associations between language measures and eye movement behaviors for deaf readers may be related to changes in their visual attention that impact reading. Previous work has shown that deaf readers have efficient eye movements despite weaker phonological skills, so a lack of correlation with phonological awareness was expected. Reading ability modulates word processing efficiency for hearing readers, but even less-skilled deaf readers have efficient eye movements. Perhaps reading ability is not as strongly linked to efficient reading for deaf people as it is for hearing people.

2.11 Conclusions

This set of parafoveal preview eye tracking experiments used TL nonword primes to investigate word processing during sentence reading for deaf and hearing readers, matched on reading skill. These studies extend the existing TL literature on deaf readers to highlight how they recognize words in sentences. In Experiment 1, deaf readers were more sensitive to letter transpositions than hearing readers, as evidenced by a stronger TL effect on refixations. Their enhanced visual attention and/or sensitivity to orthotactics in the parafovea gave them an advantage in the orthographic processing that supports word recognition.

In Experiment 2, deaf readers were able to detect the location of letter transpositions in TL primes presented in the parafovea. They then directed their saccades towards the transpositions when they fixated the target words, resulting in different initial landing positions for targets with pronounceable and unpronounceable primes. This finding is consistent with the idea that deaf readers are more sensitive to visual-orthographic information in the parafovea compared to hearing readers. However, both deaf and hearing readers appeared to treat targets similarly regardless of the pronounceability of their primes. This finding refutes phonological interpretations of pronounceability effects, as no group differences were found despite marked differences in their phonological awareness. However, it is consistent with the notion that deaf and hearing readers represent orthographic information similarly and flexibly.

Across both experiments, deaf readers used more efficient eye movements to recognize words in sentences compared to hearing readers. These findings support the WPEH and provide further evidence that deaf readers have tighter orthography-to-semantic connections and are more attuned to the visual-orthographic makeup of words. Finally, efficient eye movement patterns were positively associated with spelling ability and phonological awareness in hearing readers, consistent with accounts that they access both codes for word recognition (Belanger et al., 2013).

Future studies should explore different methods for investigating pronounceability/orthotactic effects with deaf readers, which may have been diminished in the sentence reading tasks employed here. Studies at the single word-level that provide less context for top-down processing could better draw out effects of pronounceability/orthotactics on word processing. In addition, electrophysiological methods better capture the rapid orthographic and phonological processes involved in word recognition.

Future research may also explore how syntax or semantics influence TL effects and word processing efficiency for deaf readers. The experiments presented here necessarily used simple sentences and controlled for predictability. Would deaf readers show the same advantages in word processing when reading more complex sentences? How would additional semantic context impact word processing efficiency? These questions may be especially interesting to address given that deaf readers tend to rely more heavily on semantics than syntax during sentence reading (Mehravari et al., 2017) and access semantic information in the parafovea (Yan et al, 2015). Additional semantic cues may therefore be especially beneficial, while added syntactic complexity may be less disruptive to word recognition for deaf compared to hearing readers. Syntactic and semantic effects on sentence reading may also relate to sign language experience. Native signers are better able to comprehend complex sentences (Traxler et al., 2014), and deaf readers activate sign translations in the parafovea (Pan et al., 2015). Sign language experience can provide a strong linguistic foundation that appears to aid deaf readers when reading sentences in their second language.

In conclusion, our findings highlight several instances of deaf gain (Bauman & Murray, 2014) related to reading: enhanced visual attention, efficient eye movements when reading words in sentences, and precise processing of orthographic information in the parafovea. More broadly, they show that phonological access is not necessary for skilled reading. This information can be used to emphasize the strengths of deaf readers and support them in becoming successful readers through alternative processes.

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Chapter 3: Sensitivity to orthographic vs. phonological constraints on word recognition: An ERP study with deaf and hearing readers

3.1 Abstract

The role of phonology in word recognition has previously been investigated using a masked lexical decision task and transposed letter (TL) nonwords that were either pronounceable (*barve*) or unpronounceable (*brvae*). We used event-related potentials (ERPs) to investigate these effects in skilled deaf readers, who may be more sensitive to orthotactic than phonotactic constraints, which are conflated in English. Twenty deaf and twenty hearing adults completed a masked lexical decision task while ERPs were recorded. The groups were matched in reading skill and IQ, but deaf readers had poorer phonological ability. Deaf readers were faster and more accurate at rejecting TL nonwords than hearing readers. Neither group exhibited an effect of nonword pronounceability in RTs or accuracy. For both groups, the N250 and N400 components were modulated by lexicality (more negative for nonwords). The N250 was not modulated by nonword pronounceability, but pronounceable nonwords elicited a larger amplitude N400 than unpronounceable nonwords. Because pronounceable nonwords are more word-like, they may incite activation that is unresolved when no lexical entry is found, leading to a larger N400 amplitude. Similar N400 pronounceability effects for deaf and hearing readers, despite differences in phonological sensitivity, suggest these TL effects arise from sensitivity to lexical-level orthotactic constraints. Deaf readers may have an advantage in processing TL nonwords because of enhanced early visual attention and/or tight orthographic-to-semantic connections, bypassing the phonologically mediated route to word recognition.

3.2 Introduction

Skilled readers activate orthographic, phonological, and semantic information when processing visual word forms. According to the Bimodal Interactive Activation Model (BIAM) (Grainger & Holcomb, 2009), a reader must first extract the visual features of a printed word, which activate the word's orthographic and phonological codes at the sublexical level. These sublexical orthographic and phonological representations are then mapped onto whole-word representations, and this mapping process is reflected in the N250 ERP component. Finally, activated whole-word orthographic and phonological representations are mapped to lexical semantic representations, a process reflected in the N400 component. Importantly, this model allows sublexical and lexical representations to interact with each other along and across these dual orthographic and phonological routes.

This model was developed with hearing readers in mind, but deaf readers may achieve word recognition by different means. Because deaf readers have reduced or altered access to auditory input, they may not rely on speech-based phonology in the same way as hearing readers. They can develop varying degrees of phonological awareness depending on their language experience (Hirshorn et al., 2015) and appear to use phonology for certain tasks (Aparicio et al., 2007; Hanson & McGarr, 1989; MacSweeney et al., 2013; Perfetti & Sandak, 2000; Sehyr et al., 2017). However, studies on whether or not deaf people activate phonological codes when reading have mixed results; some studies show that they do (Hanson & Fowler, 1987; Perfetti & Sandak, 2000; Nielsen & Luetke-Stahlman, 2002), and others indicate they do not (Clark et al., 2016; Miller & Clark, 2011; Izzo, 2002; Mayberry et al., 2011; Fariña et al., 2017; Bélanger, Baum, et al., 2012; Bélanger et al., 2013).

Although deaf readers may rely less on a phonological route to lexical access compared to hearing readers, they appear to process words along the orthographic route in a similar fashion (Meade et al., 2020). One way to assess how orthographic information is represented and processed is with transposed-letter (TL) nonword studies. A TL nonword (e.g., tosat) contains the same letters as a real word (e.g., toast) but transposes two of its letters. Because TL nonwords contain all the same letters as a real word, they activate the orthographic representation of real words to a greater extent than control nonwords that differ by one grapheme (e.g., torat). As a result, TL nonwords are more easily mistaken for words and lexical decisions (i.e., no, this is not a word responses) are slower and less accurate for TL nonwords compared to control nonwords for both deaf (Fariña et al., 2017) and hearing readers (e.g., Chambers, 1979; O'Connor & Forster, 1981). Because TL nonwords share more letters and activate the orthographic representations of words to a greater extent than control nonwords, they also facilitate processing for target words in priming studies with deaf (Bélanger et al., 2013; Bélanger, Baum et al., 2012; Fariña et al., 2017) and hearing readers (Carreiras et al., 2009; Eddy et al., 2016; Grainger, 2008; Grainger et al., 2006; Pollastek et al., 2005). Overall, the behavioral evidence from these studies points to similar use of orthographic information for deaf and hearing readers despite differences in their phonological awareness.

ERP studies featuring TL nonwords allow us to further examine the time-course of orthographic processing. For hearing readers, target words (toast) preceded by transposed-letter (TL) primes (tosat) elicit smaller amplitude N250s and N400s compared to those preceded by nonword controls (torat) (Carreiras et al., 2009a; Carreiras et al., 2009b; Grainger et al., 2006; Ktori et al., 2014; Vergara-Martínez et al., 2013, Zimman et al., 2019). Deaf readers appear to show similar TL priming effects. In a masked priming experiment with deaf and hearing readers, Meade et al. (2020) asked deaf and hearing readers to make lexical decisions about target words (CHICKEN) that were preceded by TL nonword primes. TL primes contained either an adjacent (chikcen) or non-adjacent (ckichen) letter transposition or an adjacent (chidven) or non-adjacent (ckichen) letter substitution for control nonwords. Target words with TL primes elicited smaller amplitude negativities in the N250 and N400 and faster lexical decisions than target words with control nonword primes for both deaf and hearing readers, reflecting similarities in sublexical and lexical processing across groups. Overall, deaf readers appear to represent and access orthographic information similarly to hearing readers despite reduced access to speech-based phonology.

One question that remains for hearing readers (and perhaps for deaf readers too) is how phonological and orthographic routes interact at the sublexical and lexical levels. For hearing readers, phonology may play a supporting role along the orthographic route to word recognition by tuning or stabilizing orthographic representations (Sachi & Lazslo, 2016), but this may not be the case for deaf readers (Emmorey et al., 2017). TL studies that also manipulate pronunciation allow us to examine this hypothesis. Pronounceable TL nonwords (barve) abide by the phonotactic and orthotactic rules of English, whereas unpronounceable TL nonwords (brvae) contain sound and letter combinations that are not permissible. Phonology and orthography are generally conflated in English, so studying pronounceability effects in readers that differ in their phonological awareness can help distinguish the unique contributions of phonological vs. orthographic constraints on word recognition.

For example, Frankish and Turner (2007) asked typical hearing readers and dyslexic readers (with weak phonological decoding skills) to perform a lexical decision task with masked target words (*brave)* and TL nonwords that were either pronounceable (*barve*) or unpronounceable (*brvae)*. Masking was used to make the target discrimination perceptually difficult, which has been shown to maximize RT differences between conditions. Unpronounceable TLs yielded more false positives than pronounceable TLs (i.e., were mistaken for words more often) for typical hearing readers, but dyslexic readers showed no such effect. Frankish and Turner (2007) therefore favored a phonotactic interpretation for the pronounceability effect; pronounceable nonwords were less likely to be mistaken for words because they automatically generate a phonological representation that conflicts with the base word's representation.

In contrast, other studies in which target words were preceded by masked nonword primes suggest an orthotactic basis for pronounceability effects. Perea and Carreiras (2006) showed that Spanish target words (*REVOLUCIÓN*) preceded by orthographic TL primes (*relovucion*) resulted in shorter response times compared to targets preceded by pseudohomophones of TL primes (*relobucion*). If the effect were driven by phonology, there would have been no difference in these conditions, as both primes have the same pronunciation. Perea and Carreiras (2008) also compared TL priming effects for Spanish word targets with TL primes that either upheld or disrupted the pronunciation of the target word. There were no significant differences in priming whether transpositions in the primes displaced the letter ‘c’ but retained its sound as /k/ (*cholocate-CHOCOLATE*), altered the phonological context of the ‘c’ and changed its pronunciation to /θ/ (*racidal-RADICAL*), or did not involve the letter ‘c’ at all (*maretial-MATERIAL*). If the effect were driven by phonology, primes with different pronunciation manipulations would have yielded different effects, but they did not. Taken together, these studies suggest an orthotactic basis for pronounceability effects.

Since the results with hearing readers are mixed, it remains unclear whether pronounceability effects are best explained by orthotactic or phonotactic sensitivity. In the present study, we aimed to fill several gaps left by existing studies in several ways. First, studying pronounceability effects in deaf readers could shed light on the nature of these effects because deaf readers can achieve comparable reading skill and orthographic sensitivity despite comparatively weaker phonological skills (see Emmorey & Lee, 2021, for review). Therefore, the present masked target lexical decision study sought to address the following research question: Are deaf and hearing readers equally sensitive to the pronounceability of TL nonwords? In order to help answer this question, we also recorded EEG while deaf and hearing readers made lexical decisions to masked words, pronounceable TL nonwords, and unpronounceable TL nonwords.

We predicted that both deaf and hearing readers would demonstrate classic lexicality effects as evidenced by (a) faster and more accurate responses to real words than nonwords, (b) smaller amplitude N250s to words compared to nonwords, and (c) smaller amplitude N400s to words compared to nonwords. If pronounceability effects are related to phonotactics, we would expect hearing readers to demonstrate faster and more accurate responses to pronounceable nonwords than unpronounceable nonwords, replicating Frankish and Turner (2007), and deaf readers would show no such effect. If pronounceability effects have an orthotactic basis, we would expect both deaf and hearing readers to treat TL nonwords similarly. Deaf readers may even have faster and more accurate responses compared to hearing readers because of their greater sensitivity to the visual-orthographic makeup of words and tighter orthographic-to-semantic connections (Bélanger & Rayner, 2015; Emmorey et al., 2017).

Second, the addition of ERPs will allow us to capture nuances of online linguistic processes that cannot be seen in behavioral studies alone. ERPs are sensitive to distinct orthographic and phonological processes involved in word recognition (Grainger & Holcomb, 2009). TL priming appears to have a distinct scalp distribution (posterior) and earlier-emerging effects on the N250 compared to pseudohomophone priming (more anterior) but similar robust effects on the N400 (Grainger et al., 2006; Zimman et al, 2019). Therefore, we might expect group differences in N250 effects if pronounceability effects are tied to phonotactics. In addition, pronounceable nonwords show a larger N400 compared to fully unpronounceable nonwords (e.g, consonant strings) in hearing readers (Massol et al., 2011). If this effect is driven by orthography, deaf and hearing readers should show similar N400 effects, but if it is driven by phonology, then deaf readers may show little or no modulation in N400 amplitude based on nonword pronounceability.

Third, we also conducted correlational analyses to determine if the size of the ERP effects or the behavioral measures (accuracy, RT) were modulated by reading ability, spelling ability, or phonological awareness. If pronounceability effects depend on access to phonology, they may correlate with phonological awareness for hearing reader. If pronounceability effects are based on orthographic sensitivity, the size of the ERP effects may correlate with spelling ability.

3.3 Methods

3.3.1 Participants. This study included 20 deaf participants (11 f; mean age 33 years) and 20 hearing participants (12 f; mean age 29 years). Deaf participants were severely or profoundly deaf and reported using ASL as their primary and preferred language. Five deaf participants were native signers (acquired ASL from birth), and 15 were early signers (acquired ASL before the age of seven). Hearing participants reported being monolingual English speakers with no exposure to another language before the age of seven. All participants were over the age of 18, reported no history of neurological disorders, and had normal or corrected-to-normal vision. Four deaf participants and three hearing participants were left-handed. One additional hearing participant and two deaf participants were run in the study but were excluded from analyses due to low accuracy on word trials (below 75% correct "yes" decisions), and three additional hearing participants were excluded due to a high proportion of critical trials contaminated by artifact (over 20%). All participants signed consent forms in accordance with the Institutional Review Board at San Diego State University and were compensated for their time.

Prior to the experiment, participants took behavioral tests for the purposes of group matching and planned correlational analyses. The deaf and hearing groups were matched on nonverbal intelligence as measured by the Kaufman Brief Intelligence Test - 2 (KBIT-2) (Kaufman & Kaufman, 1990), $t(38) = -0.07$, $p = 0.94$, and reading level as measured by the comprehension subtest of the Peabody Individual Achievement Test-Revised (PIAT-R) (Markwardt, 1989), $t(38) = 0.43$, $p = 0.67$ (see Table 3.1). Deaf readers had marginally better spelling skill than hearing readers, as measured by a Spelling Recognition Test (Andrews & Hersch, 2010), $t(38) = 1.85$, $p = 0.07$. The hearing group had significantly better phonological awareness compared to the deaf group as measured by the Phonological Awareness Tests developed by Hirshorn and colleagues (2015), which were specially designed for testing deaf adults, $t(38) = 3.65$, $p < 0.001$.

Table 3.1. Nonverbal intelligence and English language scores for deaf and hearing readers (mean (SD)).

Group	Nonverbal Intelligence Out of 46	Reading Comprehension Out of 100	Spelling Recognition Out of 88	Phonological Awareness Out of 100
Deaf Readers (N = 20)	38.75 (4.69) (107.00 standard)	87.55 (7.29)	75.85 (9.21)	70.68 (14.68)
Hearing Readers (N = 20)	38.85 (4.03) (106.58 standard)	85.63 (6.32)	70.45 (9.24)	85.95 (11.62)

3.3.2 Stimuli. The stimuli consisted of a total of 225 critical trials: 75 words, 75 pronounceable TL nonwords, and 75 unpronounceable TL nonwords. All words and nonwords contained five letters. Nonwords were created by transposing either the second and third letters or the third and fourth letters of the 75 real words. The pronounceability of nonwords was determined through a norming study taken by 20 hearing monolingual speakers on Mechanical Turk. Participants were asked to rate the nonwords using a four-point scale (1= not pronounceable at all, 4= totally pronounceable). Nonwords with ratings of 1 from 80% of the participants were deemed unpronounceable, and nonwords with ratings of 4 from at least 80% of the participants were deemed pronounceable. Only words (e.g., brave) whose letter transpositions yielded both a pronounceable (e.g., barve) and unpronounceable (e.g., brvae) nonword were selected for critical trials in the experiment. Twenty-five filler words were added to achieve a 2:3 ratio of words to nonwords. Thus, participants saw a total of 250 trials, but only the 225 critical trials were analyzed.

In order to make the lexical decision more difficult, for each trial, the stimulus was displayed for 70 ms and followed by a mask for 300 ms. The mask was made up of jumbled letter fragments. Stimulus duration was determined though a pilot study to ensure both groups would be able to perceive the stimuli and yield comparable error rates on the lexical decision task. Frankish and Turner (2007) used a 60 ms stimulus duration, which yielded 94% accuracy on words and 60% accuracy on nonwords. Our pilot study indicated that similar accuracy on words (92% for deaf readers; 93% for hearing readers) and nonwords (65% for deaf readers; 47% for hearing readers) could be achieved with a 70 ms stimulus duration in our study. A blank screen was then displayed until the participant responded. A purple fixation cross was displayed for 1500ms between trials, followed by a white fixation cross for 500ms to indicate that the next trial was coming up.

Each participant saw a given word (e.g., brave), its pronounceable nonword derivative (barve), and its unpronounceable nonword derivative (brvae). Three lists were created to avoid order effects or possible repetition effects for stimuli derived from the same base word. Stimuli derived from the same base word were also spaced at least 30 trials apart to limit repetition effects. The lists were pseudorandomized to ensure that no more than three consecutive trials prompted the same response for the lexical decision task.

3.3.3 Procedure. Instructions were given in ASL and English to deaf participants and in English to hearing participants. A native signer was present to answer any questions during data collection with all deaf participants. The experiment took place in a dimly lit room. Participants were seated in a chair 101 cm from the stimulus presentation monitor. Participants viewed single, masked presentations of the stimuli and completed a lexical decision task. They used a videogame controller to respond after each stimulus, pressing one button if they thought the stimulus was a real word and another button if they did not. Response hand was counterbalanced across participants. Participants were asked to respond as quickly and accurately as possible. They were asked to blink during purple fixation crosses displayed between trials and during longer blink breaks every 12-15 trials.

Following the experiment, participants completed an offline stimulus visibility task. Real words were presented with the same masking as in the experiment for variable durations between 20 and 120 ms. Hearing participants read the words aloud, and deaf participants provided the ASL translation for words that they were able to perceive. This task ensured that all participants able to perceive stimuli presented at 70 ms (the duration chosen for the experiment).

3.3.4. EEG Methods. Participants were fitted with an elastic cap (Electro-Cap) with 29 tin electrodes. An electrode placed on the left mastoid was used as a reference during recording and for subsequent analyses. An electrode over the right mastoid was used to assess any lateral asymmetries between the mastoids, but none were observed. An electrode located below the left eye was used to identify blink artifacts, and an electrode on the outer canthus of the right eye was used to identify artifacts due to horizontal eye movements. Saline gel (Electro-Gel) was used to maintain all electrode impedances below 2.5 kΩ. EEG was amplified with SynAmpRT amplifiers (Neuroscan-Compumedics) with a bandpass of DC to 100Hz and was sampled continuously at 500 Hz. Offline, ERPs were time-locked to stimulus onset and averaged over a 1000 ms epoch, including a 100 ms pre-stimulus-onset baseline. A 15 Hz low-pass filter was applied to the data. Trials contaminated by eye movement or drift artifacts were excluded from all analyses.

3.3.5 Analyses. Accuracy and reaction times (RTs) were recorded for behavioral analyses. We used mixed-design ANOVAs with factors Lexicality (Word, Nonword) and Group (Deaf, Hearing) to analyze the behavioral effects of lexicality. We used mixed-design ANOVAs with factors Pronounceability (Pronounceable, Unpronounceable) and Group (Deaf, Hearing) to analyze the behavioral effects of pronounceability for the nonwords.

For ERPs, we used 200-350 ms and 350-600 ms windows for the N250 and N400 analyses, respectively, because masking may delay the time course of processing. To analyze the ERP lexicality effects, we used a mixed-design ANOVA with factors Lexicality (Word, Nonword), Laterality (Left, Midline, Right), Anterior/Posterior (Prefrontal, Frontal, Central, Parietal, Occipital), and Group (Deaf, Hearing). To analyze the ERP pronounceability effects for the nonwords, we used a mixed-design ANOVA with factors Pronounceability (Pronounceable, Unpronounceable), Laterality (Left, Midline, Right), Anterior/Posterior (Prefrontal, Frontal, Central, Parietal, Occipital), and Group (Deaf, Hearing). We analyzed correct trials only for the ERP effects of lexicality and pronounceability.

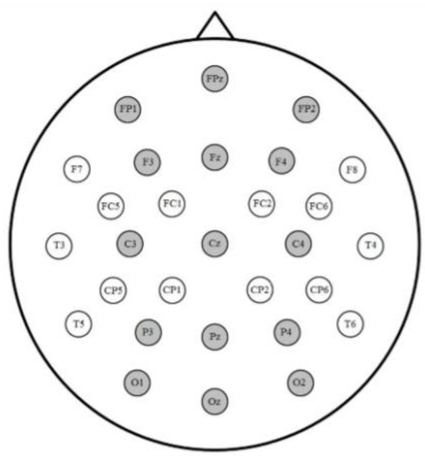

Figure 3.1. Electrode montage with gray channels included in event-related potential (ERP) analyses. Fifteen analyzed channels were distributed across five levels of Anterior/Posterior (Prefrontal, Frontal, Central, Parietal, Occipital) and three levels of Laterality (Left, Midline, Right).

3.4 Results

3.4.1 Behavioral Results

3.4.1.1 Lexicality. Behavioral results are presented in Table 3.2. For the lexicality analysis, there was a main effect of Group, $F(1,38) = 8.54$, $p = 0.01$, $\eta_p^2 = 0.18$, with deaf participants (82%) responding more accurately overall compared to hearing participants (72%).

There was also a main effect of Lexicality, $F(1,38) = 138.47$, $p < 0.001$, $\eta p^2 = 0.78$, with participants responding more accurately to words (95%) compared to nonwords (60%). Finally, there was a Group x Lexicality interaction, $F(1,38) = 11.5$, $p < 0.002$, $\eta p^2 = 0.23$. The difference in accuracy between words and nonwords was greater in the hearing group, who were only performing at chance on nonword trials.

There was a main effect of Group in the RTs, $F(1,38) = 4.47$, $p = 0.04$, $\eta p^2 = 0.11$, with deaf participants (783 ms) responding faster overall compared to hearing participants (907 ms). There was also a main effect of Lexicality, $F(1,38) = 78.96$, $p < 0.001$, $\eta p^2 = 0.68$, with participants responding faster to words (758 ms) compared to nonwords (933 ms). Finally, there was a Group x Lexicality interaction, $F(1,38) = 7.88$, $p = 0.008$, $\eta p^2 = 0.17$. The difference in RTs between words and nonwords was greater in the hearing group (230 ms difference) than in the deaf group (119 ms difference).

3.4.1.2 Nonword Pronounceability. For the behavioral effects of pronounceability, there was a main effect of Group, $F(1,38) = 10.34$, $p = 0.003$, $\eta p^2 = 0.21$, with deaf participants (69%) responding more accurately to nonwords compared to hearing participants (50%). There was also a main effect of Pronounceability, $F(1,38) = 5.46$, $p = 0.02$, $\eta p^2 = 0.13$, with participants responding more accurately to unpronounceable nonwords (62%) compared to pronounceable nonwords (57%). There was no Group x Pronounceability interaction, $F(1,38) = 0.74$, $p = 0.39$, $\eta p^2 = 0.02$.

There was also a main effect of Group in RTs, $F(1,38) = 6.1$, $p = 0.02$, $\eta p^2 = 0.14$, with deaf participants (843 ms) responding faster to nonwords compared to hearing participants (1015 ms). There was a main effect of Pronounceability, $F(1,38) = 24.11$, $p < 0.001$, $\eta p^2 = 0.39$, with participants responding faster to pronounceable nonwords (892 ms) compared to unpronounceable nonwords (967 ms). The Group x Pronounceability interaction did not reach significance, $F(1,38) = 2.98$, $p = 0.09$, $\eta_p^2 = 0.07$.

Table 3.2. Behavioral results [Mean (SD)].

		Accuracy (%)		RTs (ms)	
		Deaf	Hearing	Deaf	Hearing
Lexicality	Words	94.6 (4.3)	95.2 (4.1)	724 (140)	792 (189)
	Nonwords	69.4 (20.4)	49.6 (18.5)	843 (195)	1022 (245)
Pronounceability	Pronounceable Nonwords	67.8 (24.1)	46.1 (21.4)	819 (210)	965 (266)
	Unpronounceable Nonwords	71.0 (17.8)	53.1 (18.7)	867 (184)	1066 (235)

3.4.2 ERP Results

3.4.2.1 Lexicality. The lexicality ERP effects for all participants are shown in Figure 3.2. The omnibus test for the lexicality N250 effect showed a main effect of Lexicality, with nonwords producing greater negativities than words, especially over more anterior sites, $F(1, 38) = 13.7$, $p < 0.001$, $\eta_p^2 = 0.26$, Lexicality × Anterior/Posterior, $F(4,152) = 3.24$, $p = 0.048$, $\eta_p^2 = 0.08$. Similarly, the omnibus test for the lexicality N400 effect showed a main effect of Lexicality, with nonwords producing greater negativities than words, $F(1,38) = 8.53$, $p = 0.006$, $\eta_p^2 = 0.18$. This effect was strongest over posterior sites, Lexicality × Anterior/Posterior, $F(4,152) = 7.28$, $p < 0.001$, $\eta_p^2 = 0.16$. There were no interactions with Group.

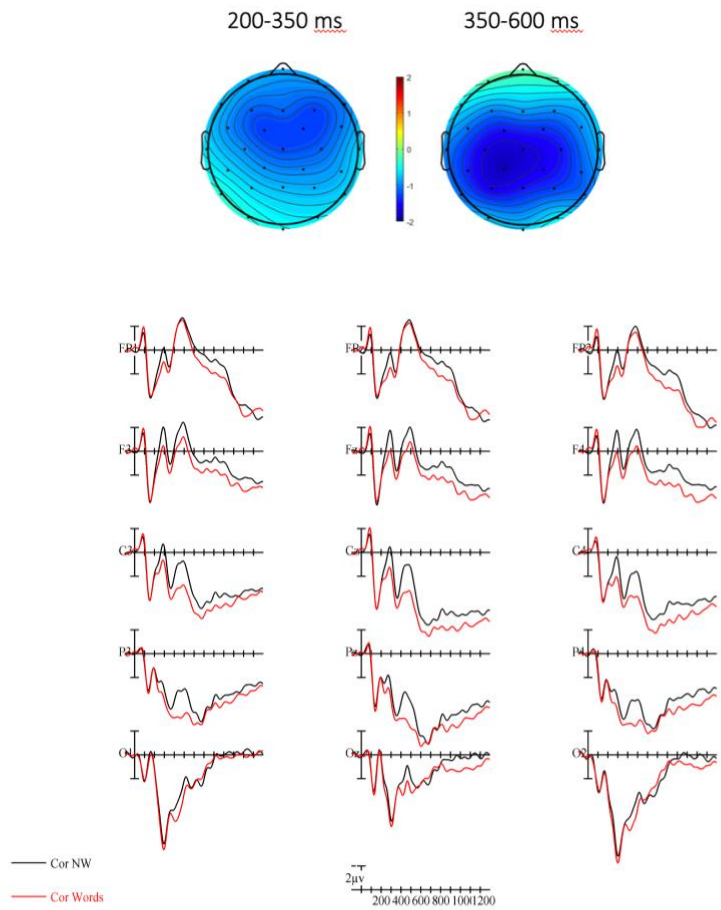

Figure 3.2. Lexicality N250 and N400 effects for deaf and hearing readers combined. Grand average ERP waveforms for nonwords (black) and words (red) at 15 sites. Time is represented on the horizontal axis in 100 ms units, while mean amplitude is represented on the vertical axis in 2 µV units. Negative is plotted up. Scalp voltage maps depict the effect of lexicality on mean N250 amplitude from 200-350 ms and mean N400 amplitude from 350-600 ms (nonwords-words).

3.4.2.2 Nonword Pronounceability. The pronounceability ERP effects for all participants are shown in Figure 3.3. There was no effect of pronounceability on the N250 component, all *p*s > 0.09. However, the omnibus test for the N400 effect yielded a main effect of Pronounceability, with pronounceable nonwords producing greater negativities than unpronounceable nonwords, particularly at more posterior sites, $F(1,38) = 14.56$, $p = 0.001$, $\eta_p^2 = 0.28$, Pronounceability × Anterior/Posterior, $F(4, 152) = 7.01$, $p < 0.001$, $\eta_p^2 = 0.16$. There were no interactions with Group.

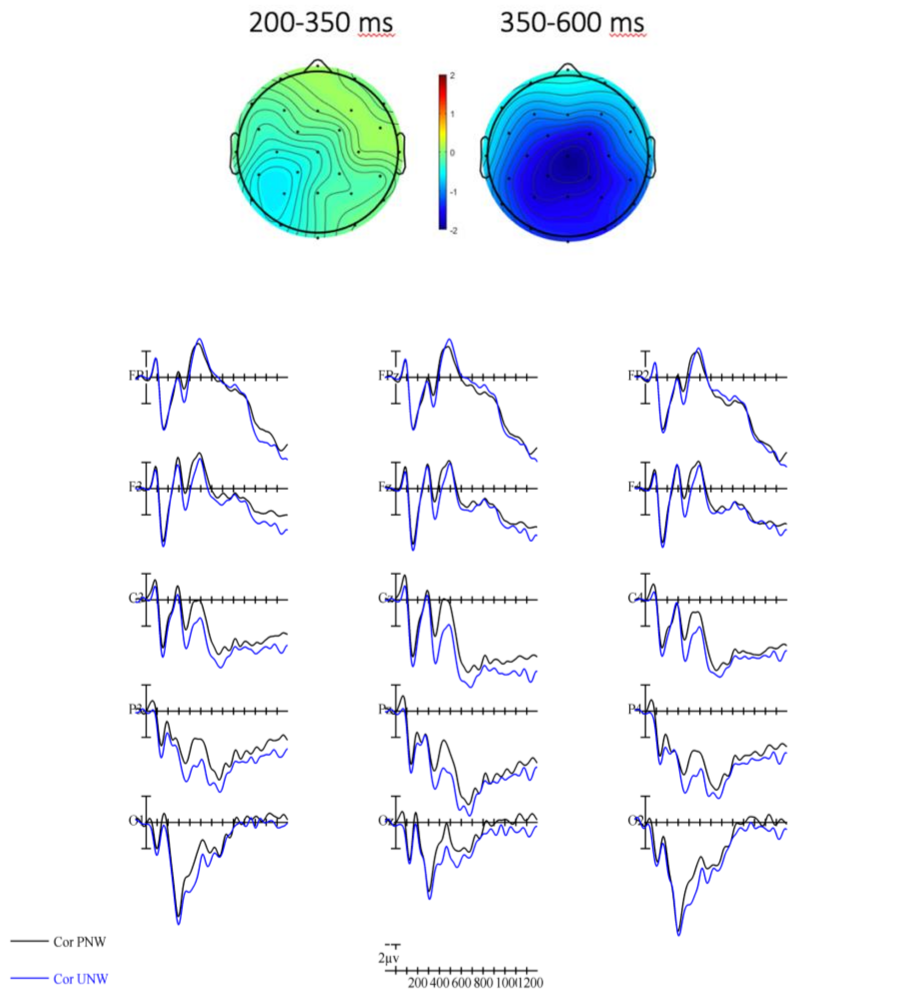

Figure 3.3. Pronounceability N250 and N400 effects for deaf and hearing readers combined. Grand average ERP waveforms for pronounceable nonwords (black) and unpronounceable nonwords (blue) at 15 sites. Time is represented on the horizontal axis in 100 ms units, while mean amplitude is represented on the vertical axis in 2 µV units. Negative is plotted up. Scalp voltage maps depict the effect of pronounceability on mean N250 amplitude from 200-350 ms and mean N400 amplitude from 350-600 ms (pronounceable-unpronounceable).

3.4.3 Correlations. For hearing readers, spelling ability was strongly correlated with lexical decision accuracy ($r = 0.57$, $p = 0.02$) and with nonword rejection accuracy ($r = 0.55$, $p = 0.02$). No correlations with accuracy were significant for the deaf readers, all *p*s > 0.12, nor with the RT for either group, all *p*s > 0.11 . None of the ERP effects correlated with reading ability, spelling ability, or phonological awareness for either group, all *p*s > 0.25.

3.5 Discussion

This ERP study investigated phonotactic/orthotactic contributions to word processing for deaf and hearing readers by manipulating nonword pronounceability in a lexical decision task. This task was made more difficult by a short stimulus duration (70 ms) and a backwards jumbled-letter mask. As expected, all readers were much faster and more accurate at classifying words compared to nonwords. In addition to these behavioral effects, we also found the expected N250 and N400 effects of lexicality, with nonwords eliciting larger amplitude negativities than words. These components are associated with mapping letters to words (N250) and words to meaning (N400) and appeared largely the same for deaf and hearing readers; we found no significant main effects or interactions with group. However, deaf readers were faster and more accurate when making lexical decisions compared to hearing readers.

Half of the TL nonwords in this experiment were pronounceable (i.e., orthotactically/phonotactically legal) and half were unpronounceable (i.e., orthotactically/phonotactically illegal). Behaviorally, both deaf and hearing readers responded more accurately to unpronounceable nonwords compared to pronounceable nonwords. This result goes in the opposite direction of the pronounceability effect in Frankish and Turner (2007) and may be due to a speed-accuracy trade off in our experiment, since participants were also slower to respond to unpronounceable than pronounceable nonwords. It is also possible that methodological differences across experiments led to the discrepancy in results (e.g., differences in masks, stimulus duration and presentation, etc.). Deaf readers were faster and more accurate in their nonword decisions than hearing readers, but they were similar in their (in)sensitivity to nonword pronounceability.

In terms of ERPs, we observed similar lexicality effects on the N250 and N400 (greater negativities for nonwords than words) for both deaf and hearing readers. There were no N250 effects of pronounceability, but there was an N400 effect, with pronounceable nonwords eliciting larger amplitude negativities than unpronounceable nonwords for both groups. Contrary to our hypothesis that pronounceability is driven by sublexical orthotactic and phonotactic structure, it appears that these constraints affected lexical-level processing for both deaf and hearing readers. Because deaf and hearing readers differ in their phonological awareness, the lack of group differences leads us to believe that the pronounceability N400 effect was driven by sensitivity to lexical-level orthotactic structure. This result is consistent with the lack of correlation between phonological ability and ERP or behavioral effects and with the correlation between spelling and nonword rejection accuracy for hearing readers.

Overall, our findings seem at odds with the interpretations put forth by Frankish and Turner (2007) for TL pronounceability effects. They argued that pronounceable nonwords are easily rejected because their phonological representations clearly conflict with those of real words. Our data do not support this hypothesis. Participants actually responded more accurately (although more slowly) to *unpronounceable* nonwords in our experiment. The ERPs showed that pronounceable nonwords elicited larger amplitude N400s compared to unpronounceable nonwords. We suggest that pronounceable nonwords activate phonological and orthographic competitors for lexical access, which results in more effortful lexico-semantic processing and larger amplitude N400s compared to unpronounceable nonwords. Frankish and Turner (2007) also argued that the pronounceability effects they observed in hearing readers must have been tied to their use of phonotactics because dyslexic readers (with poorer phonological abilities) did not show the same effects. Following this same logic, we would have expected that deaf readers would not have been as sensitive to pronounceability as hearing readers. In reality, pronounceability effects were similar across groups despite marked differences in their phonological awareness.

A second hypothesis put forth by Frankish and Turner (2007) was that unpronounceable nonwords might be more easily mistaken for words because they are more likely to undergo an orthographic repair process, i.e., they are “autocorrected” to real words. The N400 pronounceability effect we observed seems more in line with this interpretation. Pronounceable nonwords typically show larger N400s than words (Massol et al., 2011). Therefore, if unpronounceable nonwords are autocorrected and treated as words, they should have smaller amplitude N400s compared to pronounceable nonwords. This pattern is indeed what we found. However, this explanation seems unlikely because unpronounceable nonwords were not mistaken for words more often in our experiment; they actually elicited more correct "no" responses and were correctly classified as nonwords more often than pronounceable nonwords.

Another possible explanation for the larger amplitude N400s for pronounceable compared to unpronounceable nonwords is that pronounceable nonwords are more plausible candidates for lexical access. Because they conform to orthographic and phonological constraints of English, they are more word-like and are more likely to be mistaken for words. They may incite activation that is unresolved when no lexical entry is found, resulting in larger amplitude N400s compared to unpronounceable nonwords. In contrast, unpronounceable nonwords are more easily rejected because they clearly violate such constraints. Like symbol strings, they are less plausible candidates for lexical access, so they demand less activation, and thus the N400 response is less pronounced. Unpronounceable nonwords may show smaller amplitude N400s not because they are being processed as real words (i.e., they were autocorrected), but because that they are so *unlike* words that they do not generate a big N400.

Finally, an important finding of this study is that deaf readers were far faster (by 172 ms) and more accurate (by 19%) at classifying nonwords compared to hearing readers, even though English is their second language. These behavioral results are consistent with a number of studies that show faster lexical and semantic word decisions for deaf compared to hearing readers (Clark et al., 2016; Morford et al., 2019; Morford et al., 2017; Villwock et al., 2021). Deaf readers may have had an advantage in processing TL nonwords because they may have advantages in visual attention and processing (see Pavani & Bottari, 2012, for review). Using data from the post-experiment stimulus test that was designed to ensure that all participants could see targets at 70 ms duration, we determined the fastest possible duration at which the deaf and hearing participants could perceive words. Deaf participants had significantly a lower threshold (mean = 23 ms, SD = 5 ms) compared to hearing participants (mean = 30 ms, SD = 14 ms), $t(38) = -2.10$, $p = - 0.04$. This difference in visibility threshold suggests that deaf participants may have had more robust or earlier visual access to the stimuli compared to hearing participants. Such early visual processing may have given deaf participants a head start in processing the stimuli.

This idea prompted us to conduct a follow-up ERP analysis to determine if differences in early visual processing were reflected in an early time window (100-200 ms). The omnibus test comparing nonwords and words in this window yielded a main effect of Group, with deaf participants producing greater negativities than hearing participants, $F(1,38) = 5.45$, $p = 0.03$, $\eta_p^2 = 0.13$. Group did not interact with Lexicality, Laterality, or Anterior/Posterior. Deaf readers had a stronger response to stimuli in this early time window, which may have precipitated processing and allowed them to make faster lexical decisions later in the processing stream.

Faster lexical decisions for deaf readers could also be due to more efficient orthographic-semantic links (Bélanger & Rayner, 2015; Emmorey et al., 2016; Gutierrez et al., 2019; Meade et al., 2019; Morford et al., 2017). In bypassing the phonological route to word recognition, deaf readers avoid activation of phonological competitors for lexical access. Thus, the orthographic route to word recognition is more efficient (Grainger & Ziegler, 2011) and may accelerate word reading and lexical decisions. These two possible explanations - enhanced early visual processing and efficient orthographic-semantic links - are not mutually exclusive.

In conclusion, this study investigated how lexicality and pronounceability affect word processing for deaf and hearing readers. As expected, we found classic behavioral and ERP effects of lexicality that were similar across groups. Counter to our predictions, effects of pronounceability also appeared similar across groups and were seen at the lexico-semantic level rather than at the sublexical level. Although the ERP data indicated that words and nonwords were processed similarly across groups, behavioral differences indicated that deaf readers had an advantage in making lexical decisions and in rejecting TL nonwords. We suggest that this advantage may be due to a heightened sensitivity to the visual-orthographic make up of words and tighter orthographic-to-semantic connections for deaf readers that support an orthographic route to word recognition that is not phonologically mediated. Future studies may wish to further explore how these visual differences relate to orthographic processing to support efficient word processing and reading skill in deaf readers.

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Chapter 4: ERP evidence for co-activation of English words during recognition of American Sign Language signs

4.1 Abstract

Event-related potentials (ERPs) were used to investigate co-activation of English words during recognition of American Sign Language (ASL) signs. Deaf and hearing signers viewed pairs of ASL signs and judged their semantic relatedness. Half of the semantically unrelated signs had English translations that shared an orthographic and phonological rime (e.g., BAR–STAR) and half did not (e.g., NURSE–STAR). Classic N400 and behavioral semantic priming effects were observed in both groups. For hearing signers, targets in sign pairs with English rime translations elicited a smaller N400 compared to targets in pairs with unrelated English translations. In contrast, a reversed N400 effect was observed for deaf signers: target signs in English rime translation pairs elicited a larger N400 compared to targets in pairs with unrelated English translations. This reversed effect was overtaken by a later, more typical ERP priming effect for deaf signers who were aware of the manipulation. These findings provide evidence that implicit language co-activation in bimodal bilinguals is bidirectional. However, the distinct pattern of effects in deaf and hearing signers suggests that it may be modulated by differences in language proficiency and dominance as well as by asymmetric reliance on orthographic versus phonological representations.

4.2 Introduction

Much research on bilingualism is focused on how a bilingual's two languages interact (e.g., Kroll & Bialystock, 2013; Marian & Spivey, 2003). A topic of particular interest is the extent to which one language is co-activated while the other is being processed. Studies of language co-activation reveal how bilingual language users organize and control their two languages. Although language co-activation has been well documented in unimodal bilinguals, i.e., users of two spoken languages (e.g., Guo et al., 2012; Midgley et al., 2008; Thierry & Wu, 2007), fewer studies have examined this topic in bimodal bilinguals, i.e., users of both a signed and spoken/written language (see Ormel & Geizen, 2014 for a review). Here we use the term 'bimodal bilingual' to describe both deaf and hearing signers. Deaf bimodal bilinguals are fluent in a signed language, are literate in the written form of a spoken language, and may have varying degrees of fluency in the spoken form of that language. Hearing bimodal bilinguals are also proficient in a signed language and are fluent in both the spoken and written forms of a spoken language. Studies with bimodal bilinguals can address how language co-activation occurs across modalities and whether the processes involved are the same or different from those involved in unimodal language co-activation (see Emmorey et al., 2016 for discussion).

Studies with unimodal bilinguals provide evidence that a bilingual's two languages are not processed independently. Both of a bilingual's languages are explicitly involved in translation tasks (e.g., Guo et al., 2012), but co-activation also appears to occur implicitly when only one language is selected for a given task and there is no apparent reason to call upon the other language (e.g., Midgley et al., 2008; Thierry & Wu, 2007; Wu & Thierry, 2010). Thierry and Wu (2007) used event-related potentials (ERPs) to investigate this implicit language co-activation. In this study, Chinese-English bilinguals were presented with pairs of English words and asked to make a semantic judgment. Unbeknownst to the participants, half of the English word primes had Chinese translations that contained a character that was repeated in the Chinese translations of the target words. Although there was no behavioral effect of the Chinese translation character repetition, ERPs revealed an effect of language co-activation. Specifically, the ERP analyses revealed an N400 priming effect such that English targets elicited smaller negativities when their Chinese translations were related in form to the Chinese translations of the primes compared to when they were unrelated. Thus, even when performing tasks in a monolingual context, unimodal bilinguals appear to activate lexical and sub-lexical representations from their other language (see also Blumenfeld & Marian, 2007; Marian & Spivey, 2003). Wu and Thierry (2010) conducted another study with Chinese-English bilinguals to dissociate the effects of phonology and orthography. They used the same implicit priming paradigm, but this time the Chinese translations contained either a sound repetition or a spelling repetition. Again, they found no behavioral effects of implicit language co-activation in either condition. ERPs revealed N400 priming effects for sound repetition but no effects of spelling repetition. They concluded that when processing English words, Chinese-English bilinguals implicitly co-activate Chinese phonology but not Chinese orthography.

Like unimodal bilinguals, there is evidence that bimodal bilinguals activate one language while processing the other. Hearing bimodal bilinguals appear to automatically access signs during auditory word recognition (Giezen et al., 2015; Shook & Marian, 2012; Villameriel et al., 2016), and a number of studies have used the same implicit priming paradigm as Thierry and Wu (2007) to demonstrate that bimodal bilinguals activate signs during visual word recognition. For example, Morford et al. (2011) conducted a behavioral study in which deaf signers read pairs of English words and made semantic judgments. Word pairs that were related in meaning (i.e., "yes" responses) were judged more quickly when the American Sign Language (ASL) translations were related in form. For instance, *bird* and *duck* are related in meaning, and their sign translations share the same location and movement. Word pairs that were not semantically related (i.e., "no" responses) were judged more slowly when the ASL translations were form related. For example, *movie* and *paper* are not related in meaning, but their sign translations share handshape and movement. Thus, the phonological relatedness of ASL translations influenced semantic decisions for English words even though there is no phonological overlap between English words and ASL signs and ASL was irrelevant to the task. Kubus et al. (2014) partially replicated these findings with German and German Sign Language (DGS): they found interference effects (for “no” responses) for form-related DGS translations but did not find facilitation effects (for “yes” responses). Finally, using the same semantic judgment task, Villameriel et al. (2016) found both facilitation and interference effects for Spanish word pairs with form-related translations in Spanish Sign Language for hearing bimodal bilinguals (both native and late signers). These results support the notion that both deaf and hearing bimodal bilinguals access signs when reading words.

Although co-activation of form representations in the non-target language appeared to impact semantic decisions in the target language, behavioral studies alone cannot deduce the mechanisms by which this co-activation occurs. Building on the behavioral studies with bimodal bilinguals described above, Meade et al. (2017) used ERPs to examine the time-course of processing for sign co-activation during word reading. This study also used the Thierry and Wu (2007) paradigm. Deaf ASL signers read pairs of English words and made semantic relatedness judgments. Semantically unrelated word pairs were manipulated so that their sign translations were related in form (i.e., shared two out of three major phonological parameters of location, movement, and handshape) or not. The authors found different patterns of co-activation for deaf signers who reported being unaware of the ASL form manipulation and those who were aware of the manipulation: the former (implicit) group showed a reduced negative response in form-related pairs 300–500 ms following target onset (an N400 effect); the latter (explicit) group showed a similar pattern but much later, 700–900 ms following target onset. The authors claimed that these early and late effects corresponded to automatic lexico-semantic processing versus more strategic translation processes that arose once participants became aware of the hidden form manipulation.

A number of studies have considered how bimodal bilinguals co-activate signs during visual or spoken word recognition, but few studies have explored whether the implicit co-activation of signs and words is bidirectional. To our knowledge, only two studies have investigated whether co-activation occurs from explicitly presented signs to implicitly activated spoken words, and both are unpublished. Van Hell et al. (2009) asked hearing users of Dutch and Sign Language of the Netherlands (NGT) to view pictures and signs and verify whether or not they matched. For trials in which the picture and sign did not match, some of the picture names shared spelling (and rhymed) with the Dutch translation of the sign. This manipulation resulted in slower reaction times when the sign and picture had translations that overlapped orthographically and phonologically in Dutch compared to those that did not. The fact that spoken language overlap interfered with the verification task is evidence that these bilingual participants were co-activating their spoken/written language while performing a task with signed stimuli, even though the task did not require translation.

Paralleling the behavioral results observed by Van Hell et al. (2009), an ERP study by Hosemann (2015) found evidence for co-activation of German translations when deaf native DGS signers viewed signed sentences. Each signed sentence contained a prime sign and a target sign whose German translations overlapped in orthography and phonology (e.g., LAST WEEK MY HOUSE, THERE MOUSE HIDE) (By convention signs are written in all capitals using the nearest translation equivalent). The EEG analysis indicated a smaller amplitude N400 to target signs preceded by related German translation primes versus those with unrelated primes. Although this priming effect is consistent with the idea that form-based representations of deaf signers' spoken language are co-activated while processing their signed language, this particular study was limited by the fact that nearly half of the trials had to be rejected due to inconsistent translations.

Despite recent progress regarding language co-activation in bimodal bilinguals, several questions remain unresolved: Is ASL-English language co-activation bidirectional? It appears that bimodal bilinguals co-activate signs during word recognition (e.g., Meade et al., 2017; Morford et al., 2011), but do they also co-activate words during sign recognition? If so, is the implicit co-activation of words the same for deaf and hearing bimodal bilinguals? In the present study, we used ERPs to address these questions and investigate co-activation of English words during recognition of ASL signs in the Thierry and Wu (2007) paradigm. Deaf and hearing bimodal bilinguals viewed pairs of ASL signs and judged semantic relatedness. Half of the semantically unrelated signs had English translations that shared an orthographic and phonological rime (e.g., BAR–STAR) and half did not (e.g., NURSE–STAR).

We predicted classic semantic priming effects (e.g., Kutas & Hillyard, 1989) for both deaf and hearing signers, with faster responses and smaller amplitude N400s for semantically related trials (e.g., DOCTOR–SICK) compared to semantically unrelated trials (e.g., NURSE–STAR). We also hypothesized that ASL-English co-activation would be bidirectional and predicted that bimodal bilinguals would show evidence of co-activating words during sign recognition. All of the existing studies of implicit sign co-activation during word recognition in deaf signers resulted in behavioral interference effects (i.e., slower "no" responses to semantic decisions about words when their sign translations were related in form; e.g., Kubus et al., 2014; Meade et al., 2017; Morford et al., 2011). We therefore predicted that deaf bimodal bilinguals would respond slower to semantically unrelated sign pairs when their English translations were related in form. There is also ERP evidence for N400 form priming effects in deaf signers, both when they co-activate signs during word recognition (Meade et al., 2017) and when they co-activate words during sign recognition (Hosemann, 2015). Based on these findings, we predicted that targets in sign pairs with form-related English translations should elicit smaller N400s compared to targets in pairs with unrelated English translations. The two studies conducted with hearing signers showed the same pattern of behavioral interference whether they were co-activating signs during word recognition (Villameriel et al., 2016) or words during sign recognition (Van Hell et al., 2009), suggesting that hearing and deaf signers may show a similar pattern of behavioral and ERP effects.

On the other hand, there is reason to believe that deaf and hearing signers might differ in their co-activation of words during sign recognition, given differences in their language dominance and proficiency and in how they acquire English. For example, less proficient bilinguals tend to have stronger co-activation of their dominant language when completing tasks in their less dominant language compared to more proficient bilinguals (e.g., Grainger et al., 2010; Kroll & Stewart, 1994). For hearing signers, English is their dominant language (see Emmorey et al., 2016 for discussion), and thus they may exhibit greater co-activation of English when processing ASL (their less dominant language). Aside from language dominance, implicit co-activation may also be influenced by language proficiency. Both Morford et al. (2011) and Meade et al. (2017) found that the degree of ASL co-activation during word reading was correlated with reading ability (less-skilled deaf readers were more likely to co-activate ASL than skilled deaf readers). Hearing signers (even early-exposed signers) tend to be less proficient in ASL than deaf signers (e.g., Hauser et al., 2015; Supalla et al., 2014). Therefore, hearing signers with lower ASL proficiency may be more likely to co-active English during sign recognition. Finally, deaf individuals develop varying degrees of phonological knowledge depending on their language experience (Hirshorn et al., 2015) but do not automatically access phonology when reading (e.g., Bélanger et al., 2013), which may affect how they develop and co-activate form-based representations of English words. Distinct patterns of processing for deaf and hearing signers could shed light on which linguistic factors influence how they co-activate words during sign recognition.

4.3 Methods

4.3.1 Participants. Twenty-four severely-to-profoundly deaf bimodal bilinguals (mean age = 35.6 years; SD = 9.4) and twenty hearing bimodal bilinguals (mean age = 36.8 years; SD = 10.2) participated in this study. Deaf participants were all native or early signers of ASL (exposed before the age of seven) and reported ASL as their primary and preferred language. Hearing participants were highly skilled signers of ASL who had been signing for at least six years (mean number of years signing = 23.7 years; SD = 9.9). These participants varied in their age of ASL acquisition (mean = 12.2 years, SD = 8.5). Five participants were native signers (acquired ASL from birth), one was an early signer (acquired ASL before the age of seven), and 14 were late signers (acquired ASL after the age of seven, range = 10–24 years). Twelve participants reported that they work as ASL interpreters. Eighteen of the hearing signers rated their ASL skill as very good or advanced, one declined to report language background information, and one rated her ASL skill as good but completed the post-experiment translation task with high accuracy (over 80%; see Procedure below). One deaf signer and two hearing signers were left handed. All participants reported having normal or corrected-to-normal vision and provided informed consent in accordance with the Institutional Review Board at San Diego

State University. Data from two additional deaf participants and one hearing participant were excluded from analyses due to blink artifacts contaminating a high proportion of trials (over 20%). One additional hearing participant was excluded from analyses because of very low accuracy on the post-experiment translation task (below 50%).

4.3.2 Stimuli. Stimuli consisted of 188 pairs of ASL signs. Video stimuli were created by filming a deaf native signer producing each of the signs. The videos were then clipped two frames before sign onset and at sign offset in order to capture the phonological movement of the sign and remove transitional movements from the video. Sign onsets and offsets were determined following the same guidelines as in previous studies (e.g., Caselli et al., 2016; Meade et al., 2018). A native signer and a fluent L2 signer independently determined the onsets and offsets for 20% of the stimuli and achieved high inter-rater reliability (98% agreement within a three-frame margin for sign onsets). The coders then split the remaining signs, with each coding onset and offset for an additional 40% of the stimuli.

Half of the ASL sign pairs (*N* = 94) were semantically related (e.g., LAUGH–HAPPY), and half of them were semantically unrelated (e.g., SHOES–HEAD). A norming study was conducted to determine how related the signs in each pair were. A group of 16 deaf participants read English glosses for each pair of signs and rated their semantic relatedness on a 7-point Likert scale (1 = totally unrelated, 7 = highly related). Sign pairs with average semantic relatedness ratings at or above 5.5 (mean = 6.36, SD = 0.35) were selected as stimuli for the semantically related condition, and sign pairs with an average rating at or below 2.5 (mean = 1.26, SD = 0.28) were selected as stimuli for the semantically unrelated condition. Semantic ratings were significantly higher for the semantically related condition than for the semantically unrelated condition, $t(187) = 102.35$, $p < 0.001$.

Half (N = 47) of the semantically unrelated pairs had translations that were form-related in English (e.g., BAR–STAR) (see Figure 4.1 for an illustration of these signs and see the Supplementary Materials Table S1 for a complete list of glosses for the ASL sign stimuli). Form-related pairs were defined as sharing both a phonological and orthographic rime. We use “rime” rather than “rhyme” to emphasize that the form overlap between the word pairs always occurred after the word onset and because the deaf participants are unlikely to be sensitive to sound-based rhymes. The other half (N = 47) of the semantically unrelated pairs did not share a rime (e.g., NURSE–STAR). To ensure participants were co-activating English translations that did in fact share a rime, only signs with consistent translations were used. In a separate norming study, we asked 20 deaf ASL signers to view videos of ASL signs and provide their English translations. Only signs that were translated as the same English word by at least 16 out of 20 participants (80%) were included. Participants also completed a post-experiment translation task to ensure that their translations maintained the shared rimes (see Procedure). Signs in each pair did not share more than one phonological parameter in ASL (handshape, location, or movement). There was no significant difference between the semantic ratings for the rime condition (mean = 1.28, SD = 0.28) and the non-rime condition (mean = 1.24, SD = 0.29), $t(93) = 0.50$, $p = 0.67$.

Figure 4.1. Example stimuli. A prime-target pair consisting of American Sign Language (ASL) signs with English rime translation (*bar–star*).

Ideally, a full 2 × 2 design would similarly divide the semantically related trials into equal numbers of rime and non-rime pairs. However, it was only possible to find four semantically related sign pairs whose English translations also shared a rime (e.g., MAD-SAD). These form-related pairs were included to help prevent participants from developing a strategy that automatically equated form-related translation pairs with a "no" response in the semantic relatedness task. A debriefing questionnaire was also administered to determine if such a strategy was used or if the participants had noticed the form manipulation (see Procedure). Thus, the 94 semantically related pairs consisted of four rime translation pairs and 90 non-rime translation pairs.

4.3.3 Procedure. During the experiment, participants were seated about 53 cm from the stimulus monitor in a dimly lit room. Deaf participants received instructions in both ASL and English, and a native deaf signer was present to answer any questions. Hearing participants received instructions in English. Participants were asked to view pairs of ASL signs and decide whether or not they were related in meaning. They used a video gamepad to respond as quickly and accurately as possible by pressing one button if the signs were related in meaning and a different button with the other hand if they were not. Response hand was counterbalanced across participants.

Each trial comprised a prime sign and a target sign with a 1300 ms stimulus onset asynchrony (SOA). Since the prime videos were variable in duration, a blank gray screen was added between the prime and target to maintain a constant SOA. Videos were presented on a black screen and subtended a visual angle of 10.8 degrees in the vertical direction and 14.0 degrees in the horizontal direction. Within the rectangular video frame, the sign model stood in front of a gray background and subtended a visual angle of 9.7 degrees in the vertical direction and 4.9 degrees in the horizontal direction. Following the target video, a black screen was displayed until 750 ms after the participant's response. A purple fixation cross then appeared on the screen for 1500 ms, indicating to the participants that they could blink. A white fixation cross then appeared for 500 ms to indicate that the next trial was upcoming, and a blank screen was displayed for 500 ms before the next trial began. Participants were instructed to blink when the purple fixation cross was displayed and during longer breaks after every 12–15 trials.

Each participant saw all 188 pairs of signs. Each target in the semantically unrelated pairs appeared once with an English form related prime (BAR–STAR) and once with an English unrelated prime (NURSE–STAR). When possible, targets in semantically related pairs also appeared once with an English form related prime (MAD–SAD) and once with an English unrelated prime (UPSET–SAD). However, due to the limited number of pairs that were related in both semantics and English form, most targets in semantically related pairs appeared with two primes whose English translations were unrelated in form (LUNG–HEART; BLOOD–HEART). Since each target appeared in the experiment twice, two pseudorandomized lists were created to minimize the effect of target repetition. For example, one list presented BAR–STAR in the first half of the experiment and NURSE–STAR in the second half, but the second list presented NURSE–STAR in the first half of the experiment and BAR–STAR in the second half. Lists were counterbalanced so that half of the participants in each group saw each list. The session began with 10 practice trials. The practice items did not contain any of the stimuli from the real experiment.

Following the EEG portion of the experiment, participants were given a questionnaire that asked whether they noticed anything special about the sign pairs or whether they used any particular strategy to make their decisions. If so, we asked what they noticed, when they noticed it, and whether the pattern they noticed affected their ability to make semantic relatedness judgments. Fourteen deaf participants did not report noticing the form overlap in English translation rimes and were therefore included in an implicit co-activation subgroup. Ten deaf participants reported noticing the form overlap in the English translations and were included in an explicit translation subgroup. All but two of the hearing participants reported noticing the English translation rimes, so the hearing signers were not divided into implicit and explicit subgroups.

Following the debrief questionnaire, a translation task was also administered to participants to ensure that they produced the anticipated English translations. Any mistranslations that caused rime pairs to lose their shared orthographic and phonological properties were excluded from analyses on an individual basis (8 pairs, or 17.6% of rime pairs, for deaf signers; 12 pairs, or 26.1% of rime pairs, for hearing signers). So as not to differentially reduce the number of trials in the rime condition, the unrelated (non-rime) pairs with the same targets were also excluded from analyses.

Several language assessments were also administered. The ASL Comprehension Test (Hauser et al., 2015) and the long version (35 items) of the ASL Sentence Repetition Task (Supalla et al., 2014) measure receptive and expressive skills in ASL, respectively. The Spelling Recognition Test (Andrews & Hersch, 2010) is a measure of orthographic precision in English. These measures of proficiency were collected for correlational analyses.

4.3.4 EEG Recording. Electrodes were placed on the participant's left and right mastoids, below the left eye, and on the outer canthus of the right eye. The electrode on the left mastoid was used as a reference during recording and for subsequent analyses. The electrode below the left eye captured vertical eye movement and, along with recordings from FP1, identified blink artifacts. The electrode next to the right eye right eye captured horizontal eye movement. Participants were then fitted with an elastic cap elastic cap (Electro-Cap) with 29 active electrodes. Saline gel (Electro-Gel) was injected into electrodes to maintain impedances below 2.5 kΩ. EEG was amplified with SynAmsRT amplifiers (Neuroscan- Compumedics) with a bandpass of DC to 100 Hz and was sampled continuously at 500 Hz.

Offline, ERPs were time-locked to target sign onset and averaged over a 1000 ms epoch, including a 100 ms pre-stimulus-onset baseline, with a 15 Hz low-pass filter at the 15 sites illustrated in Figure 4.2. Trials contaminated by artifacts from blinking, drift, or horizontal eye movement were excluded from analyses (5.2 trials, or 2.8%, on average for hearing signers; 7.1 trials, or 3.8%, on average for deaf signers).

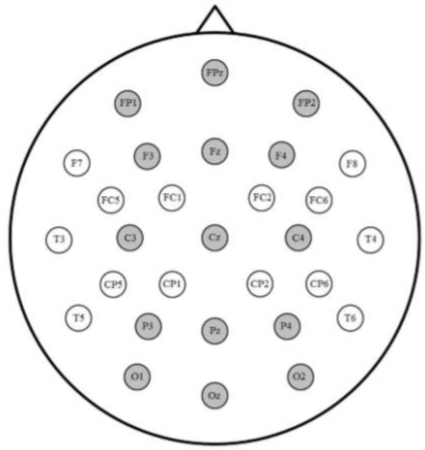

Figure 4.2. Electrode montage with gray channels included in event-related potential (ERP) analyses. Fifteen analyzed channels were distributed across five levels of Anterior/Posterior (Prefrontal, Frontal, Central, Parietal, Occipital) and three levels of Laterality (Left, Midline, Right).

4.3.5. Analysis. Reaction times (RTs) were recorded for behavioral analyses. Linear mixed effects (LME) models with items and participants as random intercepts and participants as random slopes were used to analyze RT effects of semantic relatedness and rime overlap in the English translations.

Turning to the ERP analyses, mean N400 amplitude was measured between 325 and 625 ms. This window is consistent with our previous study of N400 effects using signed stimuli [26]. To analyze the N400 semantic priming effect, we used a mixed-design ANOVA with factors Semantics (Related, Unrelated), Laterality (Left, Midline, Right), Anterior/Posterior (Prefrontal, Frontal, Central, Parietal, Occipital), and Group (Deaf, Hearing), including only trials with correct semantic judgments. To analyze the N400 English translation effect, we used a mixed-design ANOVA with factors English translation (Rime, Non-Rime), Laterality (Left, Midline, Right), Anterior/Posterior (Prefrontal, Frontal, Central, Parietal, Occipital), and Group (Deaf, Hearing), including all semantically unrelated trials with correct translations.

Meade et al. (2017) also found evidence for a late effect (700–900 ms) of ASL co-activation when deaf signers were aware of the relationship among the ASL translations of the

English word pairs they were reading. Thus, a mixed-design ANOVA with factors English (Rime, Non-Rime), Laterality (Left, Midline, Right), Anterior/Posterior (Prefrontal, Frontal, Central, Parietal, Occipital), and Group (Deaf, Hearing) was used to analyze mean amplitude within this late window. The semantic N400 effects, implicit English translation N400 effects, and later English translation effects were analyzed separately for the deaf and hearing groups as well as for the implicit and explicit deaf subgroups in planned comparisons. Greenhouse-Geisser corrections were applied to all ERP analyses with more than one degree of freedom in the numerator, and only significant effects are reported.

Finally, Pearson correlations were used to explore associations between the ERP effects and language proficiency in the deaf and hearing signers. ERP difference waves were calculated (mean amplitude of the unrelated–related conditions) for each of the 15 analyzed sites. Correlations were performed with the behavioral measures of ASL production, ASL comprehension, and English spelling for the N400 semantic effect, the N400 English translation rime effect, and the late (700–900 ms) English translation rime effect. Correlations were corrected for multiple comparisons using false discovery rate (FDR) corrections (Groppe et al., 2011).

4.4 Results

4.4.1 Behavioral. Trials with incorrect responses were excluded from all behavioral analyses (12 trials, or 6.4%, on average for hearing participants; 10 trials, or 5.3%, for deaf participants). Trials with RTs shorter than 200 ms or longer than 2.5 standard deviations above each participant's average RT were also discarded (4 trials, or 2.1%, on average in each group).

4.4.1.1 Semantic Priming Effects. Mean RTs and error rates are presented in Table 4.1. The LME analysis of RTs indicated that deaf signers had faster responses overall compared to hearing signers, t = 3.25, 95% CI = [171.68,695.43]. The model also revealed a significant Group × Semantics interaction, with the hearing signers showing a larger semantic priming RT effect than the deaf signers, t = −2.43, 95% CI = [−189.99,−20.34]. Even though the semantic effect was larger in the hearing group, follow-up analyses confirmed a main effect of Semantics in both groups (deaf group, t = −8.18, 95% CI = [−142.13,−87.16], hearing group, t = −9.73, 95% CI = [−260.12,−172.88]).

Table 4.1. Semantic and rime reaction times (mean (SD)).

Group	RT (ms)			
	Semantically Related	Semantically Unrelated	Rime	Non-Rime
Hearing Signers	1193 (243)	1383 (304)	1375 (295)	1392 (321)
Deaf Signers	1016 (176)	1132 (210)	1140 (208)	1123 (218)

Within the deaf group, there was no Subgroup × Semantic interaction, meaning there was no difference in the size of the semantic priming RT effect for the implicit subgroup and the explicit subgroup, t = 0.72, 95% CI = [−95.30,44.03]. The implicit and explicit subgroups also had similar RTs overall, t = −0.09, 95% CI = [−186.25,205.03].

4.4.1.2 English Rime Translation Effects. Only semantically unrelated trials were included in English translation analyses; half of these sign pairs had English translations that shared a rime and half did not. The LME analysis revealed a main effect of Group with deaf signers showing faster responses overall compared to hearing signers, t = 3.28, 95% CI = [145.56,577.72]. However, rime translations neither facilitated nor interfered with RTs, as there was no main effect of Rime, t = 1.00, 95% CI = [−40.22,123.21], or Rime × Group interaction, t = −0.88, 95% CI = [−71.25,27.02]. Within the deaf group, there was no difference in the size of the translation rime RT effect between the implicit subgroup and the explicit subgroup, t = 1.23, 95% CI = [−20.74,90.38]. Moreover, the implicit and explicit subgroups had similar RTs overall (main effect of sub-group: $t = -0.47$, 95% CI = [−228.90,140.78]).

4.4.2 ERP. Tables containing means and variances for each of the ERP effects reported below are available in the Supplementary Materials Table S2.

4.4.2.1 Semantic Priming

4.4.2.1.1. Hearing vs. Deaf Signers (325–625 ms). The semantic priming ERP results for the hearing and deaf signers are shown in Figure 4.3. The omnibus test for the semantic priming ERP effect yielded a main effect of Semantics, with semantically unrelated target signs producing greater negativities than semantically related trials especially over more midline and central-parietal sites, $F(1,42) = 44.38$, $p < 0.001$, $\eta p^2 = 0.51$, Semantic × Anterior/Posterior × Laterality, $F(8,336) = 5.95$, $p < 0.001$, $\eta p^2 = 0.12$. There was also a significant Group × Semantics interaction, $F(1,42) = 5.78$, $p = 0.02$, $\eta p^2 = 0.12$, indicating that the N400 priming effect was stronger for deaf signers (M = −2.43 μV) than for hearing signers (M = −1.14 μV).

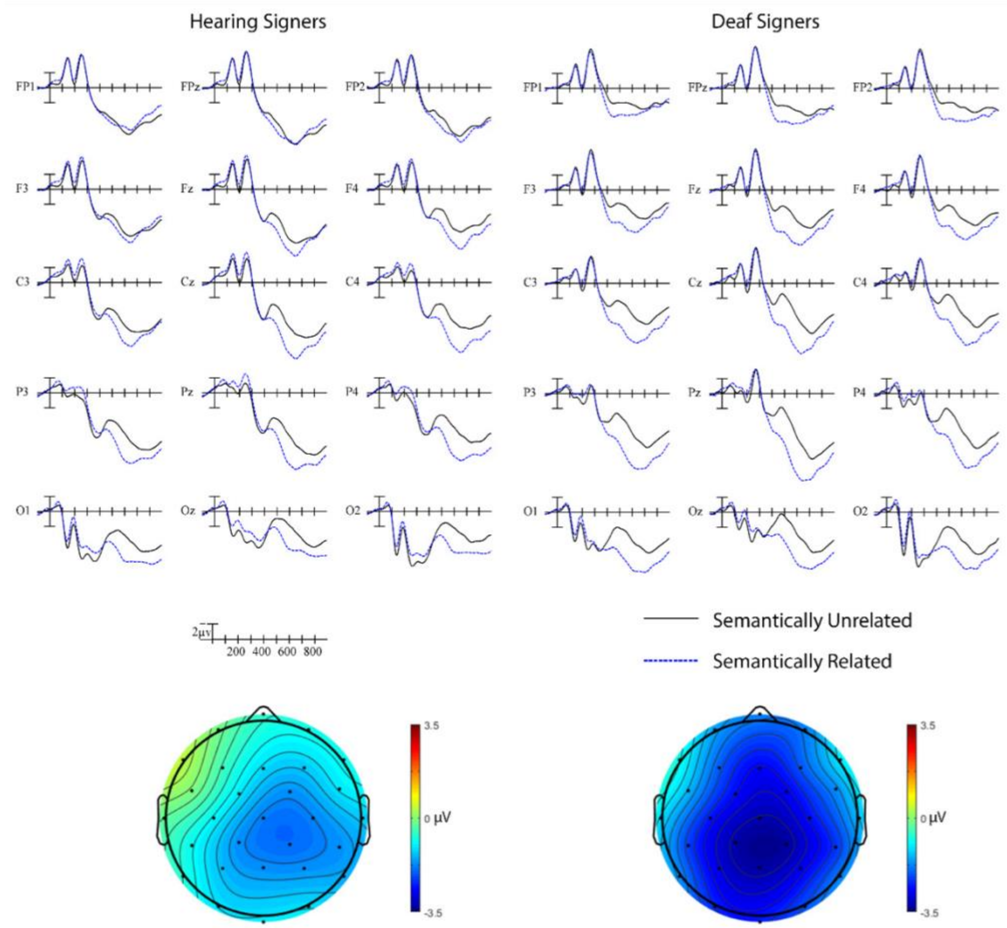

Figure 4.3. Semantic priming effects in hearing and deaf signers. Grand average ERP waveforms elicited by targets in semantically unrelated (black) and semantically related (blue) pairs at 15 sites. Each vertical tick marks 100 ms, and negative is plotted up. The calibration bar marks 2 μV. Scalp voltage maps showing the semantic priming effect on mean N400 amplitude (unrelated–related) from 325–625 ms.

4.4.2.1.2 Hearing Signers (325–625 ms). Within the hearing group, there was a clear N400 semantic priming effect such that semantically unrelated trials elicited larger N400s than semantically related trials, $F(1,19) = 8.36$, $p = 0.01$, $\eta_p^2 = 0.31$. This effect was strongest over right posterior sites, Semantics × Laterality × Anterior/Posterior, $F(8,152) = 5.13$, $p < 0.001$, $\eta_p^2 = 0.21$.

4.4.2.1.3 Deaf Signers (325–625 ms). Like the hearing group, the deaf group also showed a significant semantic priming effect, $F(1,23) = 44.97$, $p < 0.001$, $\eta_p^2 = 0.66$. For deaf signers, the effect was strongest over midline posterior sites, Semantics × Laterality ×

Anterior/Posterior, $F(8,184) = 2.56$, $p = 0.04$, $\eta p^2 = 0.10$. This effect remained significant for both the implicit subgroup, Semantics, $F(1,13) = 34.94$, $p < 0.001$, $\eta p^2 = 0.73$, Semantics × Laterality, $F(1, 13) = 4.33$, $p = 0.049$, $\eta p^2 = 0.25$, Semantics × Anterior/Posterior, $F(1, 13) = 4.70$, $p = 0.02$, $\eta p^2 = 0.27$, and the explicit subgroup, Semantics, $F(1,9) = 11.86$, $p = 0.01$, $\eta p^2 = 0.57$.

4.4.2.2 English Translation Rime Priming Effect

4.4.2.2.1 Hearing vs. Deaf Signers (325–625 ms). The English translation rime priming results for hearing and deaf signers are shown in Figure 4.4. An omnibus ANOVA was conducted on the translation rime priming N400 ERP the deaf signers. A significant Group × Rime interaction indicated that the effect went in the standard priming direction (unrelated more negative than related) in the hearing signers (M = −0.53 μV) but in the opposite direction (related more negative than unrelated) in the deaf signers (M = 0.56 μV), $F(1,42) = 4.71$, $p = 0.04$, $\eta p^2 = 0.10$.

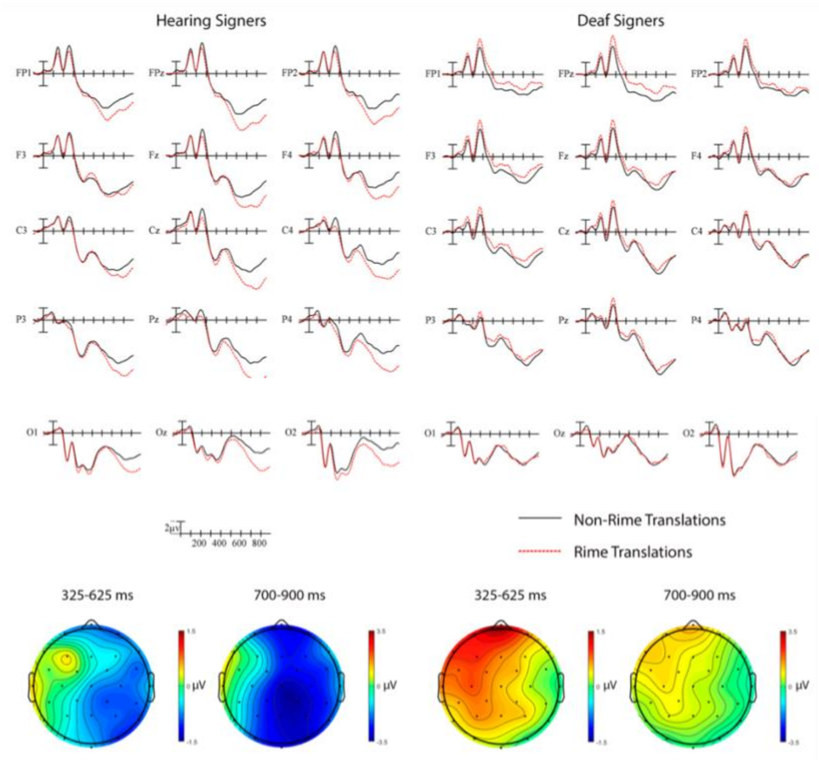

Figure 4.4. English translation rime priming effects in hearing and deaf signers. Grand average ERP waveforms elicited by targets in non-rime translation (black) and rime translation (red) pairs at 15 sites. Each vertical tick marks 100 ms, and negative is plotted up. The calibration bar marks 2 µV. Scalp voltage maps showing the English translation maps showing the English translation priming effect on mean N400 amplitude (unrelated–related).

4.4.2.2.2 Hearing vs. Deaf Signers (700–900 ms). The omnibus test for the late effect of translation rime priming yielded a Group × Rime × Laterality interaction, $F(2,84) = 9.58$, $p = 0.001$, $\eta_p^2 = 0.19$. Targets in unrelated pairs elicited larger negativities compared those in related pairs, especially over right hemisphere electrodes, in the hearing group while in the deaf group it was the targets in related pairs that elicited larger negativities, especially over left hemisphere sites.

4.4.2.2.3 Hearing Signers (325-625 ms). There was a significant English translation rime priming N400 effect in the hearing signers. Sign targets in pairs with non-rime English translations elicited larger negativities than sign targets in pairs with rime translations, especially at right hemisphere sites, Rime × Laterality, $F(2,38) = 6.41$, $p = 0.01$, $\eta_p = 0.25$ (see

Figure 4.4, left panel).

4.4.2.2.4 Hearing Signers (700-900 ms). A large widespread English translation effect continued into the later window for hearing signers, Rime, $F(1,19) = 11.41$, $p = 0.003$, $\eta p^2 = 0.38$, Rime × Laterality, $F(2,38) = 15.96$, $p < 0.001$, $\eta p^2 = 0.46$, with greater negativities for targets with non-rime primes than for targets with rime primes, especially at right hemisphere sites (see Figure 4.4, left panel).

4.4.2.2.5 Deaf Signers (325-625 ms). There was a significant reversed N400 effect of translation rime priming in the deaf signers. Sign targets in non-rime translation pairs elicited smaller negativities than targets in rime pairs within the N400 window, especially at left anterior sites, Rime × Laterality × Anterior/Posterior, $F(8,184) = 3.24$, $p = 0.002$, $\eta p^2 = 0.12$ (see Figure 4.4, right panel).

4.4.2.2.6 Deaf Signers (700-900 ms). Targets in non-rime translation pairs continued to elicit smaller negativities than targets in rime translation pairs in the later window, especially at left hemisphere sites, Rime × Laterality, $F(2,46) = 7.56$, $p = 0.002$, $\eta p^2 = 0.25$ (see Figure 4.4, right panel).

4.4.2.2.7 Deaf Implicit Subgroup (325–625 ms). The English rime translation results for the implicit and explicit deaf subgroups are shown in Figure 4.5. In separate analyses that included only the subgroup of deaf signers who were unaware of the English rime translation manipulation, we still observed the reversed N400 effect such that sign targets in non-rime translation pairs elicited smaller negativities than sign targets in rime translation pairs. This effect had the same left anterior distribution as in the whole deaf group, Rime × Laterality × Anterior/Posterior, $F(8,104) = 2.98$, $p = 0.03$, $\eta p^2 = 0.19$ (see Figure 4.5, top).

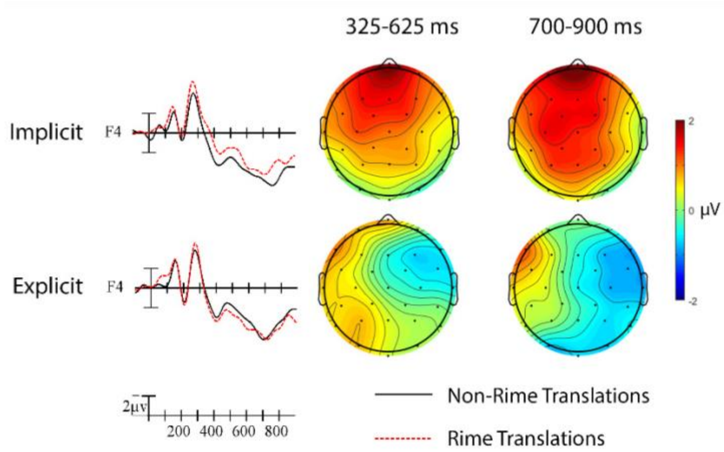

Figure 4.5. English translation rime effects in implicit and explicit subgroups of deaf signers at representative site F4. Scalp voltage maps showing the difference in mean amplitude between non-rime and rime translation trials for each of the analyzed time windows.

4.4.2.2.8 Deaf Implicit Subgroup (700–900 ms). For the implicit subgroup, sign targets in rime translation pairs continued to elicit larger negativities than targets in non-rime translation pairs in this later window, especially in the left hemisphere, Rime × Laterality, $F(2,26) = 4.19$, $p = 0.04$, $\eta p^2 = 0.24$ (see Figure 4.5, top).

4.4.2.2.9 Deaf Explicit Subgroup (325–625 ms). For the explicit subgroup of deaf signers who reported being aware of the English translation manipulation, the effect in the N400 window showed that the direction of the rime effect differed as a function of laterality, Rime × Laterality, $F(2,18) = 4.71$, $p = 0.046$, $\eta p^2 = 0.34$ (see Figure 4.5, bottom). Sign targets in non-rime translation pairs elicited larger negativities than sign targets in rime translation pairs over right hemisphere sites (similar to the hearing signers), but smaller negativities than sign targets in rime translation pairs over left hemisphere sites (similar to the deaf implicit group).

4.4.2.2.10 Deaf Explicit Subgroup (700–900 ms). The right-lateralized translation rime priming effect continued into the 700–900 ms epoch, Rime × Laterality, $F(2,18) = 6.63$, $p = 0.01$, $\eta p^2 = 0.42$ (see Figure 4.5, bottom).

4.4.3 Correlations. Mean scores on each of the language assessments are reported in Table 4.2 for the hearing and deaf groups and the implicit and explicit deaf subgroups.

Table 4.2. Language assessment scores for hearing and deaf signers (mean (SD)).

Group	English Spelling	English Reading	ASL Production	ASL Comprehension
Hearing (*N* = 20)	79.0 (3.5)	91.8 (5.8)	14.8 (5.1)	82.0 (5.1)
Deaf (*N* = 24)	74.4 (7.3)	79.6 (13.1)	22.6 (5.13)	86.5 (9.4)
Implicit (*N* = 14)	72.1 (6.9)	75.0 (14.3)	21.4 (5.8)	83.3 (10.8)
Explicit (*N* = 10)	77.7 (6.9)	86.1 (7.7)	24.3 (3.7)	91.1 (4.5)

Correlations between these language measures and the ERP effects are reported below. All of the reported significant correlations were significant at multiple electrode sites. The site at which the correlation was strongest is reported below. See Supplementary Materials Table S3 for scatterplots of significant correlations at representative sites and Table S4 for a complete table of r values and corrected p-values for correlations across all sites.

4.4.3.1 Hearing Signers

4.4.3.1.1 Semantic (325–625 ms). The amplitude of the semantic N400 priming effect was correlated with sign production ability. Less-skilled signers showed a larger semantic N400 effect at anterior sites (e.g., FP1), $r = 0.61$, $p = 0.03$. The correlations between the ERP semantic effect and the other ASL and English language measures were not significant, all ps > 0.20.

4.4.3.1.2 Rime (325–625 ms). The English translation rime priming N400 effect was correlated with ASL comprehension test scores in hearing signers. Better sign comprehenders showed a larger N400 English translation rime priming effect at posterior and right hemisphere sites (e.g., Pz), $r = -0.75$, $p < 0.001$. The correlations between the N400 translation rime priming effect and the other ASL and English language measures were not significant, all ps > 0.25.

4.4.3.1.3 Rime (700–900 ms). The late English translation rime priming ERP effect was also correlated with sign comprehension. Better sign comprehenders continued to show a larger translation priming effect at posterior sites (e.g., Pz), $r = -0.63$, $p = 0.04$. This late effect was also correlated with spelling ability. Better spellers exhibited a larger translation priming effect at posterior sites (e.g., P3), $r = -0.67$, $p = 0.02$. The correlation between the translation ERP effect and sign production was not significant, all ps > 0.96.

4.4.3.2 Deaf Signers. For deaf signers, none of the ERP translation or semantic effects were correlated with any of the language measures, all ps > 0.11.

4.5 Discussion

This ERP study was one of the first to examine cross-modal, cross-linguistic co-activation of a written/spoken language when deaf and hearing bimodal bilinguals process a signed language. Participants viewed pairs of ASL signs and decided whether they were related in meaning or not. As predicted, we found behavioral and N400 semantic priming effects in both deaf and hearing signers. Half of the sign pairs that were unrelated in meaning contained a hidden manipulation such that their English translations shared orthographic and phonological rimes. We found evidence to suggest that both deaf and hearing signers do in fact co-activate English words during sign recognition, supporting the claim that ASL-English co-activation is bidirectional. Counter to our predictions, we found no behavioral effect of the hidden English form manipulation in either group. Despite the lack of behavioral evidence for English translation effects, we found the predicted N400 priming effect in hearing signers. However, we were surprised to find a reversed N400 effect of English translation for deaf signers. Analyses of implicit and explicit subgroups within the deaf group revealed that deaf signers had a reversed N400 effect regardless of whether or not they were aware of the hidden English form manipulation. For deaf signers who were unaware of the manipulation, this reversed effect persisted into the later 700–900 ms window. For deaf signers who reported being aware of the manipulation, the early reversed effect was overtaken by a later, more typical ERP priming effect similar to that found with the hearing signers. Thus, although ASL-English co-activation appears to be bidirectional, it manifests differently for deaf and hearing signers.

Language dominance could account for some of the differences in effects between deaf and hearing signers. Hearing signers completed the task in their less dominant language (ASL), which could explain their slower RTs as well as the later and weaker semantic N400 effects compared to deaf signers. These differences in RTs and in the strength and latency of the N400 effect are consistent with studies of bilingual processing (Midgley et al., 2009a; Midgley et al., 2009b]. The semantic N400 priming effect was also correlated with signing ability for hearing signers, with less-skilled signers showing a larger semantic N400 effect and benefitting more from the semantic relationship between primes and targets than more skilled signers.

However, language dominance does not seem to explain the English translation effects. When deaf signers read English words in a previous study, ASL translation priming effects correlated with reading ability (Meade et al., 2015). Less-skilled deaf readers co-activated ASL when reading English words to a greater extent than skilled deaf readers, which might aid in the processing of English, their less dominant language. Based on this pattern, we would expect the English translation priming effects in the hearing signers of the present study to correlate with signing skill such that signers who were less proficient in ASL (their less dominant language) would show greater co-activation of English (their dominant language). However, the reverse was true: better hearing signers showed stronger English translation priming effects for both the N400 and later windows than less-skilled hearing signers. One possible explanation for this pattern relates to the fact that the majority of the hearing participants (18/24) were professional ASL-English interpreters and the remaining participants were either training to be interpreters or had some experience as volunteer interpreters (e.g., for deaf family and friends). Experience with simultaneous interpreting could establish strong lexical connections between ASL signs and English words, such that more skilled signers activate the English translations of signs more robustly than less skilled signers.

Based on previous results, we expected slower RTs to targets in semantically unrelated pairs whose English translations were related in form compared to those that were not (Kubus et al., 2014; Meade et al., 2017; Morford et al., 2011; Villameriel et al., 2016). However, there were no behavioral effects of English translation in either group. One speculative explanation for the different findings is that the bidirectional links between words and signs are asymmetric, with stronger links from words to signs than from signs to words. Our findings also differ from Van Hell et al. (2009), who reported slower RTs in a sign-picture verification task when translations were phonologically and orthographically related in Dutch. It is possible that pictures activate word forms more strongly than sign translations, such that the word form overlap interferes more with the sign-picture verification task than with the semantic relatedness task.

The absence of behavioral interference effects in the present study more closely resembles the findings in studies of unimodal bilinguals by Thierry and Wu (2007) and Wu and Thierry (2010). Unlike most alphabetic scripts that conflate phonology and orthography, Chinese allows for independent manipulation of either sound or spelling. The hidden form manipulation in Wu and Thierry (2010) used English word pairs whose Chinese translations either sounded alike (shared phonemes) or looked alike (shared graphemes). If the lack of behavioral effects was related to the weak correspondence between the spoken and printed forms of Chinese, perhaps a dissociation of phonology and orthography could also explain the lack of behavioral effects in the present study since ASL has no written form. In fact, Wu and Thierry (2010) argued that cross-language N400 priming was due to implicit co-activation of phonology as opposed to orthography.

Despite the lack of behavioral effects, we did find ERP evidence for co-activation of English translations that differed for hearing and deaf signers. Hearing signers likely accessed both the orthographic and phonological rimes of the English translations. As in the study by Wu and Thierry (2010), the smaller N400 in the hearing signers was likely due to the phonological overlap of the English translation rimes more so than the orthographic overlap. The deaf signers did not show the N400 priming effect because they have reduced access to English phonology.

Why, then, did deaf signers show any N400 effect at all? Since they are not likely to automatically access phonology (Bélanger et al., 2012; Bélanger et al., 2013; Mayberry et al., 2011), they may make use of alternative or supplementary approaches to reading. For example, deaf readers may build cross-language associations and improve vocabulary through methods like "chaining" (Humphries & MacDougall, 1997). With this instructional method, a teacher models a sign along with its corresponding fingerspelled word and its English translation in print. These successive multi-modal representations of the same concept strengthen associations between printed words, signs, and concepts. This difference in language acquisition may affect how deaf readers organize orthographic, phonological, and semantic information in their lexicon. More specifically, they may rely more heavily on orthography and direct orthographic-to-semantic connections (e.g., Bélanger & Rayner, 2015).

One speculative explanation for the reversed N400 seen in deaf participants, then, is that co-activation of orthographically similar words results in competition, rather than facilitation.

Meade et al. (2019) found a reversed N400 priming effect among deaf and hearing readers; words preceded by orthographically similar prime words elicited larger amplitude N400s than those preceded by orthographically similar pseudowords. They interpreted this effect as an indication of lexical competition and inhibition between orthographic neighbors when the primes were real words. Presumably, hearing signers also experienced orthographic competition when they automatically co-activated orthographic representations in the present study, but the effect of phonological priming appears to have been so strong as to override it. Orthographic competition may be more apparent in deaf signers because they may rely more heavily on orthography (and less on phonology) for lexical access.

The deaf participants who reported being aware of the hidden English manipulation are key to interpreting the results, as their English translation effects were reversed in the N400 window (like the implicit deaf signers) but went in the direction of priming in the later window (like hearing signers). Specifically, the early reversed effect may indicate that they were implicitly co-activating English orthography (leading to competition between orthographic neighbors), but the later priming effect could indicate that they explicitly activated phonology once they accessed the lexical representation and were aware of the manipulation. In support of this hypothesis, Cripps et al. (2005) found a facilitative phonological effect for hearing readers and an inhibitory orthographic effect for deaf readers in a masked priming study. They argue that early orthographic processing is distinct from later phonological processing for deaf readers and attribute late priming effects to a “phonological post-access check.” The late priming effects seen in the hearing group and the explicit deaf subgroup in the present study could also be evidence for participants verifying the phonological representations generated top-down from the accessed lexical entry against those generated bottom-up from orthography. Indeed, the late English translation effect correlated with spelling skill for hearing signers and showed a trend in this direction for deaf signers. This relationship suggests that the late English translation priming effect is linked to orthographic precision and that orthography is checked against phonology at this later stage of processing.

Future studies should tease apart the role of orthography and phonology in language co-activation for bimodal bilinguals. However, since orthography and phonology are conflated in English, separate sound and spelling manipulations as in Wu and Thierry (2010) may not be possible in studies with ASL-English bilinguals. A potential follow-up study could make use of phonological overlap with and without orthographic overlap (e.g., *dance-chance* versus *pants-chance*). This design could dissociate the different effects of co-activating orthography versus phonology for deaf and hearing ASL-English bilinguals. Alternatively, language co-activation could be studied in bimodal bilinguals who are literate in languages that use non-alphabetic scripts. Logographic characters like those used in Chinese and Japanese would allow for easier separation of orthographic and phonological effects.

In sum, this study suggests that implicit cross-language co-activation in bimodal bilinguals is bidirectional. However, co-activation of sign from print does not look the same as co-activation of print from sign in deaf bimodal bilinguals. We also noted differences between deaf and hearing bimodal bilinguals and between deaf signers with and without explicit knowledge of the hidden cross-language manipulation. These findings enhance our understanding of how bimodal bilinguals represent and use their two languages, which may be especially important for promoting literacy in the deaf population and contribute to our knowledge of bilingualism overall.

4.6 Acknowledgements

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Chapter 5: General Discussion

The primary goal of this dissertation was to investigate how deaf readers represent and process words. The word representations in question are orthographic and phonological representations at both sublexical and lexical levels that eventually feed up to lexical semantic representations. I used behavioral, ERP, and eye tracking evidence to investigate how this system is engaged when deaf adults recognize single words and signs or read sentences. In Chapter 2, I presented eye tracking data that suggest deaf readers are more efficient at processing words in sentences compared to hearing readers. In Chapter 3, deaf readers were faster and more accurate at classifying nonwords and showed evidence of robust early visual processing but appeared similar to hearing readers in how they processed words and nonwords at linguistic levels. In Chapter 4, I demonstrated that language co-activation is bidirectional for bimodal bilinguals, as deaf readers co-activate English word representations when recognizing ASL signs. In this concluding chapter, I consider what these experiments together tell us about how deaf readers recognize and comprehend words.

Across studies, there were several instances of deaf readers showing enhanced sensitivity to the visual-orthographic make up of words. In Chapter 2, deaf readers' enhanced visual attention in the parafovea gave them an advantage in pre-processing upcoming words in sentences and allowed them to attain similar levels of reading comprehension with shorter and fewer fixations compared to hearing readers. Deaf readers' sensitivity to visual-orthographic information also enabled them to precisely detect and direct eye movements towards letter transpositions presented in the parafovea. In Chapter 3, there was evidence of early visual processing that allowed deaf readers to perceive stimuli at shorter durations and made them less susceptible to masking. This early processing may have given deaf readers an advantage in processing nonwords, resulting in faster and more accurate lexical decisions. In Chapter 4, deaf readers' activation of English orthographic rather than phonological representations could have resulted in competition for lexical access that may explain the reversed N400 priming effect, i.e., the finding that prime-target sign pairs whose English translations shared a rime elicited a larger N400 than sign pairs that did not. However, engagement of English word representations did not affect the speed of semantic decisions to signed stimuli. Overall, deaf readers' enhanced sensitivity to the visual-orthographic structure of words represents an area of deaf gain (Bauman & Murray, 2014) that supports deaf people in becoming skilled and efficient readers.

A second major theme across studies is that deaf readers actually appear similar to hearing readers in a number of ways despite differences in their visual processing, phonological awareness, and bilingualism. In Chapter 2, neither group was sensitive to nonword pronounceability in the context of sentences. In Chapter 3, the groups exhibited similar ERP effects when processing words and nonwords; though we anticipated differences in their activation of sublexical orthographic and phonological representations, deaf and hearing readers actually processed nonword pronounceability at a lexical level and in a similar fashion. We argued that these similarities in processing despite differences in phonological awareness point to comparable orthographic processing in transposed-letter (TL) studies. In Chapter 4, hearing signers activated both phonological and orthographic representations of English words during sign recognition. Deaf signers appeared to activate orthographic representations of sign translations, but only engaged phonology at a later stage if they were explicitly aware of the hidden English manipulation. Thus, some deaf signers were able to explicitly call upon phonological representations and evoked an English rime priming effect similar to that of hearing signers, but it was not a necessary or automatic part of lexical access as it was for hearing signers.

In conclusion, deaf and hearing readers appear similar in their orthographic and lexico-semantic processing for word recognition, but differ in terms of their visual processing, phonological awareness, and cross-language activation. The studies presented in this dissertation help characterize skilled reading in deaf adults and contribute to a broader understanding of reading processes overall.

5.1. Future Directions

Future research should further explore the visual, orthographic, and bilingual effects in deaf readers. Though there is now corroborating evidence for the Word Processing Efficiency Hypothesis (Bélanger & Rayner, 2015; Traxler et al., 2021; Chapter 2), future studies should address how the efficient eye movements in deaf readers are modulated by other variables like syntactic complexity and semantic context. It may also be useful to know whether the visual advantages seen in deaf readers is attributed to deafness and/or sign language experience. There is also a growing body of evidence showing that deaf readers are more sensitive to orthographic than phonological information (see Emmorey & Lee, 2021 for a review). However, translational research is still needed to ensure that this finding is reflected in educational practices designed to boost reading outcomes for emergent deaf readers. Finally, since language co-activation is bidirectional is bimodal bilinguals (Meade et al., 2017; Chapter 4/Lee et al., 2019), further psycholinguistic evidence is needed to evaluate methods for establishing cross-language associations. In particular, sign-based phonological awareness and fingerspelling skill may help deaf readers leverage their ASL knowledge in support of proficient reading in English. Research should continue to identify the unique abilities of deaf readers and inform practices that capitalize on these abilities to boost reading outcomes.

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