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An Event-Related Potential Investigation of Orthographic Precision

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An Event-Related Potential Investigation of Orthographic Precision

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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2020

The dissertation of Gabriela Francis Meade is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

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Dedication

To my parents, who taught me to be tenacious in pursuing my lofty dreams and supported me every step of the way.

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Acknowledgements

Chapter 2 has been submitted for publication and appears as it is intended for publication of the material as it may appear in Meade, G., Mahnich, C., Holcomb, P. J., & Grainger, J. (submitted). Orthographic neighborhood density modulates the size of transposed-letter priming effects. *Cognitive, Affective, & Behavioral Neuroscience*. The dissertation author was the primary investigator and author of this paper. Preparation of this manuscript was supported by National Institutes of Health grant HD025889 and by National Science Foundation Graduate Research Fellowship 2016196208.

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ABSTRACT OF THE DISSERTATION

An Event-Related Potential Investigation of Orthographic Precision

by

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Doctor of Philosophy in Language and Communicative Disorders

University of California San Diego, 2020
San Diego State University, 2020

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Orthographic precision refers to the specificity with which letters are assigned to positions within words. In some theoretical models of visual word processing, precision is the optimal end state of a lexical representation; the associations between letters and positions are initially approximate and noisy, but they become more precise as readers gain exposure to the

word. In other models, flexible orthographic codes that allow for rapid access to semantics are the optimal end state, and precise representations are only relied upon under specific circumstances. I will introduce a series of event-related potential transposed-letter priming studies designed to test the predictions of these opposing models and determine the functionality of precision within the orthographic system. More specifically, I examine the lexical properties that modulate precision within readers and the skills that modulate precision across readers. In Chapter 2, I demonstrate that words from high-density orthographic neighborhoods that are easy to confuse are encoded more precisely than words from low-density orthographic neighborhoods. In Chapter 3, I demonstrate that precision differs across languages in two groups of bilinguals with different levels of proficiency. In Chapter 4, I compare orthographic precision across hearing and deaf readers to examine how access to phonology contributes to orthographic tuning. However, the results indicate that there were negligible differences between groups. Overall, the results are consistent with a dynamic orthographic system in which precision varies systematically but does not necessarily characterize more developed representations.

Chapter 1: Introduction

Despite decades of research, fundamental questions about how the brain represents and processes visual words remain unanswered. One persisting question pertains to how individual letter representations feedforward to activate lexical representations. In English and many other languages, letters are the basic building blocks of visual word recognition; a very limited set of letters combine in unique ways to form an exponentially larger set of words. To accomplish this, letters must be assigned to positions in a manner that is specific enough to reliably dissociate similar words (e.g., *use*, *sue*), yet flexible enough to allow variations and misspellings (e.g., *seperate*). The precision with which letters are assigned to positions within words is the issue at hand in this dissertation. I begin by reviewing theoretical models of visual word recognition, with a focus on how letter position information is encoded during the transition from letter representations to lexical representations. I then introduce the transposed-letter (TL) priming paradigm as a means to index the precision with which letters are assigned to positions. Finally, I present a series of three studies in which I combined the TL priming paradigm with the high temporal resolution of event-related potentials (ERPs) to examine the factors that drive variability in orthographic precision across readers and across representations within the same reader. This close investigation of precision helps to adjudicate between theoretical models of visual word recognition.

1.1. Orthographic precision in models of visual word recognition

The precision with which letters are associated with positions has been a point of theoretical contention over time and continues to be debated today. Early computational models of orthographic processing relied on a slot coding system in which each letter was assigned to a specific position within the word. For example, the interactive-activation model introduced by

McClelland and Rumelhart (1981) has a letter level that was composed of nodes for each letter in each letter position in a four-letter string. These position-specific letter nodes have excitatory connections with the word nodes that contain them and inhibitory connections with other word nodes. There is now largely consensus that the brain does not assign one-to-one correspondences between letters and positions with perfect precision, a conclusion that was largely based evidence from the TL literature described in detail below (see, e.g., Davis & Bowers, 2006). Yet, several models continue to regard precision as the ultimate end goal of a developed representation. For example, precision is one of the primary characteristics of a high-quality representation according to Perfetti's (1992, 2007) lexical quality hypothesis. Perfetti contrasts precise representations with variable representations that "include free variables in the positions where the precise, fully specified representations include specific letters" (1992, p. 157). He argues that precise representations are advantageous because they are only triggered by a specific set of input features, allowing for rapid and accurate visual word recognition in the absence of context. This model has the appeal of allowing for differences in precision across representations and readers but may be somewhat antiquated in assuming that perfect precision is the end goal of the orthographic system.

Taking one step away from slot-based coding, several contemporary models still assume that each letter is assigned to a position but allow for some degree of flexibility in those associations. For example, the overlap model posits that position information is spread across a normal distribution such that a letter is associated with the correct position and, to a less extent, other nearby positions (Gómez, Ratcliff, & Perea, 2008). Fischer-Baum and colleagues have advocated for a similar approach (Fischer-Baum, Charny, & McCloskey, 2011). In their both-edge representation of letter position model, letters in adjacent positions are more closely related (and therefore easier to confuse) than those in non-adjacent positions (see Vandendaele, Snell, & Grainger, 2019). The novelty of this model is that position assignment is done based on relative positioning from the beginning (e.g., B+2 is the second letter) and end (e.g., E-2 is the second-to-last letter) of the word. Thus, both of these models continue the tradition of assigning letters to specific positions, but they allow for some flexibility to account for empirical results from TL and letter migration paradigms, among others.

Moving even further away from the classic model that assigns each letter to a specific position, open bigrams only encode the relative positions of letters within words. Open bigrams are formed by taking all combinations of adjacent and non-adjacent letters in the correct order (e.g., Grainger, 2008; Grainger & van Heuven, 2003; Grainger & Whitney, 2004). For example, the open bigrams for the word *sore* are *s-o, s-r, s-e, o-r, o-e,* and *r-e.* In the dual-route model of orthographic processing, Grainger and Ziegler (2011) divide visual word recognition into two possible processing streams. The coarse-grained route allows for direct access to semantics via "good enough" representations formed of open bigrams. In contrast, the fine-grained route is more similar to the models discussed above in that it involves assigning letters and commonly occurring multi-letter graphemes (e.g., *th*, *ch*, *ing*) to specific positions, leading to precise orthographic representations. Each grapheme is also associated with sublexical phonology. In the original proposal, the incremental fine-grained route was thought to be used by beginning readers who sound out words or when adults read aloud, whereas the coarse-grained route was optimized for silent reading. The results in Chapters 2 and 3 challenge this broad generalization and offer a new conception of how the varying levels of precision offered by these two routes might be utilized.

Finally, at the other extreme, spatial models have position-independent letter representations (e.g., Davis, 2010; Davis & Bowers, 2006). Each representation reflects letter identity irrespective of where in the word the letter occurs. Position information is then encoded in temporary activation values assigned to each letter in the word. The relative activation of each representation allows the reader to identify the word and to distinguish it from other words that share the same letters.

In sum, the precision with which letters can be assigned to positions falls along a spectrum across theoretical models, with some viewing precision as the optimal end state of individual representations and others giving it a more cursory role. Moving forward, I often use the lexical quality hypothesis and the dual-route model to represent these opposing ends of the spectrum. These models have the appeal of offering specific mechanisms by which precision can differ among readers and among representations within the same reader.

1.2. Transposed-letter effects as an index of orthographic precision

TL effects have been integral in establishing that some degree of flexibility exists in the way in which letters are assigned to positions within words. In one paradigm that relies on the TL manipulation, nonwords are created both transposing two letters (i.e., TL nonwords; e.g., *fliud*) in a base word (e.g., *fluid*) and by changing the letters in those same positions (i.e., substitution nonwords; e.g., *flead*). In the lexical decision task, participants are slower and less accurate at rejecting the TL nonwords than they are at rejecting the substitution nonwords (e.g., Fariña, Duñabeitia, & Carreiras, 2017; Vergara-Martínez, Perea, Gómez, & Swaab, 2013). This is commonly interpreted to suggest that the TL nonwords activate the lexical representations of the base words to a greater extent, making them more tempting to accept as words. In a second paradigm that capitalizes on the TL manipulation, masked nonword primes precede target base words. Participants are generally not aware of the prime items due to their short duration and because they are masked by a subsequent stimulus. TL primes (e.g., *fliud-FLUID*) facilitate processing more than substitution primes (e.g., *flead-FLUID*), as indexed by faster and more accurate responses to target words in the lexical decision task (see, e.g., Perea & Lupker, 2004b, for a review). These priming effects provide further evidence for the proposal that TL nonwords are more effective at activating the lexico-semantic representations of their base word, thereby giving the target base word more of a "head start" before it is presented.

These basic TL effects establish that there is some level of imprecision in the associations between letters and their positions in words; however, they do not decisively support one model over another (see also, Davis & Bowers, 2006, for discussion). With the exception of a strict slot-based model with perfect precision, all of the models discussed above allow for some degree of flexibility. For example, the assumption in the overlap model that letter identities are normally distributed across positions implies that the letters that were transposed are still associated with their target positions (though to a lesser degree than they would be by the target itself). Presumably, this general principle of noisy associations would apply irrespective of the anchor point. TL nonwords share more open bigrams with their targets than substitution nonwords. Such an increase in overlap of the sublexical code could also account for facilitation of target processing. Finally, TL nonwords share all of the same letters and are therefore considered to be more similar in spatial that have position-independent letter identity processing. The relative weights of the transposed letters will differ between a TL nonword and its base word, but the TL nonword remains more similar than the substitution nonword. Thus, all modern theories of word recognition can readily account for why TL nonwords activate the lexical representations of their base words to a greater extent.

More theoretically influential results have come from comparisons of the size of TL priming across various conditions. A substantial number of TL studies have centered around an investigation of the saliency of different types of letters and different positions. For example, there is a line of research that addresses how the distance between transposed letters modulates the size of TL effects. Converging evidence indicates that the orthographic system is quite flexible; TL effects hold even transpositions between distant letters (e.g., *caniso-CASINO*). However, the size of the effect is inversely related to the distance between the letters (e.g., Ktori, Kingma, Hannagan, Holcomb, & Grainger, 2014; Massol, Duñabeitia, Carreiras, & Grainger, 2013; Perea, Duñabeitia, & Carreiras, 2008; Perea & Lupker, 2004a; see also Chapter 4). In addition to relative distance, the position of the letters within the word matters. TL nonwords formed by inversing word-internal letters are more effective at activating the lexical representations of their base words compared to those involving the initial and final letters (e.g., Perea, Rosa, & Gómez, 2003), at least for short words (Schoonbaert & Grainger, 2004). This emphasis on the initial and final letters for accurate word recognition falls out of some models and requires additional mechanisms in others.

In contrast to the emphasis on sublexical variables, there has been little consideration for how the size of TL effects might vary across lexical representations. Manipulating lexical-level variables is critical for understanding how precision functions in the orthographic system; words that are represented more precisely will be less susceptible to activation by TL primes and should yield smaller TL effects. Extant evidence regarding frequency illustrates this point. For example, Vergara-Martínez et al. (2013) compared processing of high- and low-frequency base words and the respective TL nonwords and substitution nonwords in a lexical decision task. They found that TL nonwords elicited slower "no" responses than substitution nonwords, but only when they were formed from high-frequency base words. TL and substitution nonwords formed from low-frequency base words elicited similar response latencies. This suggests that TL nonwords were especially effective at activating the high-frequency base words, which may have less precise representations. Few models can account for how precision differs across representations, and even fewer can account for an inverse relationship between precision and frequency. For example, the lexical quality hypothesis posits that precision should increase as the reader continues to be exposed to the word and would therefore predict a positive relationship between frequency and precision. In Chapters 2 and 3, I extend these results to consider how other variables, including orthographic neighborhood density and language dominance in bilinguals, modulate orthographic precision within the same reader.

The TL manipulation has also been used to index changes in orthographic precision across developmental time, although the results remain somewhat controversial (e.g., Castles, Davis, Cavalot, & Forster, 2007; Colombo, Sulpizio, & Peressotti, 2017; Comesaña, Soares, Marcet, & Perea, 2016; Lété & Fayol, 2013; Ziegler, Bertrand, Lété, & Grainger, 2014). Castles and colleagues compared the behavioral priming effects elicited by one-letter substitution primes (e.g., *rlay-PLAY*) and TL primes (e.g., *lpay*) relative to unrelated control primes (e.g., *meit-PLAY*). Whereas targets in both of the related conditions elicited faster RTs than those in the unrelated control condition in third graders, only the TL priming effect persisted when the same students were tested in fifth grade. Neither effect was significant in a separate group of adults, which the authors attributed to the use of short words from high-density orthographic neighborhoods (see Chapter 2). The authors interpreted the developmental results to suggest that precision increased from third to fifth grade "as a function of the increasing size and density of the overall lexical system" (p. 176), seemingly in line with the lexical quality hypothesis. They further argued that spatial models that emphasize similarity in letter identities rather than letter positions could best account for the fact that TL priming persisted longer than one-letter substitution priming. Ziegler et al. reported a contradictory pattern in their cross-sectional study of first through fifth graders using a more traditional comparison between TL (e.g., *talbe-TABLE*) and substitution primes (e.g., *tarfe-TABLE*) and a sandwich priming paradigm in which a brief preview of the target is presented before the prime (see Chapter 4). In this study, the size of TL priming increased monotonically as a function of both grade and reading age. The authors argue that their results diverge from previous studies because they had had five developmental data points instead of two and because they analyzed transformed RTs rather than raw RTs to account for overall age-related changes in response latencies. These results are perfectly in line with the dual-route model, as older readers are postulated to shift away from the incremental fine-grained route toward more rapid semantic access along the coarse-grained route.

Building on this developmental work, there is also preliminary evidence to suggest that reading and spelling skill might impact orthographic precision among adult readers. For example, Andrews and Lo (2012) found that principal components that reflected overall reading proficiency and spelling ability captured variance in the size of behavioral TL priming effects. More specifically, less proficient readers showed facilitatory TL effects (i.e., facilitation for targets preceded by TL primes compared to those preceded by unrelated primes), whereas more proficient readers showed the opposite pattern. In Chapter 4, I advance this line of inquiry by comparing the size of the adjacent and non-adjacent TL priming effects in hearing versus deaf readers. This comparison allowed me to examine how spoken language phonology contributes to the tuning of orthographic representations (see Meade, 2020).

1.3. Event-related potential indices of transposed-letter effects

In the three studies presented here, I paired the masked TL priming paradigm with ERPs. The high temporal resolution of ERPs yields further insight into the time course with which TL primes affect target processing. Based on their systematic study of ERP effects across masked priming paradigms, Grainger and Holcomb (2009) associated each ERP component with functional processes. Building on that framework and previous TL priming studies, I focused on the N250 and N400 (e.g., Carreiras, Vergara, & Perea, 2009; Grainger, Kiyonaga, & Holcomb, 2006; Ktori et al., 2014; Vergara-Martínez et al., 2013; Vergara-Martínez, Perea, Marín, & Carreiras, 2011). The N250 is associated with sublexical processing and initial lexical access, whereas the N400 is associated with later lexico-semantic processing. In the present context, we interpret N250 priming in terms of the way(s) in which lexical representations are accessed and N400 priming in terms of how strongly the lexical representation has been activated. As will be evident in later chapters, ERPs have the benefit of lending insight into these earlier aspects of processing, which do not always have ramifications for behavioral responses.

With respect to TL manipulations, the ERP literature has largely paralleled the behavioral literature. To establish the basic effects, Grainger and colleagues (2006) compared ERPs elicited by targets preceded by masked TL primes (e.g., *barin-BRAIN*) versus substitution primes (e.g., *bosin-BRAIN*). They found that targets in the TL condition elicited smaller amplitude negativities (i.e., less effortful processing) within two distinct windows: the earlier portion of the N250 (150-250 ms) and the N400 (350-550 ms). They associated the N250 effect with activation of the sublexical orthographic code and the N400 with convergence on lexical representations. Subsequent studies have investigated how these effects differ as a function of various manipulations, including adjacent versus non-adjacent transpositions (e.g., Ktori et al., 2014) and high- versus low-frequency base words (e.g., Vergara-Martínez et al., 2013), largely replicating behavioral patterns.

To my knowledge, the only study to compare the size of ERP TL priming effects across individuals is a recent study with children between the ages of eight and 10 (Eddy, Grainger, Holcomb, & Gabrieli, 2016). In this study, Eddy and colleagues found significant priming effects within the N250 and N400 windows. Intriguingly, they also reported that the size of these effects correlated with standardized behavioral measures of reading proficiency, such that stronger readers had larger N250 and N400 priming effects. Though consistent with the dual-route model, this pattern appears to contradict the patterns reported in young adults by Andrews and Lo (2012), in which stronger readers showed inhibitory TL priming effects. These inconsistencies highlight the need for a greater understanding of how language proficiency relates to TL priming. Which is more reflective of a better developed orthographic system – precise representations that minimize activation by TL primes or flexible "good enough" representations that allow for rapid access to semantics? This is the overarching question that motivated this dissertation.

1.4. Contribution of the Dissertation

The goal of the present dissertation is to gain better insight into the function that precision has in the orthographic system. To accomplish that, I examined how a number of factors influence orthographic precision across lexical representations within the same reader and across readers. In Chapter 2, I consider how orthographic neighborhood influences the precision with which words are accessed and represented. In Chapter 3, I present two studies in which I compare TL effects across languages in bilinguals of varying degrees of proficiency to examine whether experience with a language increases or decreases orthographic precision. Finally, in Chapter 4, I examine the extent to which adjacent and non-adjacent TL effects differ between deaf and hearing readers in order to understand the role of spoken language phonology in tuning precise orthographic representations (see Meade, 2020). Together, these studies provide a body of evidence that can be used to inform theoretical models of visual word recognition.

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Chapter 2: Orthographic neighborhood density modulates the size of transposed-letter priming effects

2.1. Abstract

We used transposed-letter (TL) priming to test if words from high-density orthographic neighborhoods have more precise orthographic codes than words from low-density neighborhoods. Replicating the standard TL priming effects, target words elicited faster lexical decision responses and smaller amplitude N250s and N400s when preceded by TL primes (e.g., *leomn-LEMON*) compared to substitution primes (e.g., *leuzn-LEMON*) overall. We expected that if high-density words have more precise orthographic representations (i.e., with each letter assigned to a specific position), then they should give rise to smaller TL priming effects. In line with our prediction, N250 (but not N400 or behavioral) TL priming effects were smaller for high-density words compared to low-density words. Consistent with the dual-route orthographic coding model, this pattern suggests that the nature of the orthographic code used to access lexical representations differs depending on the number of neighboring words in the lexicon.

2.2. Introduction

There are minimal differences at a visual level between the words *tight*, *light*, and *fight*, and yet fluent readers are able to distinguish them with remarkable accuracy within a fraction of a second. Words like these, that look similar to many other words in the lexicon, are said to come from high-density (HD) orthographic neighborhoods. Words that have distinct letter combinations and do not resemble many other words (e.g., *awful*, *kayak*) belong to low-density (LD) orthographic neighborhoods. Here, we asked whether the orthographic neighborhood density of a word influences the way in which it is represented in lexical memory, and how the nature of these representations impacts word recognition. More specifically, we examined whether or not orthographic neighborhood density modifies the precision of orthographic representations by comparing the size of masked transposed-letter (TL) priming effects for HD and LD targets.

There is general consensus that priming effects – particularly those obtained in the masked priming paradigm – reflect the extent to which a prime stimulus pre-activates the representations needed for subsequent target processing, as well as the lexical representations that compete with the target for identification. By comparing the effects of different types of primes, we gain insight into the dimensions of similarity to which the orthographic processor is sensitive. For example, targets elicit faster lexical decision responses following TL primes formed by transposing two letters in the target word (e.g., *tgiht-TIGHT*) compared to substitution primes formed by replacing the letters in those same positions (e.g., *tjoht-TIGHT*; e.g., Comesaña, Soares, Marcet, & Perea, 2016; Ktori, Kingma, Hannagan, Holcomb, & Grainger, 2014; Perea & Carreiras, 2006, 2008; Perea, Duñabeitia, & Carreiras, 2008; Perea & Lupker, 2004a). In the ERP waveform, there is some evidence that targets in the TL condition elicit smaller amplitude negativities (i.e., less effortful processing) than those in the substitution condition, at least in some conditions (e.g., Carreiras, Vergara, & Perea, 2009; Grainger, Kiyonaga, & Holcomb, 2006; Ktori et al., 2014). Across studies, the effect has been reported within the N250 and N400 windows, suggesting that processing at both the sublexical and lexical levels is facilitated (see Grainger & Holcomb, 2009, for a summary of the evidence that the N250 reflects sublexical processing and the N400 reflects lexical processing). Theoretically, these TL priming effects indicate that there must be some degree of flexibility or imprecision in the assignments between letters and their positions in the word. If each letter was assigned an absolute position with perfect precision, then both types of primes would be equally similar to the target word and should have equal influence on target processing.

The finding that lexical representations are not encoded with perfect precision prompts a number of intriguing questions, not the least of which is how the human brain represents and processes orthographic information. In the present study, we test two opposing accounts of how differences in orthographic precision could be achieved. Some authors have contended that TL priming is made possible by noise in the assignment of letters to positions (Davis, 2010; Fischer-Baum, Charny, & McCloskey, 2011; Gómez, Ratcliff, & Perea, 2008; Norris, Kinoshita, & van Casteren, 2010). Within this general theoretical framework, the lexical quality hypothesis (Perfetti, 1992, 2007) posits that increased exposure to a given word diminishes the noise in the assignment of letter identities to letter positions, leading to more precise (i.e., higher quality) lexical representations over time. Thus, precision is the optimal end state of lexical representations. Others have argued that TL priming is made possible by flexible orthographic coding, such as the open bigram coding scheme (e.g., Grainger, 2008; Grainger & van Heuven, 2003; Grainger & Whitney, 2004). Open bigrams are formed by taking combinations of adjacent and non-adjacent letters in the correct order (e.g., f-i, f-g, f-h, f-t, i-g, i-h, and so on for the word *fight*). This coding scheme can readily account for TL priming effects given that TL primes share more open bigrams with their targets than substitution primes. Grainger and Ziegler (2011) further proposed that orthographic processing proceeds along two possible routes. The coarse-grained route makes use of relative letter positions through an open bigram coding scheme, and is hypothesized to provide a fast means of mapping sublexical orthographic representations onto lexical representations. The fine-grained route is more precise; it involves assigning letters and commonly occurring multi-letter graphemes (e.g., *th*, *ch*) to specific positions and likely does not produce strong TL priming effects. According to this account, differences in precision for various words are achieved by modulating the relative weight assigned to these two routes.

The lexical quality hypothesis (Perfetti, 1992, 2007) and the dual-route model of orthographic coding (Grainger & Ziegler, 2011) differ most notably with respect to their definition of optimal orthographic processing and how that is achieved. According to the lexical quality hypothesis, a high degree of orthographic precision is the optimal end state of lexical representations, and exposure to print (i.e., frequency) is the principle driving factor. In contrast, the dual-route model favors "good enough" orthographic representations that provide efficient direct semantic access along the coarse-grained route. Optimal readers use just the right amount of orthographic information to access a given word. The amount of information that is needed is largely determined by the orthographic characteristics of words, and most notably their orthographic neighborhoods. Comparatively more precise orthographic information must be extracted to access HD words since they bear similarity with so many other lexical representations. Thus, HD words might be more likely to be processed along the fine-grained route, whereas LD words can be reliably recognized along the coarse-grained route.

In order to test these two accounts of orthographic precision, the present study compares the size of TL priming effects between HD and LD words. As noted above, the dual-route model predicts that TL priming effects should be smaller for HD words, which are more likely to be processed along the precise fine-grained route, compared with LD words, which are more likely to be processed along the coarse-grained route. In contrast, the lexical quality hypothesis predicts equivalent TL priming for the two types of words, as long as they are matched for word frequency. The two behavioral studies that have already investigated this issue have yielded inconsistent results (Kinoshita, Castles, & Davis, 2009, Experiment 1; Perea & Lupker, 2004b). Perea and Lupker reported that TL priming effects were significantly reduced for HD word targets compared to LD word targets. Although the effects went in the same direction numerically in the study reported by Kinoshita et al., the interaction between the size of TL priming and neighborhood density failed to reached significance. Especially considering that null effects like the one reported by Kinoshita and colleagues are notoriously difficult to interpret, the issue of whether the size of TL priming is modulated by orthographic neighborhood density remains unresolved. The present study therefore provides a further investigation of TL priming with HD and LD words, this time with the added sensitivity of ERPs. Any facilitatory TL priming effects seen in RTs should be accompanied by smaller amplitude N250s and N400s for word targets preceded by TL primes (e.g., Carreiras et al., 2009; Grainger et al., 2006; Ktori et al., 2014). Neighborhood density might also be expected to modulate the size of these electrophysiological TL priming effects, at least according to the dual-route model.

2.3. Methods

2.3.1. Participants. Participants included 48 young adults (34 F; mean age 21.6, *SD* 3.1) who were right-handed and had normal or corrected-to-normal vision. By self report, all participants were native speakers of English and were not fluent in any other language. Participants had no history of neurological dysfunction and had not been diagnosed with a language or reading disorder. An additional eleven participants took part in the experiment; however, their data were excluded from analyses due to high artifact rejection rates (>20% of all trials) or experimenter error. All participants were recruited and provided written informed consent in accordance with the Institutional Review Board at San Diego State University.

2.3.2. Stimuli. Each trial consisted of a lowercase prime followed by an uppercase target, both of which were five letters long. There were 100 word targets and 100 pseudoword targets. Half of the targets in each condition came from HD neighborhoods and the other half came from

LD neighborhoods (see Table 2.1). Neighborhood density was determined using OLD20, which reflects the number of additions, deletions, or substitutions required to obtain the twenty closest orthographic neighbors. All HD targets had an OLD20 of 1.75 or less; all LD targets had an OLD20 of 1.85 or greater. These restrictions and the resulting mean OLD20 values for each condition are comparable to previous ERP studies of neighborhood density in which this measure was used (e.g., Meade, Grainger, & Holcomb, 2019; Meade, Midgley, Dijkstra, & Holcomb, 2018; Vergara-Martínez & Swaab, 2012). HD words had a significantly smaller OLD20 than LD words, $t(98) = 11.44$, $p < .001$, and HD pseudowords had a significantly smaller OLD20 than LD pseudowords, $t(98) = 12.81$, $p < .001$. However, HD word and pseudoword targets had a comparable OLD20, $t(98) = 0.00$, $p = 1.00$, as did LD word and pseudoword targets, $t(98) = 0.00$, $p = 1.00$. HD and LD word targets were also balanced for SUBTLEX frequency (Brysbaert & New, 2009), and concreteness (Brysbaert, Warriner, & Kuperman, 2014), both of which are known to affect N400 amplitude (e.g., Dufau, Grainger, Midgley, & Holcomb, 2015; Kounios & Holcomb, 1994), *p*s > .92.

Table 2.1. Target characteristics [mean (SD)]

Target	OLD20	Frequency	Concreteness
HD Words	1.57 (0.15)	109.14 (179.03)	3.68 (0.95)
LD Words	2.10 (0.29)	108.88 (136.81)	3.70 (1.12)
HD PWs	1.57 (0.12)	----	----
LD PWs	2.10 (0.27)	----	----

PWs = pseudowords

Each target was presented twice to each participant, preceded by both a TL prime and a substitution prime. TL primes were formed by inversing two adjacent word-internal letters in the target (e.g., *leomn-LEMON*, *vgiht-VIGHT*). All transpositions were between a consonant and a vowel. Substitution primes were formed by replacing the letters in those same positions with other letters (e.g., *leuzn-LEMON, vpoht-VIGHT*) such that the CV structure and visual shape (i.e., ascenders and descenders) of the TL primes were maintained. TL and substitution primes preceding word targets were closely matched for OLD20 within each neighborhood condition, both *p*s = 1.00 (see Table 2.2).

Table 2.2. Prime neighborhood densities [mean (SD)]

Target	Prime	OLD20
HD Words	TL	2.27 (0.27)
	Substitution	2.27 (0.32)
LD Words	TL	2.27 (0.35)
	Substitution	2.27 (0.34)

2.3.3. Procedure. The main experiment consisted of 400 trials. Each trial began with a white fixation cross presented at the center of the screen for 500 ms. A forward mask (#######) then appeared for 300 ms, followed by a lowercase prime for 50 ms, a backward mask (#######) for 20 ms, and an uppercase target for 300 ms. Participants were instructed to respond as quickly and accurately as possible, pressing a button with one hand if the word that appeared on the screen was a real word and a button with the other hand if it was not (i.e., no mention was made of the prime). Responses were made with a videogame response box and response hand was counterbalanced across participants. The screen remained blank for 750 ms after the response before a purple fixation cross appeared for 1500 ms. We asked participants to try to blink during this purple fixation cross in between trials and during occasional longer breaks.

Stimuli were displayed in Courier font such that they subtended a horizontal visual angle of 1.7 degrees. Trials were presented in one of two pseudorandomized orders. Half of the participants saw any given target preceded by a TL prime in the first half of the experimental list and by a substitution prime in the second half of the list and the other half of participants received the opposite order. TL and substitution primes were equally distributed between the first and second halves of the experimental lists. Orthographic and semantic relatedness of the targets was minimized between consecutive trials and no more than three consecutive trials had the same lexical status or belonged to the same neighborhood density condition. The experiment began with a practice that consisted of 20 trials, half of which had word targets.

2.3.4. EEG Recording and Analysis

Participants wore an elastic cap (Electro-Cap) with a standard montage of 29 electrodes. Impedances for all electrodes were maintained below 2.5 kΩ. EEG was amplified with SynAmps RT amplifiers (Neuroscan-Compumedics) with a bandpass of DC to 100 Hz and was sampled continuously at 500 Hz. One electrode was placed on each mastoid bone; the left was used as a reference during recording and for subsequent analyses, whereas the right was only used to monitor differential mastoid activity. Epochs were time-locked to word target onset and extended 1000 ms, including a 100 ms pre-target-onset baseline. All trials with artifacts during this epoch of interest were excluded from analyses (10 trials, or 5%, on average). An electrode next to the right eye was used to detect horizontal eye movements and another electrode below the left eye was used to identify blinks in conjunction with the electrodes on the forehead.

Artifact-free trials with correct responses between 200 and 2000 ms after word target onset were averaged separately for HD and LD word targets and low-pass filtered at 15 Hz. For each participant, mean amplitude was calculated between 150 and 275 ms after word target onset for N250 analyses and between 350 and 550 ms after word target onset for N400 analyses. Analyses were conducted on the grid of 12 electrodes illustrated in Figure 2.1. Separate ANOVAs were used for the N250 and N400 windows that included factors Prime (TL, substitution), Neighborhood (HD, LD), Laterality (left, midline, right), and Anterior/Posterior (frontal, central, parietal, occipital). The key predictions revolve around the interaction between Prime and Neighborhood, which indicates that the size of the TL priming effect differs for HD versus LD words. Greenhouse-Geisser correction was applied for all within-subject measures with more than one degree of freedom in the numerator. Partial eta squared (η_p^2) is reported as a measure of effect size.

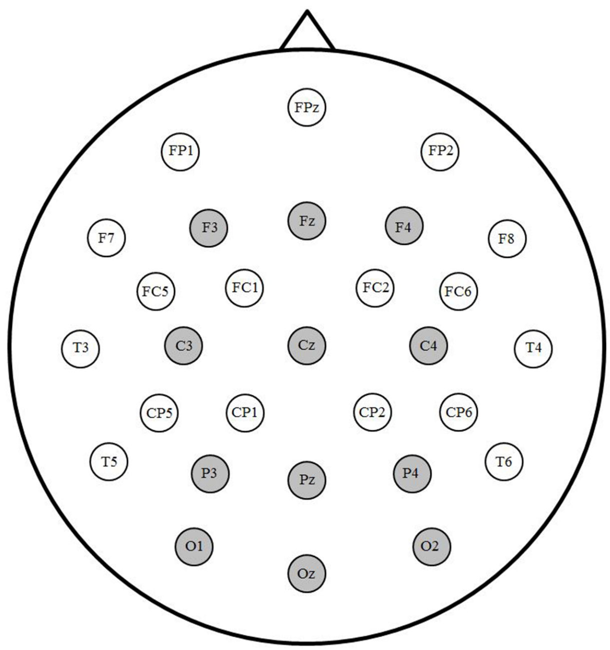

Figure 2.1. Electrode montage. Sites indicated in grey were included in analyses.

2.3. Results

2.3.1. Behavior. Behavioral results are presented in Table 2.3. All RT analyses were conducted on word target trials with correct responses between 200 and 2000 ms (10 trials, or 0.1%, were excluded as outliers). The RT and error data were analyzed using linear and logistic mixed-effects regression modeling, respectively (Baayen, Davidson, & Bates, 2008; Jaeger, 2008). Both participants and items were considered random factors with both fixed effects (i.e., Prime and Neighborhood) and their interaction varying by all random factors (Barr, Levy, Scheepers, & Tily, 2013). A significant main effect of Prime indicated that target words elicited faster responses following TL primes compared to substitution primes (see Table 2.4). A significant main effect of Neighborhood further indicated that HD words elicited slower responses than LD words. Although the TL priming effect was numerically smaller for HD words (26 ms) compared to LD words (34 ms), the Prime × Neighborhood interaction failed to reach significance.

Table 2.3. Behavioral results [mean (SD)]

Target	**Prime**	**RT (ms)**	**Errors (%)**
HD Words	TL	586 (86)	2.96 (3.27)
	Substitution	612 (77)	5.83 (4.34)
LD Words	TL	562 (80)	2.00 (2.37)
	Substitution	596 (74)	3.12 (3.14)

Table 2.4. *b*-, *t*-values, and standard errors of the reaction time analysis for word targets

Factors	*b*-value	SE	*t*-value	*p*-value
Prime	30.13	3.62	8.31	< .001
Neighborhood	20.50	8.18	2.51	.014
Prime × Neighborhood	7.15	6.69	1.07	.288

Error analyses revealed a significant main effect of Prime, such that targets preceded by TL primes elicited fewer errors than those preceded by substitution primes (see Table 2.5). The main effect of Neighborhood was also significant, indicating that LD words elicited fewer errors than HD words. However, the Prime × Neighborhood interaction was not significant.

Table 2.5. *b*-, *z*-values, and standard errors of the error analysis for word targets.

Factors	*b*-value	SE	*z*-value	*p*-value
Prime	.58	.22	2.61	.009
Neighborhood	.58	.26	2.24	.025
Prime × Neighborhood	.24	.36	.68	.495

2.3.2. N250. Target words elicited smaller amplitude N250s in the TL condition compared to the substitution condition, especially across anterior and midline sites (see Figure 2.2), Prime, $F(1,47) = 67.17$, $p < .001$, $\eta_p^2 = .59$, Prime × Laterality, $F(2,94) = 8.72$, $p = .001$, $\eta_p^2 = .16$, Prime × Anterior/Posterior, $F(3,141) = 12.39$, $p < .001$, $\eta_p^2 = .21$. HD words elicited larger amplitude negativities than LD words over anterior sites (see Figure 2.3), Neighborhood × Anterior/Posterior, $F(3,141) = 12.09$, $p < .001$, $\eta_p^2 = .20$. Critically, in contrast to the behavioral results, the effect of Prime differed significantly for HD versus LD words (see Figures 2.4 and 2.5), Prime × Neighborhood, $F(1,47) = 4.31$, $p = .043$, $\eta_p^2 = .08$, Prime × Neighborhood × Laterality, $F(2,94) = 3.69$, $p = .043$, $\eta_p^2 = .07$, Prime × Neighborhood × Laterality × Anterior/Posterior, $F(6,282) = 2.91$, $p = .031$, $\eta_p^2 = .06$. To qualify this interaction, we examined the effect of Prime on N250 amplitude separately for HD and LD words. In both cases, target words preceded by TL primes elicited significantly smaller amplitude N250s than those preceded by substitution primes (see Figures 2.4 and 2.5). For HD words, the effect was largest across more anterior sites, Prime, $F(1,47) = 13.71$, $p = .001$, $\eta_p^2 = .22$, Prime × Anterior/Posterior, $F(3,141) = 9.00$, $p = .002$, $\eta_p^2 = .16$. For LD words, the effect was largest over the central midline and right hemisphere sites, Prime, $F(1,47) = 52.52$, $p < .001$, $\eta_p^2 = .53$, Prime × Laterality, $F(2,94) = 11.20$, $p < .001$, $\eta_p^2 = .19$, Prime × Anterior/Posterior, $F(3,141) = 4.73$, $p = .025$, $\eta_p^2 = .09$, Prime × Anterior/Posterior × Laterality, $F(6,282) = 3.71$, $p = .009$, $\eta_p^2 = .07$.

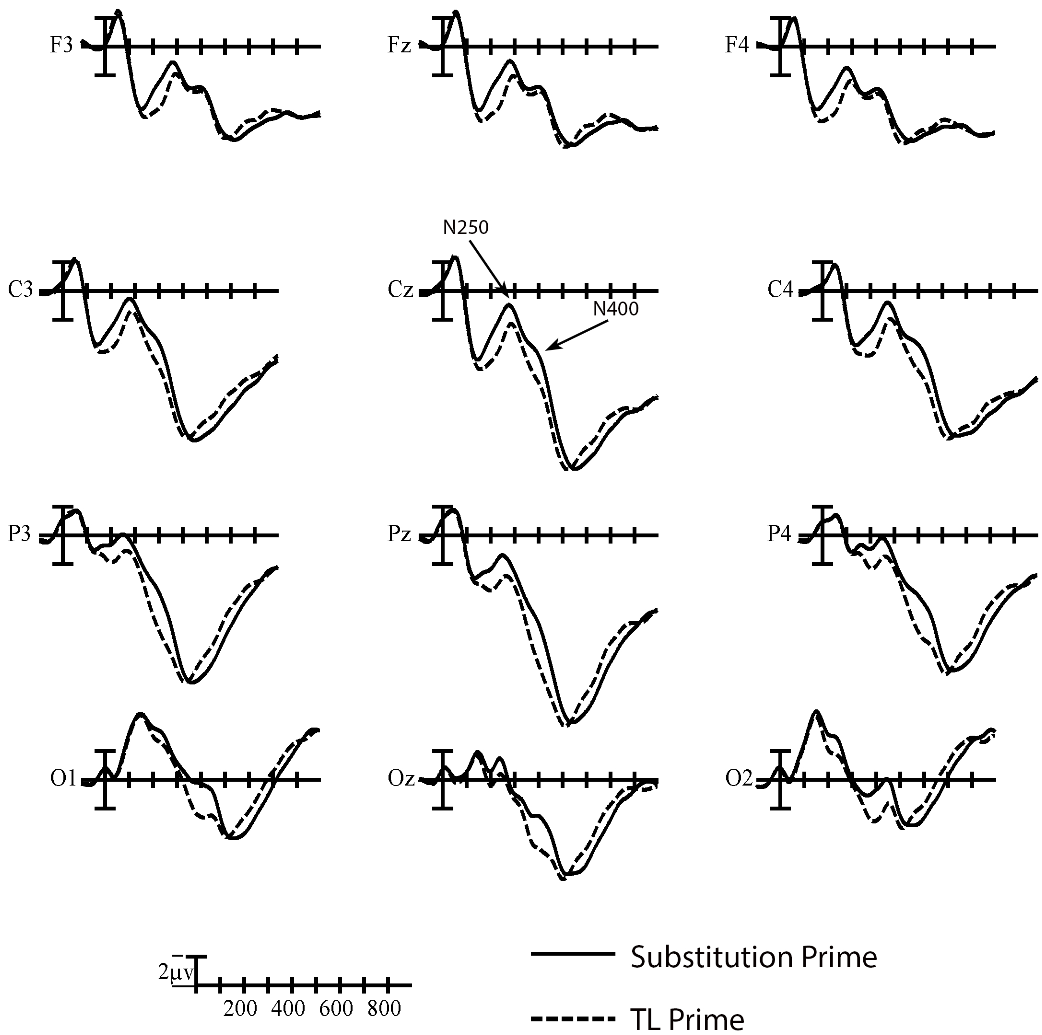

Figure 2.2. Grand average ERP waveforms showing the main effect of TL priming for word targets. Targets preceded by TL primes (dotted line) elicited smaller amplitude negativities than those preceded by substitution lines (solid line). Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 2 μV. The N250 and N400 are indicated at representative site Cz.

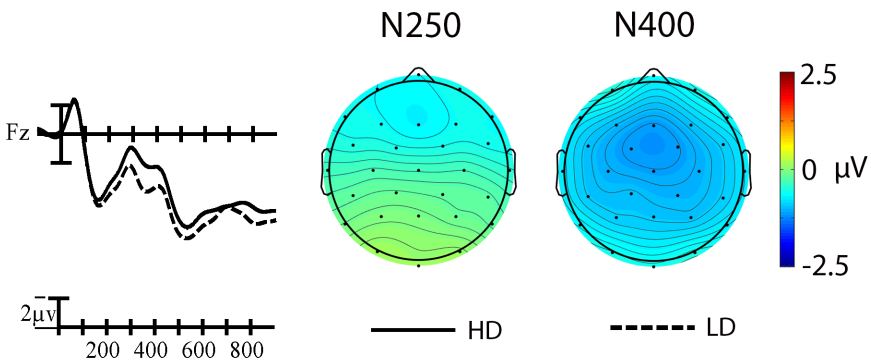

Figure 2.3. The left part of the figure illustrates the main effect of neighborhood density over time for word targets at representative site Fz. HD words (solid line) elicited larger amplitude negativities than LD words (dotted line). Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 2 µV. The scalp voltage maps show the distribution of the effect (HD-LD) within the N250 and N400 windows that were analyzed.

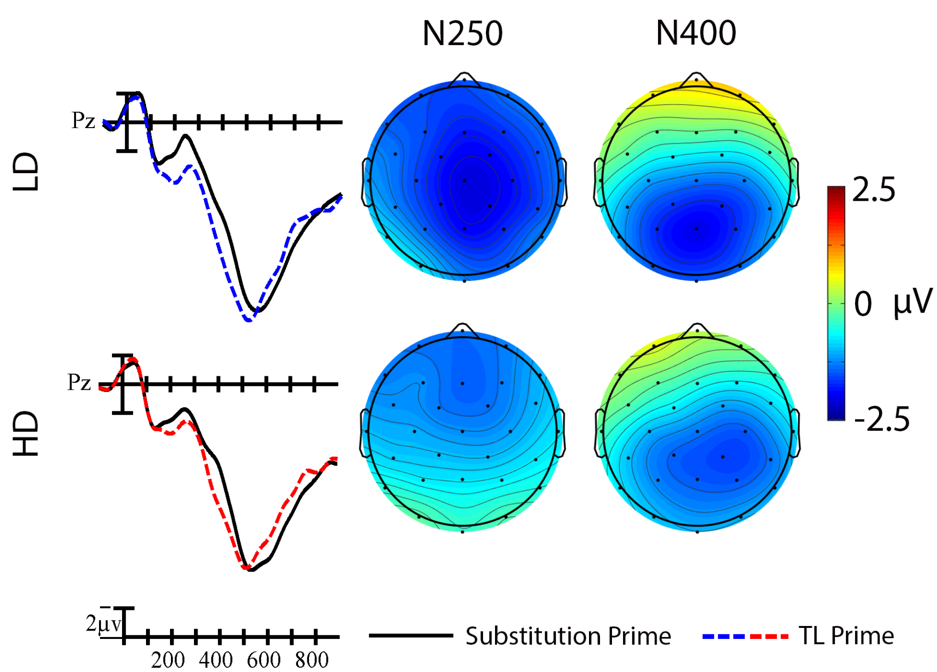

Figure 2.4. The effect of TL priming for LD (top) and HD (bottom) words. Grand average waveforms on the left illustrate the time course of the effect at representative site Pz. For both types of words, targets preceded by TL primes (dotted lines) elicited smaller amplitude negativities than those preceded by substitution lines (solid black lines). Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 2 µV. The scalp voltage maps to the right show the distribution of the effects (substitution-TL) within the N250 and N400 windows that were analyzed.

2.3.3. N400. As in the N250 window, target words elicited smaller amplitude N400s in the TL condition compared to the substitution condition (see Figure 2.2), Prime, $F(1,47) = 27.39$, $p < .001$, $\eta_p^2 = .37$. The TL priming effect interacted with distributional factors such that it was strongest over central midline and right hemisphere sites, Prime × Laterality, $F(2,94) = 3.97$, $p = .029$, $\eta_p^2 = .08$, Prime × Anterior/Posterior, $F(3,141) = 19.22$, $p < .001$, $\eta_p^2 = .29$, Prime × Anterior/Posterior × Laterality, $F(6,282) = 3.16$, $p = .019$, $\eta_p^2 = .06$. The effect of Neighborhood was significant and strongest at anterior sites within this N400 window (see Figure 2.3), Neighborhood, $F(1,47) = 37.35$, $p < .001$, $\eta_p^2 = .44$, Neighborhood × Anterior/Posterior, $F(3,141) = 5.86$, $p = .007$, $\eta_p^2 = .11$. Although it appears that the TL priming effect on N400 amplitude may be larger for HD words than for LD words at select sites (e.g., O1; see Figure 2.5), none of the interactions involving Prime and Neighborhood reached significance, all *p*s > .14.[1]

[1] To confirm that the patterns were different between the N250 and N400 windows, we conducted an omnibus analysis on mean amplitude from both windows that included Time Window as a factor. The three-way Prime × Neighborhood × Time Window interaction was significant, $F(1,47) = 4.12$, $p = .048$, $\eta_p^2 = .08$.

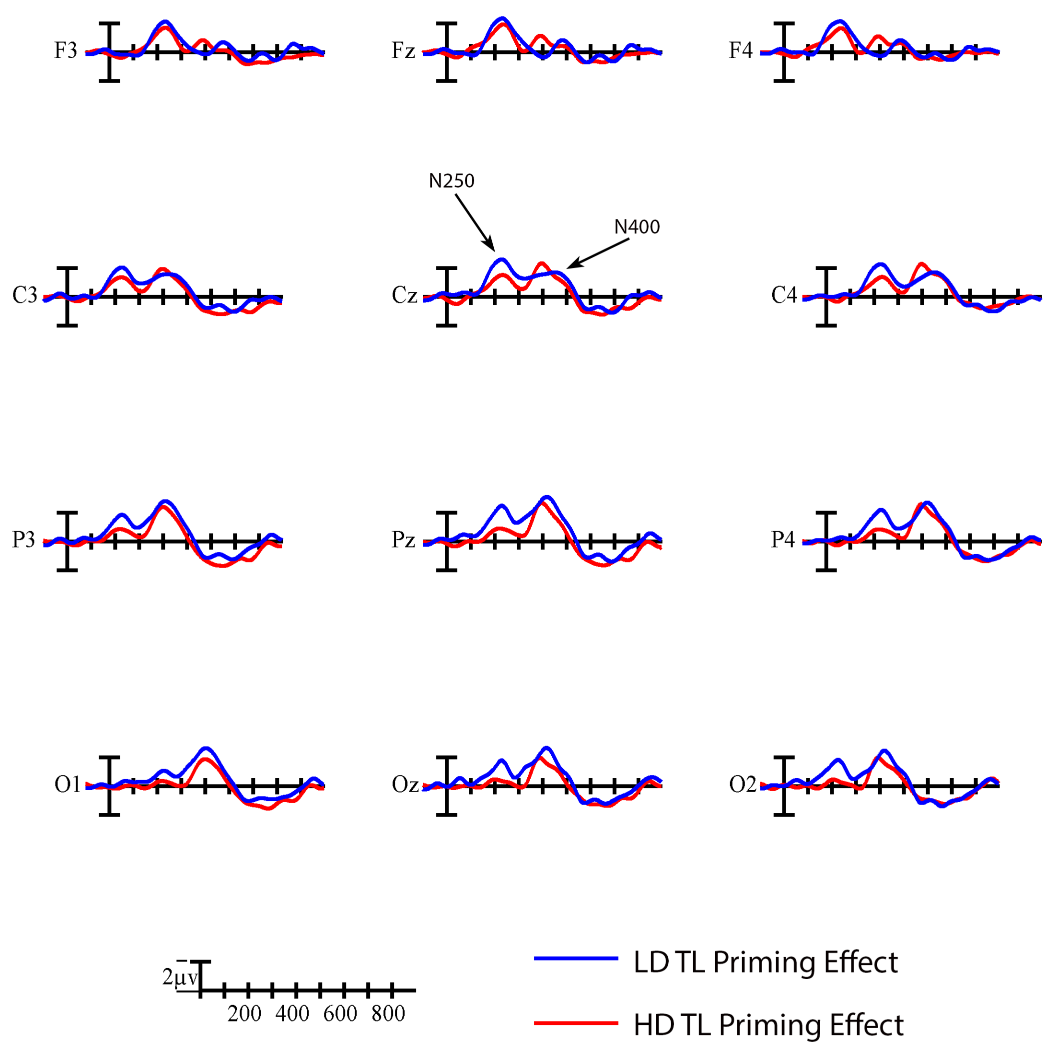

Figure 2.5. Difference waves (substitution-TL) show the relative size of the TL priming effect over time for LD words (blue line) and HD words (red line). Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 2 µV.

2.4. Discussion

In the present study, we used TL priming to investigate potential differences in the precision with which HD and LD words are accessed and represented. Greater precision for HD words is posited to help differentiate them from surrounding neighbors whereas LD words that do not resemble many other words may not require such a high level of precision (Andrews &

Hersch, 2010; Forster & Taft, 1994; Grainger, 2008; Meade, Grainger, Midgley, Emmorey, & Holcomb, 2018). We reasoned that this difference in precision might make TL primes less effective at activating the orthographic representations of HD target words. Consistent with this hypothesis, we found some evidence of smaller TL priming effects for HD words compared to LD words. Both HD and LD target words elicited smaller amplitude N250s when preceded by TL primes compared to substitution primes, but the N250 effect was significantly smaller for HD words. Target words preceded by TL primes continued to elicit smaller amplitude negativities than those preceded by substitution primes into the N400 window, as well as faster and more accurate responses, but the size of the N400 and behavioral effects did not significantly differ as a function of neighborhood density. Taken together, these results demonstrate that TL priming is sensitive to differences in the precision of HD and LD words, but that ERPs might be required to reliably measure these differences.

The most general implication of these results is that the size of electrophysiological indices of TL priming effects differ as a function of lexical-level characteristics. Until now, TL manipulations have centered around how the effect changes depending on the letters that are transposed (e.g., vowels versus consonants; e.g., Carreiras et al., 2009; Lupker, Perea, & Davis, 2008; Perea & Acha, 2009; Perea & Lupker, 2004a; Vergara-Martínez, Perea, Marín, & Carreiras, 2011) and their positions within words (e.g., internal versus boundary; e.g., Perea & Lupker, 2004c), but not how these processes might vary for different types of words. The finding that neighborhood density modulates the size of TL priming effects confirms that this is a valuable approach for tapping into differences in orthographic precision. However, the temporal sensitivity of ERPs appears to be necessary for measuring these early differences given that we failed to find a significant interaction between prime type and neighborhood density in the behavioral data.

The additional benefit of having ERP data is that the specific pattern that we found, together with the body of literature characterizing the N250 and N400 in masked priming experiments, also allows us to make inferences about the underlying mechanisms. The interaction between the size of the TL priming effect and neighborhood density only held within the N250 window, which is generally characterized as reflecting the transition from sublexical processing to lexical processing (see Grainger & Holcomb, 2009, for review). This timing would appear to be consistent with the mechanisms of orthographic precision built into the dual-route model of orthographic coding (Grainger & Ziegler, 2011). More specifically, we would argue that HD and LD words differ in terms of differences in the relative weight assigned to the different types of sublexical orthographic representations included in the dual-route account. HD words have more weight (i.e., stronger connections strengths) assigned to more precise representations along the fine-grained route and LD words have more weight assigned to less precise representations (e.g., open bigrams) along the coarse-grained route. The latter suffices for accurate identification of LD words that are not easily confused with other words in the lexicon and lends itself to larger TL priming within the N250 window.

To some degree, the scalp topographies within the N250 window might also support this argument of the two types of words being processed differently. The TL priming effect was predominantly anterior for HD words, whereas it extended more posteriorly for LD words. Previous work has indicated that more anterior N250 scalp distributions are associated with phonology (e.g., pseudohomophone priming), whereas more posterior N250 scalp distributions are associated with orthographic processing (e.g., Grainger et al., 2006). In the dual-route model of orthographic coding, sublexical phonological representations are only accessed along the fine-grained route. Thus, if HD words were more likely to be processed along that route, they might be expected to elicit an effect that has a more anterior scalp distribution; greater use of more fine-grained orthography should entail greater involvement of phonological representations. The expansion toward the posterior sites for LD words could be explained by priming driven by the coarse-grained route being more orthographic in nature. These dissociations remain speculative for the time being. What is important to note, however, is that priming effects can presumably be obtained along both processing routes, with differences in both the size and the nature of the effects.

The absence of a significant interaction in the N400 window suggests that these qualitative differences in the nature of sublexical orthographic processing led to similar levels of lexical activation. This was also reflected in the finding that behavioral indices of TL priming were similar for HD and LD words. This pattern of results follows from the principle that the relative weight assigned to different types of sublexical orthographic representation is driven by the goal to optimize orthographic processing and word identification. In other words, the final process of word identification, as reflected in lexical decision responses and the N400 ERP component, can be equally optimal independently of the means used to achieve identification. This highlights the importance of ERP studies that can reveal the nature of processing prior to the final product of that processing. With respect to the present results, an analysis limited to behavior would have led to the conclusion that neighborhood density does not impact on TL effects, in line with the lexical quality hypothesis. The pattern of effects seen in the N250 ERP component clearly support an interpretation in terms of different types of sublexical orthographic representation.

In conclusion, the present study used TL priming in order to test the hypothesis that HD and LD words differ in terms of the precision of their orthographic representations. Differences in TL priming for HD versus LD words were especially prominent during the N250 window, suggesting that it is the way in which lexical representations are accessed that differs between them. This pattern of results is most consistent with the dual-route orthographic coding model. More specifically, we suggest that HD words are more likely to be accessed along the fine-grained route in order to be differentiated from their neighbors that share many of the same open bigrams, whereas LD words are more likely to be acessed along the coarse-grained route. Future studies might extend this approach to examining how other lexical-level factors influence lexical access, as well as how this process differs across adult readers of different skill levels.

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Chapter 3: An ERP investigation of transposed-letter priming across languages in late bilinguals

3.1. Abstract

Models of visual word recognition diverge as to whether orthographic precision comes or goes with experience. In some theoretical models of visual word processing, precision is the optimal end state of a lexical representation; the associations between letters and positions are initially approximate and noisy, but they become more precise as readers gain exposure to the word. In other models, flexible orthographic codes that allow for rapid access to semantics are the optimal end state, and precise representations are only relied upon under specific circumstances. To adjudicate between these two classes of models, we compared the size of TL priming effects across languages in two sets of bilinguals. Results were remarkable similar between a group of monolingual participants who participated in a laboratory learning study (Experiment 1) and late English-Spanish bilinguals. In both groups, targets preceded by TL primes elicited smaller amplitude N250s and N400s and faster responses than those preceded by substitution primes. The size of the N400 TL priming effect was larger in the L1 than in the L2. We interpret these results in favor of models in which precision decreases as a function of exposure.

3.2. Introduction

Bilingualism can be a useful tool for investigating fundamental questions about language processing. In the present study, we compared orthographic precision across languages in late bilinguals of varying levels of proficiency. Orthographic precision refers to the degree of specificity with which letters are associated with positions within words. To index orthographic precision, we used a masked transposed-letter (TL) priming paradigm. TL primes formed by reversing two of the letters in a subsequent target word (e.g., *sopon-SPOON*) facilitate target processing more than substitution primes in which those letters are replaced (e.g., *sejon-SPOON*). The presence of these TL effects has been used as evidence that orthographic processing does not involve precise one-to-one correspondences between letters and positions; if that were the case, the two types of primes would be equally similar to the target and should have equal influence on target processing. The relative size of the TL effects has recently been exploited as a measure of orthographic precision. The reasoning goes that words that are represented precisely should be less robustly activated by TL primes and should therefore show smaller TL priming effects. Here, we extend this approach to examine the relationship between language proficiency and precision.

The question of how proficiency modulates orthographic precision is an important one for dissociating among models of visual word recognition. There are models in which increased exposure to words increases precision and others that postulate that orthographic representations are only precise at early stages of learning and when needed. To illustrate, the lexical quality hypothesis (e.g., Perfetti, 1992, 2007) postulates that increased exposure leads to high-quality lexical representations that are precise and redundant. They are precise in that each letter is represented in its correct position and redundant in that the same fine-tuned form information is represented orthographically and phonologically. In contrast, the dual-route orthographic model offers two pathways that vary in degree of precision. Along the fine-grained route, letters and common multi-letter graphemes (e.g., *th*, *ch*) are assigned to specific positions, leading to more precise orthographic representations. This incremental process also involves activation of sublexical phonology and is traditionally associated with reading aloud. This route is also useful for newer words that the reader needs to sound out. In contrast, the coarse-grained route makes use of relative letter positions (i.e., open bigrams) and provides a fast track from orthography to semantics. These less precise representations are optimal for silent reading in the dual-route model, especially for words that are easily identifiable (see Meade, Mahnich, Holcomb, & Grainger, submitted, for further discussion). Thus, these two classes of models assign divergent roles to precision within the orthographic system.

A number of studies have already begun to address the trajectory of precision by investigating how TL effects change over developmental time, as beginning readers gain exposure to visual words and their orthographic lexical representations mature (e.g., Castles, Davis, Cavalot, & Forster, 2007; Colombo, Sulpizio, & Peressotti, 2017; Comesaña, Soares, Marcet, & Perea, 2016; Lété & Fayol, 2013; Ziegler, Bertrand, Lété, & Grainger, 2014). For example, Ziegler and colleagues found that the size of behavioral TL priming effects increases from Grade 1 through Grade 5 (see also Colombo et al., 2017). In an ERP extension of this work, Eddy and colleagues (2016) found that the size of TL priming effects in children between the ages of eight and 10 were correlated with standardized behavioral measures of reading proficiency, such that stronger readers had larger effects. These changes are difficult to explain if we attribute TL priming to positional noise, as they would imply that system noise increases over developmental time. However, the pattern falls out of the dual-route model, which posits that one of the primary mechanisms driving TL priming is the positional flexibility afforded by open bigrams. As children become more mature readers, they are thought to maximize use of the coarse-grained orthographic route (i.e., open bigrams; Grainger & Ziegler, 2011), which in turn increases the effectiveness of TL primes and the relative size of TL priming effects (Eddy et al., 2016; Ziegler et al., 2014).

Another approach has been to investigate how TL effects differ across representations within the same adult reader at the same point time (e.g., Andrews & Lo, 2012; Meade et al., submitted; Vergara-Martínez, Perea, Gómez, & Swaab, 2013). For example, readers should be more proficient at recognizing high frequency words relative to low frequency words. According to the lexical quality hypothesis, the increased exposure to high frequency words should sharpen precision and lead to smaller TL priming effects. The limited empirical evidence suggests otherwise. Vergara-Martínez and colleagues reported that N400 amplitude differentiated TL nonwords (e.g., BRIGDE) from substitution nonwords (e.g., BRITGE), only when the base words had a high frequency. In other words, increased exposure appears to lead to more flexible representations that were more susceptible to activated by the TL prime, more in line with optimization of a system like open bigrams that does not involve assigning letters to specific positions. Here, we extend these results to try to characterize differences in precision between words in languages with which bilinguals have varying levels of proficiency.

3.2.1. The Present Study. The goal of the present study was to investigate how language dominance modulates orthographic precision in bilinguals. Previous research has demonstrated that TL priming is a useful index of orthographic precision; representations that are more precise (i.e., that have each letter assigned to a specific position in the word) are not as easily activated by TL nonwords and yield smaller TL effects (e.g., Lally, Taylor, Lee, & Rastle, 2019; Meade et al., submitted; Vergara-Martínez et al., 2013; Ziegler et al., 2014). Here, we compared the size of TL priming effects for L1 and L2 words in two groups of bilinguals with varying levels of L2 proficiency who performed a language decision task. We measured priming in terms of behavioral facilitation and mean amplitude within the N250 and N400 windows of the ERP waveform. Whereas the N250 is associated with the transition from sublexical to lexical processing, the N400 is associated with later lexico-semantic processing (see, Grainger & Holcomb, 2009). In Experiment 1, the participants learned an artificial language within a controlled laboratory setting and were tested after four consecutive days of training. In Experiment 2, the participants are late English-Spanish bilinguals who learned their L2 across a variety of more naturalistic settings. The lexical quality hypothesis posits that precision is the optimal end state of lexical representations. As the reader gains exposure to a word, the representation for that word increases in precision. Thus, this model postulates that the dominant language will have *more* precise representations that generate *smaller* TL priming effects. In contrast, the dual-route model of orthographic coding posits that flexible orthographic codes that allow rapid access to semantic representations are the optimal way to access a well-established word. Thus, the dominant language is expected to have *less* precise (i.e., more flexible) representations that generate *larger* TL priming effects.

3.3. Experiment 1: Methods

3.3.1. Participants. Participants were 24 native speakers of English (21 female; mean age 21.4 years, SD 2.0 years) who reported not being exposed to another language before the age of six and only being fluent in English. All participants were right-handed, had normal or corrected-to-normal vision. None of them reported a history of neurological dysfunction or language/reading disorders. Participants provided informed consent and were compensated in accordance with the Institution Review Board at San Diego State University. Data from these same participants were reported by Meade and Holcomb (in preparation).

3.3.2. Stimuli. The stimuli are described in detail by Meade and Holcomb (in preparation). Briefly, targets consisted of 96 L1 English words and 96 pseudowords, which we refer to as L2 words. Participants completed a series of training exercises over the four days that preceded the ERP posttest in which they learned to associate the L2 words with pictures that represented their meanings. By the fourth day, participants were able to type the L2 words in response to the pictures with an average of 89.1% accuracy (*SD* 9.9%). When given a picture, they could choose the correct L2 word from a field of two with 99.1% (*SD* 1.1%) accuracy on average. Only the L2 words that they typed accurately were included in the analyses reported here. All targets were five letters long. The L1 and L2 targets were closely matched for L1 OLD20, SUBTLEX frequency, and concreteness overall, all *p*s > .65 (see Table 1). OLD20 is a measure of neighborhood density that involves calculating the average number of substitutions, deletions, and insertions required to obtain the 20 closest words.

Each target was preceded by a TL prime and a substitution prime. TL primes were formed by reversing two word-internal letters; half of the transpositions in each language were between the 2nd and 3rd positions and half of them were between the 3rd and 4th positions. The transpositions were always between a consonant and a vowel. Substitution primes were formed by replacing the letters in the same position such that the consonant/vowel structure and visual outline (i.e., ascenders and descenders) were identical to the TL primes. The L1 English neighborhood density, quantified using OLD20, was also matched between the TL and substitution primes for each type of target, both *p*s > .79.

Table 3.1. Characteristics of the L1 and L2 targets in Experiment 1 [mean (SD)]

Target	OLD20	Frequency	Concreteness	TL Prime OLD20	Sub Prime OLD20
L1	1.92 (.22)	47 (84)	4.77 (.24)	2.14 (.27)	2.14 (.25)
L2	1.92 (.17)	50 (98)	4.79 (.26)	2.13 (.27)	2.14 (.22)

Note: The frequency and concreteness of the L1 translations were used as a proxy in these calculations since the L2 words themselves do not have values for these variables.

3.3.3. Procedure. The full procedure, including the learning protocol, is described by Meade and Holcomb (in preparation). Here, we focus on the ERP posttest in which participants completed a language decision task. They were instructed to press one button on a videogame response box if the word was English and another button if the word was from the language that they had learned (i.e., no mention was made of the primes). Response hand was counterbalanced across participants. Participants saw one of four pseudorandomized lists. Targets were presented with a substitution prime in one half of the list and with a TL prime in the other half. The prime that each target occurred with first was counterbalanced across lists. Orthographic and semantic relatedness of the targets was minimized between consecutive trials and no more than three consecutive trials belonged to the same language. The experiment began with a practice that consisted of eight trials, half of which were L2 words that were included in the learning exercises.

The structure of individual trials was identical to our previous masked TL priming study (Meade et al., submitted). Each trial began with a white fixation cross presented at the center of the screen for 500 ms. A forward mask (#######) then appeared for 300 ms, followed by a lowercase prime for 50 ms, a backward mask (#######) for 20 ms, and an uppercase target for 300 ms. After a response was registered, the screen remained blank for 750 ms and then a purple fixation cross appeared at the center of the screen for 1500 ms. Participants were instructed to blink during this purple cross in between trials and during occasional longer breaks. Stimuli were displayed in Courier font such that they subtended a horizontal visual angle of 1.7 degrees.

3.3.4. EEG Recording and Analysis. Participants were fitted with an elastic cap (Electro-Cap) with 29 electrodes. An additional four electrodes were placed. The electrode on the left mastoid was used as a reference during recording and for subsequent analyses. The electrode on the right mastoid was only used to monitor differential mastoid activity. The electrode below the left eye was used to identify blinks in conjunction with the recordings from FP1 and the electrode next to the outer canthus of the right eye was used to monitor horizontal eye movement. Using saline gel (Electro-Gel), the impedances of all electrodes were maintained below 2.5 kΩ. EEG was amplified with SynAmpsRT amplifiers (Neuroscan-Compumedics) with a bandpass of DC to 100 Hz and was sampled continuously at 500 Hz.

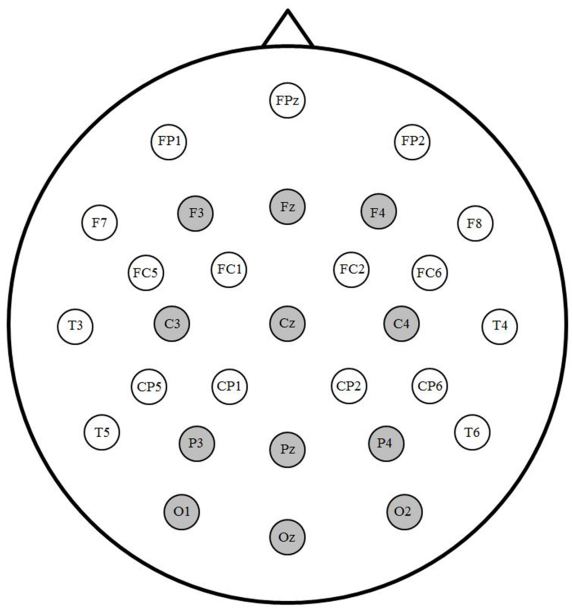

Figure 3.1. Electrode montage. Sites highlighted in gray were included in analyses.

ERPs were time-locked to target onset and low-pass filtered at 15 Hz. Epochs spanned 1000 ms including a 100 ms pre-target-onset baseline. Trials with artifacts related to eye movement or drift during this epoch (4.2 trials, or 1.1% on average) were excluded from analyses, as were trials with incorrect language decision responses. Separate ERPs for each language and prime combination were averaged for each participant at the 12 representative electrodes that are depicted in Figure 1. Consistent with our previous masked TL priming study (e.g., Meade et al., submitted), mean N250 amplitude was calculated between 150 and 275 ms and mean N400 amplitude was calculated between 350 and 550 ms. For each time window, repeated-measures ANOVAs were conducted with within-subject factors Language (L1, L2), Prime (TL, Substitution), Laterality (Left, Midline, Right) and Anterior/Posterior (Frontal, Central, Parietal, Occipital). Greenhouse-Geisser correction was applied for all within-subject measures with more than one numerator degrees of freedom. Partial eta squared (η_p^2) is reported as a measure of effect size.

3.4. Experiment 1: Results

3.4.1. Behavior. A significant main effect of Prime indicated that targets preceded by TL primes elicited faster responses than targets preceded by substitution primes overall, $F(1,23) = 24.14$, $p < .001$, $\eta_p^2 = .51$. Neither of the factors had a significant effect on accuracy in the language decision task.

Table 3.2. Behavioral results from Experiment 1 [mean (SD)]

Target	Prime	RT (ms)	Accuracy (%)
English	TL	645 (116)	97.6 (2.1)
	Substitution	668 (104)	96.3 (3.0)
L2	TL	659 (115)	97.2 (3.1)
	Substitution	676 (107)	97.0 (1.7)

3.4.2. N250 Amplitude. English targets elicited larger amplitude N250s than the newly learned L2 words, especially across more posterior sites, Language, $F(1,23) = 10.60$, $p = .004$, $\eta_p^2 = .32$, Language × Anterior/Posterior, $F(3,69) = 10.39$, $p = .002$, $\eta_p^2 = .31$ (see Figure 2). A significant main effect of Prime indicated that targets preceded by TL primes elicited smaller amplitude N250s than targets preceded by substitution primes overall, $F(1,23) = 21.74$, $p < .001$,

η_p^2 = .47 (see Figure 3). This effect was strongest across more anterior sites, $F(3,69) = 5.82$, p = .012, η_p^2 = .20. None of the interactions involving the two variables of interest were significant, all ps > .11.

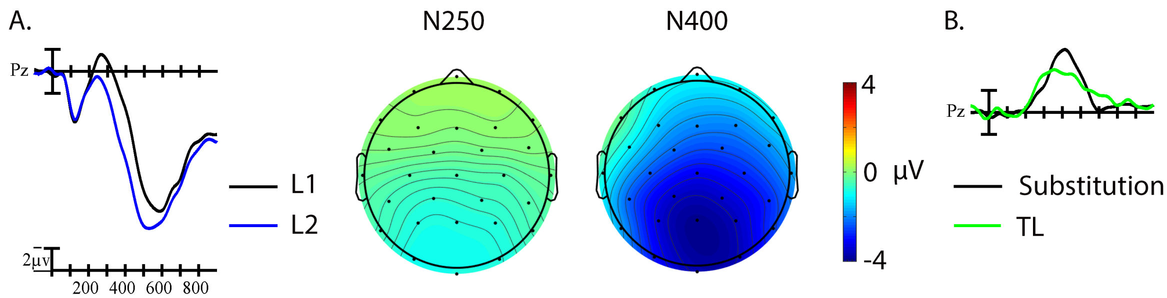

Figure 3.2. (A) The main effect of language in Experiment 1 at representative site Pz. L1 targets (black line) elicited larger amplitude negativities than L2 targets (blue line) overall. Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 2 µV. The scalp voltage maps in the middle show the distribution of the effects (L1-L2) within the N250 and N400 windows that were analyzed. (B) Difference waves at representative site Pz to illustrate that this language effect (L1-L2) was larger for targets preceded by substitution primes (black line) relative to those preceded by TL primes (green line).

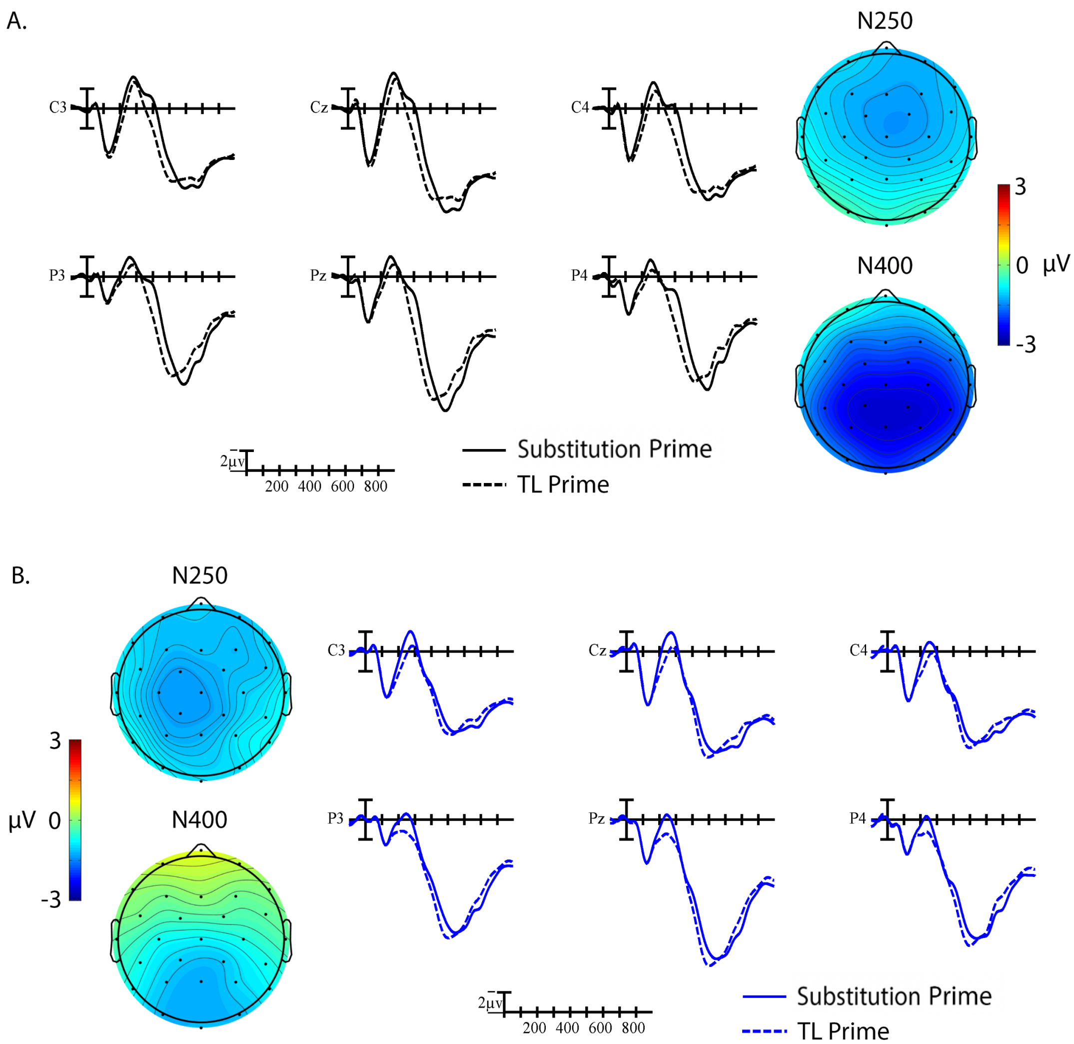

Figure 3.3. Grand average ERP waveforms showing the main effect of TL priming for word targets in the L1 (A) and L2 (B) in Experiment 1. Targets preceded by TL primes (dotted line) elicited smaller amplitude negativities than those preceded by substitution lines (solid line). Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 2 µV. The scalp voltage maps show the distribution of the effects (substitution-TL) for each language within the N250 and N400 windows that were analyzed.

3.4.3. N400 Amplitude. A significant main effect of Language indicated that English targets elicited larger amplitude N400s than the newly learned L2 words, $F(1,23) = 46.89$, $p < .001$, $\eta_p^2 = .67$ (see Figure 2). This difference was especially strong across midline and parietal sites, Language × Laterality, $F(2,46) = 4.09$, $p = .048$, $\eta_p^2 = .15$, Language × Anterior/Posterior,

$F(3,69) = 10.91$, $p = .001$, $\eta_p^2 = .32$. A significant main effect of Prime indicated that targets preceded by TL primes elicited smaller amplitude N400s than targets preceded by substitution primes overall, $F(1,23) = 29.92$, $p < .001$, $\eta_p^2 = .56$ (see Figure 3). This effect was also strongest at parietal sites, Prime × Anterior/Posterior, $F(3,69) = 8.47$, $p = .002$, $\eta_p^2 = .27$. Critically, and in contrast to the N250 window, the size of the priming effect differed for the two languages, Language × Prime, $F(1,23) = 6.13$, $p = .021$, $\eta_p^2 = .21$ (see Figure 4). In follow-up analyses separately for each language, there was a significant main effect of Prime for L2 words, $F(1,23) = 5.28$, $p = .031$, $\eta_p^2 = .19$, and English words, $F(1,23) = 29.49$, $p < .001$, $\eta_p^2 = .56$. The distribution of the effect was also similar in both languages, such that a Prime × Anterior/Posterior interaction indicating a stronger effect at parietal sites was significant in the L2, $F(3,69) = 8.35$, $p = .002$, $\eta_p^2 = .27$, and just failed to reach significance in English, $F(3,69) = 3.46$, $p = .057$, $\eta_p^2 = .13$. In follow-up analyses separately for each type of prime, the effect of Language was strongest over occipital sites for targets preceded by TL primes, Language, $F(1,23) = 28.56$, $p < .001$, $\eta_p^2 = .55$, Language × Anterior/Posterior, $F(3,69) = 11.52$, $p < .001$, $\eta_p^2 = .33$. For targets preceded by substitution primes, the effect of Language was strongest at parietal and midline sites, Language, $F(1,23) = 40.68$, $p < .001$, $\eta_p^2 = .64$, Language × Laterality, $F(2,46) = 4.12$, $p = .046$, $\eta_p^2 = .15$, Language × Anterior/Posterior, $F(3,69) = 6.12$, $p = .011$, $\eta_p^2 = .21$. Thus, the TL N400 priming effect was robust but it was stronger in English than in the L2 (see Figure 3.4), largely due to differences in the substitution condition (see Figure 3.2B).

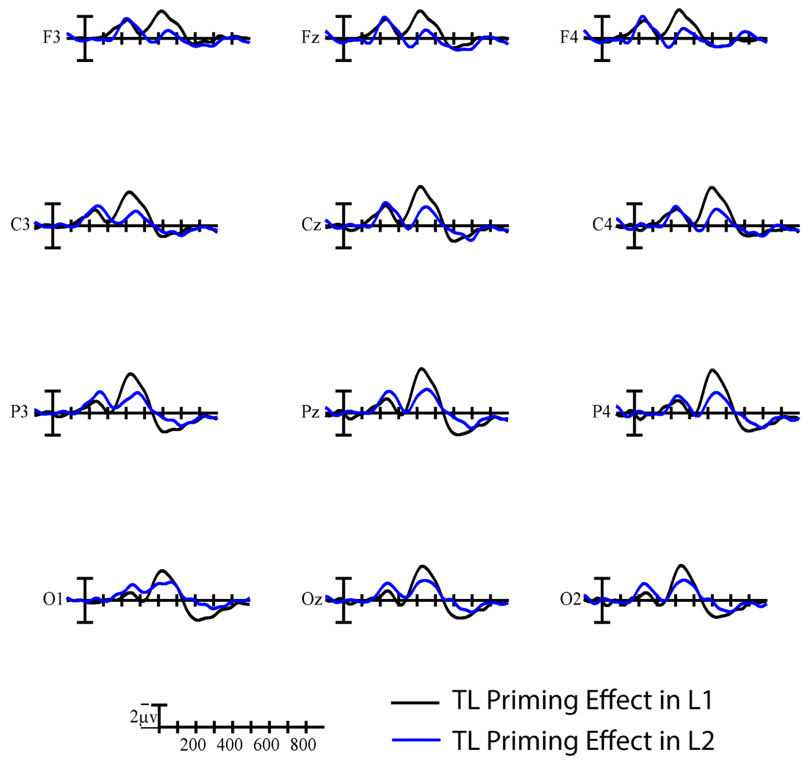

Figure 3.4. Difference waves showing the time course of TL priming effects (substitution-TL) in the L1 (black) and L2 (blue) in Experiment 1. Each vertical tick marks 100 ms and negative is plotted up. The calibration bar marks 2 µV.

3.5. Experiment 1: Discussion

The pattern of results in Experiment 1 was clear. The difference in processing of targets preceded by TL versus substitution primes was evident within the N250 and N400 windows and language decision response times. Whereas the N250 effect of TL priming appeared similar across languages, the N400 effect was significantly larger in L1 English than it was for the newly learned L2 words. This result would seem to suggest that the L1 words had less precise representations than the L2 words, providing evidence against models in which precision is the optimal end state of the orthographic system. However, the interpretation is complicated by the fact that the primary difference across languages was the N400 elicited by targets in the substitution prime condition, not in the TL prime condition. Given that these participants only had four days of experience with the L2 words and learned them under somewhat contrived circumstances, we set out to test whether these N400 differences persist or converge in more proficient bilinguals.

3.6. Experiment 2: Introduction

The goal of Experiment 2 was to further investigate how proficiency modulates TL priming effects. We compared TL priming effects across languages in late English-Spanish bilinguals to determine whether they show a similar pattern as the learners in Experiment 1 or whether they have more similar TL priming effects across their two languages.

3.7. Experiment 2: Methods

3.7.1. Participants. Data were analyzed from 20 late English-Spanish bilinguals (14 female; mean age 24.5 years, *SD* 4.3 years) who considered themselves to be proficient in L2 Spanish. All participants had been exposed to English since birth. In contrast, they began learning Spanish at age 11 or later (average age of Spanish: 14.3 years, *SD* 3.0 years). Self-reported proficiency data for both languages, presented in Table 3, confirmed that participants perceived themselves as more proficient in L1 English than in L2 Spanish at the time of testing. On a dominance scale from 1 (Spanish) to 9 (English), the mean rating was 7.6 (*SD* 0.9). As an objective measure of proficiency, the LexTALE was administered in both languages (see Table 1 Izura, Cuetos, & Brysbaert, 2014; Lemhöfer & Broersma, 2012). All participants were right-handed and had normal or corrected-to-normal vision. They were volunteers who received monetary compensation for their time. All participants provided informed consent in accordance with the Institutional Review Board at San Diego State University. Five additional participants who met these criteria were excluded for low accuracy on the translation post-test (< 50%; see Stimuli below) and two were excluded due to high artifact rejection rate in the ERP task.

Table 3.3. Mean (SD) self-reported proficiency (1=unable, 5=expert) and LexTALE scores in the two languages.

	Reading	Spelling	Speaking	Listening	LexTALE[2]
Spanish	3.80 (0.77)	4.05 (1.15)	3.80 (0.77)	3.70 (0.66)	65.92 (7.58)
English	5.00 (0.00)	4.55 (0.83)	4.90 (0.31)	4.95 (0.22)	93.94 (7.02)

3.7.2. Stimuli. Targets were real L1 English or L2 Spanish words that were five letters long and had a noun meaning. Using the respective SUBTLEX databases, frequency was controlled between L1 English (mean 64, *SD* 114) and L2 Spanish (mean 65, *SD* 133) targets, $t(98) = .03$, $p = .976$ (see Table 4, Brysbaert & New, 2009; Cuetos, Glez-Nosti, Barbón, & Brysbaert, 2011). Nevertheless, presumably the L2 Spanish words had a lower subjective frequency for our participants. Orthographic neighborhood density was also balanced between L1 English and L2 Spanish targets, $t(98) = .09$, $p = .930$, given recent evidence that TL priming effects are larger for words from low-density orthographic neighborhoods (Meade et al., submitted). To achieve this for our bilingual participants, we calculated OLD20 taking into account all words between three and eight letters long in the respective databases for the two languages (Balota et al., 2007; Duchon, Perea, Sebastián-Galles, Martí, & Carreiras, 2013). To confirm that participants were familiar with the L2 Spanish targets, they were asked to translate them into English immediately following the ERP task. On average, participants provided a

[2] The formulas recommended to score these two versions of the LexTALE are different. To calculate scores that were more obviously comparable across the two tests, which have different numbers of items, we summed across the percentage of correct words and nonwords. A perfect score was therefore 100 across the two tests.

translation for 38.3 (*SD* .76) of the 50 Spanish words. This decreased accuracy is the tradeoff of recruiting late bilinguals who were strongly L1 English dominant. As in Experiment 1, only familiar Spanish words were included in the analyses reported below.

TL and substitution primes were formed as in Experiment 1. The positions and letters that were transposed were identical across trials in the two languages. None of the primes were words in either language. OLD20 of the primes was controlled between the two types of primes that occurred before targets in each languages, both *p*s > .10.

Table 3.4. Characteristics of the L1 and L2 targets in Experiment 2 [mean (SD)]

Target	OLD20	Frequency	TL Prime OLD20	Sub Prime OLD20
L1	1.66 (.17)	64 (113)	1.98 (.18)	2.03 (.18)
L2	1.66 (.17)	65 (133)	1.95 (.16)	2.01 (.20)

3.7.3. Procedure. The trial structure was identical to Experiment 1. Participants pressed one button on a videogame controller for Spanish words and another button for English words, with response hand counterbalanced across participants. Trials were presented in two possible pseudorandomized list orders that met the same constraints as in Experiment 1. The experiment began with a practice list containing 10 trials, half of which had Spanish targets.

3.7.4. EEG Recording and Data Analysis. EEG recording and analysis procedures were the same as in Experiment 1. On average, 9.5 trials, or 5.3%, were rejected for artifacts.

3.8. Experiment 2: Results

3.8.1. Behavior. Behavioral results mirrored the pattern reported in Experiment 1. There was a significant main effect of Prime such that targets preceded by TL primes elicited faster responses than targets preceded by substitution primes overall, $F(1,19) = 4.57$, $p = .046$, $\eta_p^2 = .19$. Neither of the factors had a significant effect on accuracy in the language decision task.

Table 3.5. Behavioral results from Experiment 2 [mean (SD)]

Target	Prime	RT (ms)	Accuracy (%)
English	TL	602 (72)	96.8 (3.7)
	Substitution	618 (84)	95.7 (4.2)
Spanish	TL	596 (67)	96.9 (3.2)
	Substitution	600 (62)	95.9 (3.2)

3.8.2. N250 Amplitude. A significant main effect of Language indicated that L1 English targets elicited larger amplitude negativities within the N250 window than L2 Spanish targets, $F(1,19) = 13.50$, $p = .002$, $\eta_p^2 = .42$ (see Figure 3.5A). A significant main effect of Prime indicated that targets preceded by TL primes elicited smaller amplitude N250s than those preceded by substitution primes overall, $F(1,19) = 7.92$, $p = .011$, $\eta_p^2 = .29$ (see Figure 3.6). The TL priming effect was largest across anterior sites, Prime × Anterior/Posterior, $F(3,57) = 8.92$, $p = .002$, $\eta_p^2 = .32$.

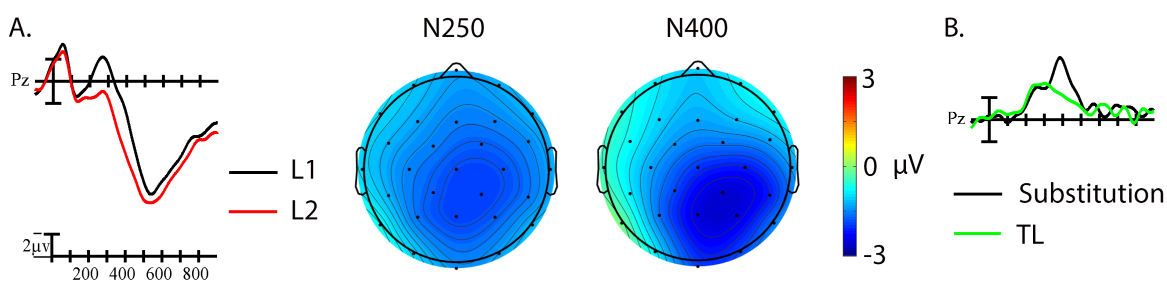

Figure 3.5. (A) The main effect of language in Experiment 2 at representative site Pz. L1 targets (black line) elicited larger amplitude negativities than L2 targets (blue line) overall. Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 2 µV. The scalp voltage maps in the middle show the distribution of the effects (L1-L2) within the N250 and N400 windows that were analyzed. (B) Difference waves at representative site Pz to illustrate that this language effect (L1-L2) was larger for targets preceded by substitution primes (black line) relative to those preceded by TL primes (green line).

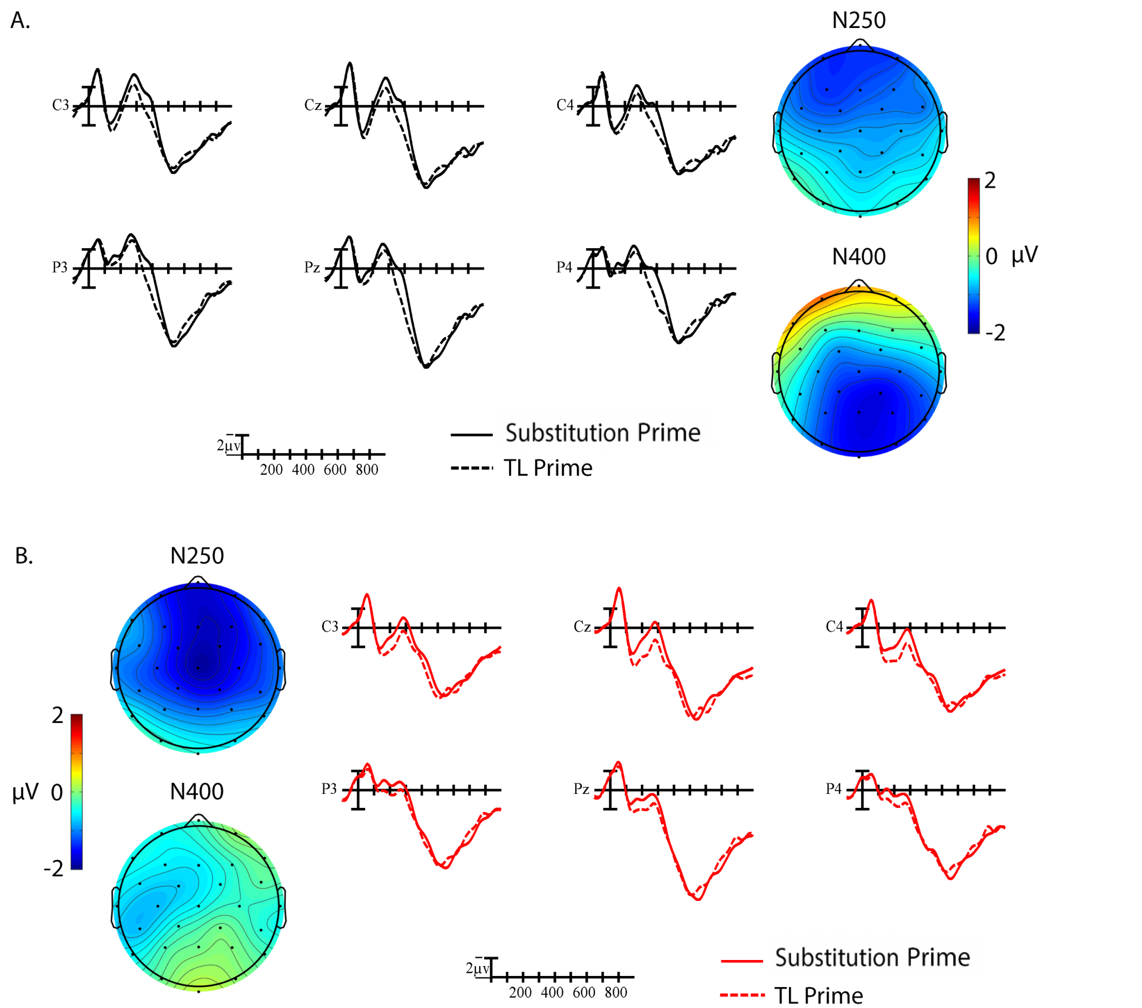

Figure 3.6. Grand average ERP waveforms showing the main effect of TL priming for word targets in the L1 (A) and L2 (B) in Experiment 2. Targets preceded by TL primes (dotted line) elicited smaller amplitude negativities than those preceded by substitution lines (solid line). Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 2 µV. The scalp voltage maps show the distribution of the effects (substitution-TL) for each language within the N250 and N400 windows that were analyzed.

3.8.3. N400 Amplitude. A significant main effect of Language indicated that L1 English targets continued to elicit larger negativities than L2 Spanish targets into the N400 window, $F(1,19) = 8.97$, $p = .007$, $\eta_p^2 = .32$ (see Figure 3.5). This difference was especially large across parietal sites, $F(3,57) = 3.80$, $p = .045$, $\eta_p^2 = .17$. A significant main effect of Prime indicated that targets preceded by TL primes elicited smaller N400s than those preceded by substitution primes, $F(1,19) = 4.97$, $p = .038$, $\eta_p^2 = .21$ (see Figure 3.6). The distribution of the TL priming effect differed across languages, Language × Prime × Anterior/Posterior, $F(3,57) = 5.20$, $p = .020$, $\eta_p^2 = .22$. In order to better characterize this interaction, we conducted follow-up analyses at each level of the Anterior/Posterior factor. The Language × Prime interaction was only significant at occipital sites, where the TL priming effect in English was larger than in Spanish, $F(1,19) = 6.09$, $p = .023$, $\eta_p^2 = .24$ (see Figure 3.7) and the language effect was more reliable for substitution primes, Language, $F(1,19) = 19.03$, $p = .003$, $\eta_p^2 = .50$, Language × Laterality, $F(2,38) = 11.21$, $p = .001$, $\eta_p^2 = .37$, compared to TL primes, Language × Laterality, $F(2,38) = 5.59$, $p = .018$, $\eta_p^2 = .23$.

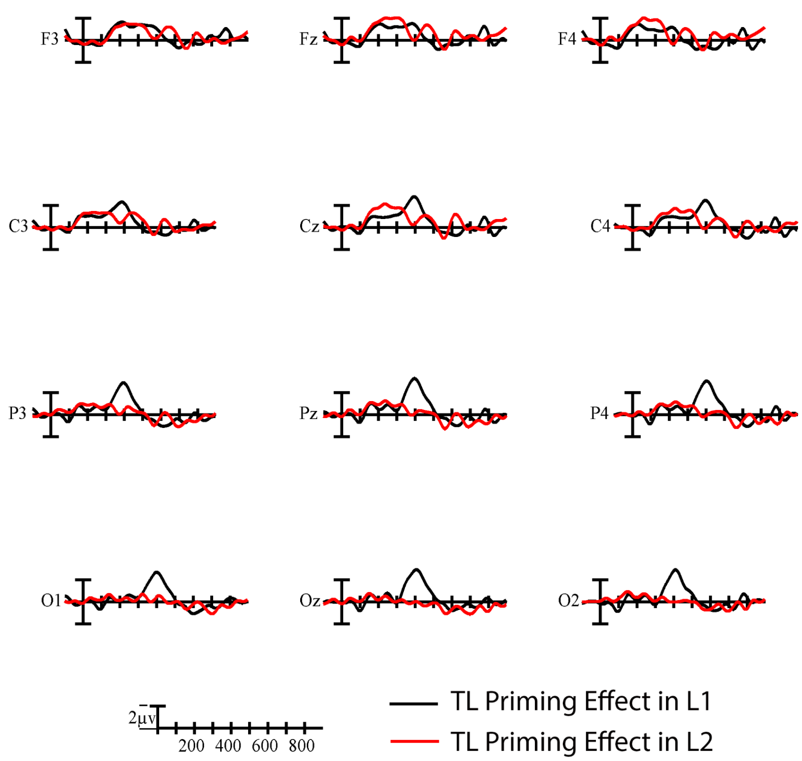

Figure 3.7. Difference waves showing the time course of TL priming effects (substitution-TL) in the L1 (black) and L2 (red) in Experiment 2. Each vertical tick marks 100 ms and negative is plotted up. The calibration bar marks 2 µV.

3.9. Experiment 2: Discussion

The results of Experiment 2 with more proficient English-Spanish bilinguals are nearly identical to the pattern of results that we found in Experiment 1 with laboratory learners of a second language. We replicated and extended the basic pattern in which TL priming effects are similar across languages in terms of N250 amplitude and response times, but larger for the L1 in the N400 window. These results suggest that the difference in precision for L1 versus L2 words persists even after bilinguals have years of experience with their L2. They also reinforce that it is primarily the substitution primes, rather than the TL primes, that are causing the difference in the size of the N400 priming effect across languages.

3.10. General Discussion

In the first comparison of ERP TL priming across languages in bilinguals, we found larger N400 priming effects for L1 words than for L2 words, both in learners of an artificial language (Experiment 1) and in more proficient English-Spanish bilinguals (Experiment 2). The priming effects were significant across the N250, the N400, and behavioral responses, but only differed across languages within the N400 window. A priori, we expected that any differences in the size of TL priming across languages would be due to the TL condition. To produce the pattern that we found, this would mean especially small amplitude negativities for L1 targets in the TL condition after being strongly pre-activated by the prime. What we found instead was that the difference across languages was primarily due to L1 targets in the substitution condition eliciting markedly larger amplitude N400s. The similar results across the two experiments here, together with robust evidence for TL priming in Spanish (e.g., Carreiras, Vergara, & Perea, 2009; Perea & Carreiras, 2006; Perea & Lupker, 2004), suggest that these results are not a result of the specific language combinations that we used. Rather, this pattern emphasizes that substitution primes also differed in their effectiveness to prime targets across languages, perhaps another byproduct of decreased precision for words in the more proficient L1.

As established in the Introduction, the dual-route model of orthographic processing is a strong candidate for a model that could explain why precision decreases as a function of proficiency. In this model, the less precise coarse-grained route is optimized for rapid, direct access to semantics and might be more characteristic of L1 word processing. In contrast, the fine-grained route is the default route for learning new written words given the emphasis on sounding them out (i.e., sublexical phonology). Thus, the fine-grained route might be more characteristic of L2 processing, particularly for the new learners in Experiment 1. These two routes allow for differential effectiveness of TL primes because position information is more precise along the fine-grained route. It is also feasible that the two routes allow for differential effectiveness of substitution primes. Along the fine-grained route, substitution primes would still share three out of five letters in the same positions as the target and could be relatively effective at activating the L2 targets. Along the coarse-grained route, substitution primes would only share three out of ten open bigrams, and would therefore be less effective at pre-activating L1 targets. If substitution primes are less effective at activating the L1 words, then larger amplitude negativities (i.e., more effortful processing) would be expected. One way to test this in the future would be to compare substitution primes (e.g., *sejon-SPOON*) to all-different control primes (e.g., *taeir-SPOON*) across languages.

Relative to the general bilingual population, our samples were quite homogenous, but that makes it difficult to determine exactly what variable is critical for yielding these differences between L1 and L2. Age of acquisition and exposure to the individual words are particularly difficult to tease apart. The finding of a similar pattern in a comparison between high- and low-frequency L1 words (i.e., greater TL effects for the words with which participants have the most experience; Vergara-Martínez et al., 2013) makes it tempting to conclude that it was the relatively higher subjective frequency of the L1 words that was driving the differences in how words in the two languages were coded. As readers gain exposure to visual words, they rely less on encoding the words phonologically and rely more on the "good enough" open bigram representations along the coarse-grained route. Precisely opposite the architecture of the lexical quality hypothesis, this account is further supported by the developmental pattern of a decrease in the size of TL effects as children become older (e.g., Colombo et al., 2017; Ziegler et al., 2014) and are better readers (e.g., Eddy et al., 2016).

One potential problem with this interpretation is that these routes describe the sublexical code that is used to access lexical representations and would be predicted to generate differences in priming between languages within the N250 window, not the N400 window (see Meade et al., submitted). It is difficult to ascertain the predicted time course of effects given the paucity of previous masked priming studies that have used the language decision task. Rather than emphasizing sublexical patterns and activation of a single lexical representation, as in the lexical decision task, this task requires higher-level information about language membership (see, e.g., Chwilla, Brown, & Hagoort, 1995; Meade, Grainger, & Holcomb, 2019; J. Ziegler, Besson, Jacobs, Nazir, & Carr, 1997, for evidence of different N400 patterns across tasks). It is also possible that the increased N400 amplitude that we observed is reflecting more general properties of the L1 and L2 networks and co-activation. We controlled for the neighborhood density of the primes to minimize differences in lexical co-activation. However, if it is true that the L1 words are more likely to be processed using an open bigram scheme, then this control may not have been effective. The TL primes and targets share many of the same open bigrams and will share many of their neighbors. The substitution primes have several unique open bigrams and will likely activate different lexical representations than the target, leading to an increase in the overall number of lexico-semantic representations that are co-activated and a larger N400. In contrast, if the L2 words are processed more along the fine-grained route with emphasis on the positions in which letters occur, the substitution prime will not have as many unique neighbors.

One might have expected these differences in processing within the N400 window, whether due to prime-target similarity or lexico-semantic co-activation, to carry over into the responses in the language decision task. However, we failed to find significant differences across languages in the size of behavioral TL priming in either experiment. Surprisingly, L1 responses had similar latencies as L2 responses overall. Whereas we found a larger N400 for L1 words compared to L2 words across experiments – the standard pattern in the literature for unbalanced bilinguals (e.g., Midgley, Holcomb, & Grainger, 2009; Soskey, Holcomb, & Midgley, 2016) – we also failed to find the standard behavioral pattern of slower RTs in the L2. These patterns suggest that sufficient language membership information was available, perhaps based on sublexical patterns (e.g., Hoversten, Brothers, Swaab, & Traxler, 2015; van Kesteren, Dijkstra, & De Smedt, 2012), for participants to make their decisions without being affected by the increased activation of L1 targets. Indeed, across both experiments, a main effect of language within the N250 window suggests that language membership information was available early in processing.

Taken together, the results across the two experiments presented here support a model in which the more proficient language is postulated to have decreased orthographic precision. They provide an example of how bilingualism can be used to address fundamental questions about visual word processing. They also emphasize the importance of considering all of the dimensions that could vary across languages and highlight the need for careful selection of baseline conditions.

3.11. Acknowledgements

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Chapter 4: An ERP investigation of orthographic precision in deaf and hearing readers

4.1. Abstract

Phonology is often assumed to play a role in the tuning of orthographic representations, but it is unknown whether deaf readers' reduced access to spoken phonology reduces orthographic precision. To index how precisely deaf and hearing readers encode orthographic information, we used a masked transposed-letter (TL) priming paradigm. Word targets were preceded by TL primes formed by reversing two letters in the word and substitution primes in which the same two letters were replaced. The two letters that were manipulated were either in adjacent or non-adjacent positions, yielding four prime conditions: adjacent TL (e.g., *chikcen-CHICKEN*), adjacent substitution (e.g., chidven- *CHICKEN*), non-adjacent TL (e.g., *ckichen-CHICKEN*), and non-adjacent substitution (e.g., *cticfen-CHICKEN*). Replicating the standard TL priming effects, targets preceded by TL primes elicited smaller amplitude negativities and faster responses than those preceded by substitution primes overall. This indicates some degree of flexibility in the associations between letters and their positions within words. More flexible (i.e., less precise) representations are thought to be more susceptible to activation by TL primes, resulting in larger TL priming effects. However, the size of the TL priming effects were virtually identical between groups. Moreover, the ERP effects were shifted in time such that the adjacent TL priming effect arose earlier than the non-adjacent TL priming effect in both groups. These results suggest phonological tuning is not required to represent orthographic information in a precise manner.

4.2. Introduction

Contrary to classic models of visual word recognition, which assumed that each letter was assigned to a specific position within a word (e.g., Coltheart, Rastle, Perry, Langdon, &

Ziegler, 2001; McClelland & Rumelhart, 1981), strong evidence for flexibility in the encoding of letter positions has accrued in recent decades. One of the paradigms that best illustrates this flexibility in orthographic processing is the transposed-letter (TL) priming paradigm. In this paradigm, targets preceded by TL primes (e.g., *chikcen-CHICKEN*) elicit faster lexical decision responses than those preceded by substitution primes (e.g., *chidven-CHICKEN*; e.g., Comesaña, Soares, Marcet, & Perea, 2016; Ktori, Kingma, Hannagan, Holcomb, & Grainger, 2014; Lupker, Perea, & Davis, 2008; Perea & Carreiras, 2006, 2008; Perea & Lupker, 2004). The critical difference between the two types of primes is that TL primes are formed by exchanging two letters that are present in the word and substitution primes are formed by replacing those same letters. If letters were assigned specific positions in a one-to-one fashion, then these two types of primes would be equally similar to the target and should facilitate target recognition to the same extent. Instead, the TL priming effect indicates that letter position coding is more flexible, or less precise, than posited in traditional computational models.

More recent models of orthographic processing can readily account for the TL priming effect. For example, the overlap model posits that letter identities are normally distributed across positions (Gómez, Ratcliff, & Perea, 2008). For example, the *h* in *chicken* would be maximally associated with the second position, to some extent with the adjacent positions (i.e., first and third), and to a lesser extent as distance increases. Position uncertainty is greater for strings that are presented for brief periods of time, as is the case for masked TL primes. This positional uncertainty (i.e., noise) facilitates activation of the target word by TL primes. In contrast, the open bigram model posits that the relative positions of letters are encoded rather than their exact positions (Grainger, 2008; Grainger & van Heuven, 2003; Grainger & Whitney, 2004). For example, the open bigrams for the word *chicken* would be *c-h*, *c-i*, *c-c*, and so on. TL primes share more open bigrams with their targets than substitution primes, which could explain why they facilitate target processing to a greater extent. The dual-route orthographic model (Grainger & Ziegler, 2011) incorporates open bigrams in addition to a more precise route of orthographic processing. Words can be processed along a coarse-grained route, which involves direct access to semantics via a system like open bigrams, or along a fine-grained route, which involves assigning individual letters to precise serial positions. Such precision was deemed necessary in order to phonologically recode a letter string for the purpose of reading aloud. In other words, the level of orthographic precision would be determined by the nature of the task. However, more recent evidence suggests that other factors might determine variations in orthographic precision, and that different tasks simply exploit this variation in order to optimize processing.

The relevant recent evidence here is that orthographic precision varies across word representations (e.g., Lally, Taylor, Lee, & Rastle, 2019; Meade, Mahnich, Holcomb, & Grainger, submitted; Vergara-Martínez, Perea, Gómez, & Swaab, 2013). Numerous factors, including orthographic neighborhood density, determine the way in which any given word is processed. Words (e.g., *fight*) that have many neighbors (e.g., *light*, *tight*) cannot be processed efficiently using coarse-grained representations because they share a large proportion of open bigrams with many other words. In contrast, the open bigrams of words with few neighbors (e.g., *kayak*) are distinct, making it easy to identify them using the coarse-grained route. If words with many neighbors require more precise (i.e., fine-grained) orthographic codes, then they should be less susceptible to activation by TL primes and should produce smaller TL priming effects. Indeed, that is the pattern that we recently observed in the ERP waveform (Meade et al., submitted). In a learning study with an artificial orthography, Lally and colleagues also used TL effects to demonstrate that participants had more precise representations for novel words learned with many anagram "neighbors" compared to those learned without. These studies not only confirm that precision differs across representations, but they also demonstrate that TL manipulations are a useful measure for indexing differences in orthographic precision.

This same approach can be applied to investigate how orthographic precision differs across readers. For example, Andrews and Lo (2012) compared target word processing following TL word and nonword primes (e.g., *colt-CLOT*, *crue-CURE*) versus unrelated word and nonword primes (e.g., *punt-CLOT*, *gine-CURE*) in a large sample of undergraduate students. Irrespective of prime lexicality, participants who had low overall levels of reading proficiency (as assessed by a principal component that included spelling, reading, and vocabulary) showed facilitatory priming (i.e., faster responses for targets preceded by TL primes), and those who had higher levels of reading proficiency showed null or inhibitory effects (i.e., slower responses for targets preceded by unrelated primes). A second principal component that captured additional variance in spelling ability was also related to the direction and size of TL priming effects. Participants who had higher spelling abilities than would be expected based on their reading and vocabulary scores showed even stronger inhibitory effects. Thus, TL priming effects are modulated by individual differences in reading ability, likely reflecting differences in the precision of the underlying representations and the way in which they are accessed.

Note the emphasis in these previous studies on the influence of factors internal to the orthographic system. Here, we widen the scope to examine whether or not phonology also contributes to orthographic tuning. Even though TL priming is thought to be primarily driven by orthographic representations rather than phonological representations (e.g., Acha & Perea, 2010; Perea & Carreiras, 2006, 2008), phonology has been argued to tune orthographic representations over time (e.g., Maurer & McCandliss, 2008; Meade, in press). Indeed, many models of reading assume interactions between orthographic and phonological representations, making it plausible that phonology might impact the nature of orthographic representations. Due to their altered access to the phonology of spoken language and potentially decreased strength in the connections between orthography and spoken phonology used for reading aloud, deaf readers offer a unique opportunity to test the extent to which phonology is involved in the tuning of orthographic representations (Fariña, Duñabeitia, & Carreiras, 2017; Gutiérrez-Sigut, Vergara-Martínez, & Perea, 2017; Meade, Grainger, Midgley, Holcomb, & Emmorey, 2019). Thus, in the present study we used TL priming to compare orthographic precision between hearing readers and deaf readers who had comparable spelling abilities.

Many TL priming studies with hearing readers have included electrophysiological data, which has the added benefit of tracking the time course of the effects and isolating the processing level(s) at which TL primes facilitate target processing (e.g., Carreiras, Duñabeitia, & Molinaro, 2009; Carreiras, Vergara, & Perea, 2009; Grainger, Kiyonaga, & Holcomb, 2006; Ktori et al., 2014; Vergara-Martínez et al., 2013). For example, Grainger and colleagues found that targets preceded by TL primes elicited smaller negativities than those preceded by substitution primes within an early N250 window (200-250 ms) and a late N400 window (450-500 ms) across middle and posterior electrode sites. In general, smaller amplitude negativities are indicative of less effortful processing. Thus, the authors interpreted the N250 effect in terms of facilitated sublexical orthographic processing and the N400 effect as stronger pre-activation of the lexical representations of the target word from TL primes compared to substitution primes (see also, Grainger & Holcomb, 2009). Ktori and colleagues extended these findings by comparing the effects of adjacent and non-adjacent TL primes in an ERP sandwich priming paradigm. Sandwich priming involves brief presentation of the target before the prime, which increases the size of priming effects compared to standard priming in which the target is only presented after the prime (see Lupker & Davis, 2009). The distance between the transposed letters modulated the size of the behavioral priming effect (i.e., larger for adjacent TLs compared to non-adjacent TLs; see also, e.g., Perea, Duñabeitia, & Carreiras, 2008) and the timing of the ERP TL priming effect. The effect lasted from approximately 200 ms to 500 ms in the adjacent condition, whereas it was only significant between 250 ms and 300 ms in the non-adjacent condition. Thus, the onset is delayed and the strength of priming is weaker when the transposition involves non-adjacent letters; the distance that separates the transposed letters determines the effectiveness with which the TL primes activate the target representations.

4.2.1. The present study. In the present study, we used masked adjacent and non-adjacent TL priming to more directly investigate orthographic precision in deaf and hearing readers. Following Ktori et al. (2014), for hearing readers we expected that targets preceded by TL primes would elicit faster responses and smaller negativities within the N250 window than targets preceded by control (substitution) primes. The ERP effect should last longer for adjacent primes compared to non-adjacent primes. Overall, we expected the same qualitative pattern of results in deaf readers. However, if deaf readers have less precise (i.e., more coarse-grained) orthographic codes than hearing readers due to their altered access to phonology (e.g., Bélanger & Rayner, 2015), then they might show larger TL priming effects. The difference between groups should be especially prominent in the non-adjacent condition which requires a greater level of flexibility. In contrast, if the precision of orthographic representations is primarily determined by orthographic factors and robust access to the phonology of the spoken language is not required, then the TL priming effects might be similar between groups.

4.3. Methods

4.3.1. Participants. Data were analyzed from a total of 44 participants who were equally divided between a hearing group (12 F; mean age 32.86 years, *SD* 9.38) and a deaf group (13 F; mean age 34.55 years, *SD* 7.75). All participants in the latter group were severely-to-profoundly deaf and used American Sign Language as their primary means of communication. One participant (age = 29 years) had a late cochlear implant (age of implantation = 28 years). One participant in each group was left-handed, and the remaining participants were right handed. Age was matched between groups, $t(42) = .648$, $p = .520$. Since spelling ability is known to affect the size of TL priming (e.g., Andrews & Lo, 2012), this was also matched between the deaf (mean 71.13, *SD* 8.54) and hearing (mean 71.23, *SD* 8.87) groups using the spelling recognition measure introduced by Andrews and Hersch (2010), $t(42) = -.035$, $p = .973$. Despite close matching on spelling ability, the hearing readers (mean 39.77, SD 3.01) had significantly higher scores on the passage comprehension subtest of the Woodcock Reading Mastery Test–Revised (Woodcock, 1987) than the deaf readers (mean. 33.36, SD 6.45), $t(42) = 4.22$, $p < .001$. An additional four participants were excluded from the deaf group due to high artifact rejection rates (>20% of all trials; N=2), not completing the experiment (N=1), or experimenter error (N=1). Seven additional hearing participants were excluded for high artifact rejection rates (N=6) and experimenter error (N=1).

4.3.2. Stimuli. The critical stimuli consisted of 160 word targets, all of which had singular noun meanings in English (see Table 4.1 for examples). Across participants, each of these targets was paired with four nonword primes: adjacent TL, adjacent substitution, non-adjacent TL, and non-adjacent substitution. In the adjacent TL prime condition, two word-internal adjacent letters were exchanged (i.e., positions 2-3, 3-4, 4-5, or 5-6). Following Ktori and colleagues (2014), the letters exchanged in the non-adjacent condition were separated by two letters (i.e., positions 2-5 or 3-6). There was one “anchor” letter in each target that was transposed in both the adjacent and non-adjacent conditions. For example, the anchor letter in the target *TOASTER* was the ‘A’ in position 3. It was swapped with the ‘O’ in position 2 to get adjacent TL prime *taoster* and with the ‘E’ in position 6 to get non-adjacent TL prime *toestar*. The anchor letter and the adjacent and non-adjacent letters with which it was transposed were all vowels for half of the targets and consonants for the other half of the targets. Substitution prime conditions were developed by replacing the two letters that were transposed with different letters, respecting both the shape and the consonant/vowel status of the letters in the TL primes. None of the primes were real words and for each transposition type (i.e., adjacent and non-adjacent), constrained and unconstrained unigram, bigram, and trigram frequencies of the TL primes and substitution primes were similar, all *p*s > .20 (see, e.g., Frankish & Turner, 2007; Perea & Carreiras, 2008, for evidence that bigram structure influences TL priming effects). An additional 160 pseudoword targets were included for the purposes of the lexical decision task and were not analyzed. Pseudoword targets were preceded by the same four types of primes as the word targets.

Table 4.1. Example stimuli

	Adjacent	**Non-Adjacent**
Substitution	*t**eu**ster-T**OA**STER,* chi**dv**en- *CHI**CK**EN*	*to**u**st**o**r- TO**A**ST**E**R* *c**t**ic**f**en-C**H**IC**K**EN*
TL	*t**ao**ster-T**OA**STER,* *chi**kc**en-CHI**CK**EN*	*to**e**st**a**r-TO**A**ST**E**R,* *c**k**ic**h**en-C**H**IC**K**EN*

Note: Bolding is for the purposes of illustration only.

Two pseudorandomized lists with two presentations of each target (i.e., 320 word trials and 320 pseudoword trials) were created such that half of participants saw any given target word (e.g., *TOASTER*) in the two adjacent conditions (i.e., preceded by TL prime *taoster* and substitution prime *teuster*) and half of them saw it in the two non-adjacent conditions (i.e., preceded by TL prime *toestar* and substitution prime *toustor*). The lists were designed such that every target occurred in both halves of the list; to minimize the confounding effects of target repetition, the lists were presented in forward order to half of participants and in reverse order to the other half of participants. With this counterbalancing scheme, each target appeared an equal number of times in each of the four prime conditions across participants and the critical TL priming comparisons are made within participant on the same target words.

4.3.3. Procedure. The trial structure was similar to the masked sandwich priming paradigm used by Ktori et al. (2014). Each trial began with a purple (--) sign that remained on the screen for 1000 ms, during which participants were instructed to blink. A blank screen was then presented for 300 ms followed by a forward mask composed of nine hashtags (#########) with lines above the central hashtag to indicate fixation for 1000 ms. After the forward mask, the target appeared in uppercase for 30 ms, followed by a lowercase prime for 50 ms, and the second presentation of the uppercase target for 500 ms. On each trial, participants were asked to decide as quickly and accurately whether the stimulus they saw was a real word or a made-up word (i.e., no mention was made of the first presentation of the target or the prime). The subsequent trial began after a response was made with a minimal inter-trial interval of 500 ms. Using a videogame response box, participants pressed a button with their right hand for real words and with their left hand for pseudowords. All stimuli were presented in white Courier font at the center of a black screen such that the targets subtended a visual angle of 2.3 degrees in the horizontal direction.

4.3.4. EEG recording and data analysis. Raw EEG from the 29 electrodes indicated in Figure 1 was amplified with SynAmpsRT amplifiers (Neuroscan-Compumedics) using a bandpass of DC to 100 Hz and sampled continuously at 500 Hz. Impedances were maintained at or below 5 kΩ for scalp electrodes and at or below 2.5 kΩ for the four additional electrodes placed on the mastoids, under 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, whereas the electrode on the right mastoid was used to monitor differential mastoid activity. The electrode located below the left eye was used together with electrodes on the forehead to identify blinks and the electrode next to the right eye was used to identify horizontal eye movements.

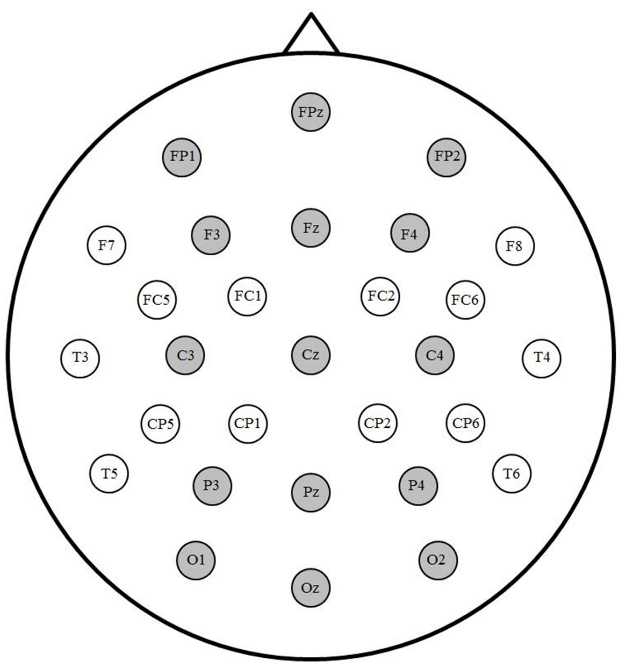

Figure 4.1. Electrode montage. Sites highlighted in gray were included in analyses.

Raw EEG was segmented into 800 ms epochs that were time-locked to target onset, including a 100 ms pre-target baseline. ERPs were calculated by averaging artifact-free segments that had correct 'word' responses between 200 and 2000 ms after target onset. Separate averages were created for each condition and each group at each electrode site and low-pass filtered at 15 Hz. Analyses focused on the 15 representative sites in Figure 1 (see also, e.g., Grainger, Lopez, Eddy, Dufau, & Holcomb, 2012; Meade, Grainger, & Holcomb, 2019; Meade et al., submitted). We measured N250 amplitude between 175 and 300 ms and N400 amplitude between 350 and 550 ms (see also, e.g., Ktori, Midgley, Holcomb, & Grainger, 2015; Massol, Grainger, Dufau, & Holcomb, 2010; Meade, Grainger, & Holcomb, 2019; Meade, Grainger, Midgley, Emmorey, & Holcomb, 2018). We used separate omnibus ANOVAs with factors Group (Deaf, Hearing), Prime (TL, Substitution), Laterality (Left, Midline, Right), and Anterior/Posterior (Prefrontal, Frontal, Central, Parietal, Occipital) to examine effects of adjacent and non-adjacent TL priming on mean N250 and N400 amplitudes. Planned follow-up analyses were also conducted separately for each group. Greenhouse-Geisser correction was applied for all within-subject measures with more than one numerator degrees of freedom. Partial eta squared (η_p^2) is reported as a measure of effect size.

4.4. Results

Behavioral results are presented in Tables 4.2 and 4.3.

Table 4.2. Reaction times in milliseconds [mean (SD)]

	Prime	Hearing Group	Deaf Group
	Substitution	612 (93)	628 (108)
Adjacent	TL	589 (93)	607 (114)
	Priming Effect	*23 ms*	*21 ms*
	Substitution	622 (90)	638 (114)
Non-Adjacent	TL	612 (104)	624 (122)
	Priming Effect	*10 ms*	*14 ms*

Table 4.3. Accuracy in percent correct [mean (SD)]

	Prime	Hearing Group	Deaf Group
	Substitution	95.1 (4.9)	93.5 (5.5)
Adjacent	TL	96.1 (4.6)	94.7 (3.9)
	Priming Effect	*-1.0%*	*-1.2%*
	Substitution	93.9 (5.2)	93.2 (4.4)
Non-Adjacent	TL	94.8 (4.4)	93.8 (3.9)
	Priming Effect	*-0.9%*	*-0.6%*

4.4.1. Adjacent TL priming

4.4.1.1. RTs. A main effect of Prime in the omnibus analysis indicated that targets preceded by adjacent TL primes elicited faster responses than those preceded by adjacent substitution primes, $F(1,42) = 55.56$, $p < .001$, $\eta_p^2 = .57$. The effect did not significantly differ between groups, Group × Prime, $F(1,42) = .07$, $p = .788$, $\eta_p^2 = .00$. In follow-up analyses, the priming effect was significant for the hearing group, $F(1,21) = 32.73$, $p < .001$, $\eta_p^2 = .61$, and the deaf group, $F(1,21) = 23.70$, $p < .001$, $\eta_p^2 = .53$.

4.4.1.2. Accuracy. A significant main effect of Prime in the omnibus analysis indicated that targets preceded by adjacent TL primes elicited more accurate responses than those preceded by adjacent substitution primes, $F(1,42) = 5.05$, $p = .030$, $\eta_p^2 = .11$. The effect did not significantly differ between groups, Group × Prime, $F(1,42) = .06$, $p = .814$, $\eta_p^2 = .00$. It was not significant for either group in separate planned follow-up analyses, both *p*s > .11, perhaps due to limited power.

4.4.1.3. N250. A significant main effect of Prime in the omnibus analysis indicated that targets preceded by adjacent TL primes elicited smaller N250s than those preceded by adjacent substitution primes, $F(1,42) = 11.51$, $p = .002$, $\eta_p^2 = .22$. The effect was strongest at right hemisphere and anterior sites, Prime × Laterality, $F(2,84) = 4.47$, $p = .023$, $\eta_p^2 = .10$, Prime × Anterior/Posterior, $F(4,168) = 6.99$, $p = .004$, $\eta_p^2 = .14$. Neither the main effect of Group nor any of the interactions involving that factor reached significance, all *p*s > .10. Planned follow-up analyses included each group separately. In the hearing group, there was a significant effect of TL priming that was predominantly anterior, Prime × Anterior/Posterior, $F(4,84) = 7.53$, $p = .005$, $\eta_p^2 = .26$ (see Figures 4.2 and 4.3). In the deaf group, a significant main effect of Prime was indicative of a more widespread effect, $F(1,21) = 8.20$, $p = .009$, $\eta_p^2 = .28$ (see Figures 4.2 and 4.3).

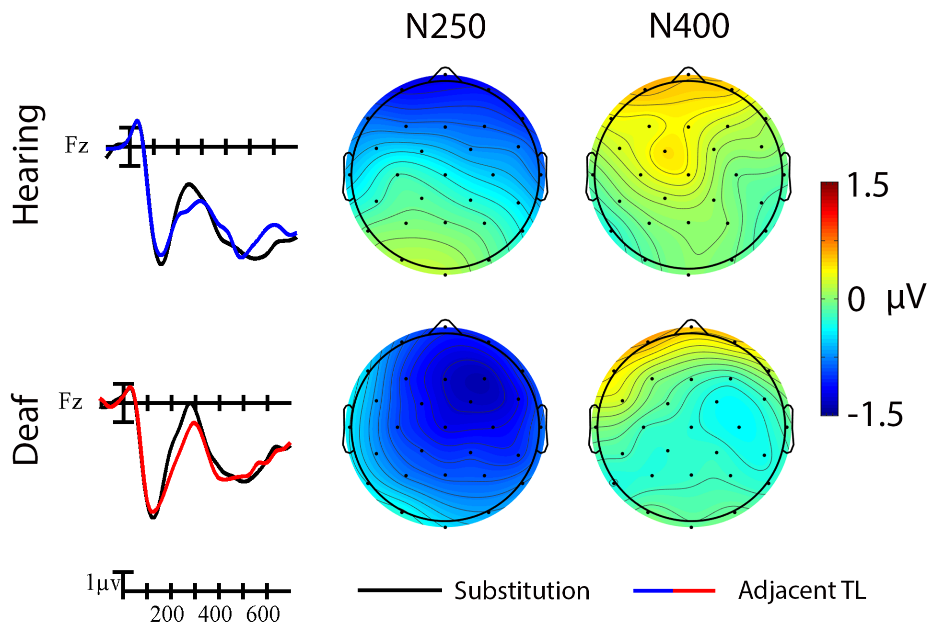

Figure 4.2. The effect of adjacent TL priming for the hearing (top) and deaf (bottom) groups. Grand average waveforms on the left illustrate the time course of the effect at representative anterior site Fz. Targets preceded by TL primes (colored lines) elicited smaller amplitude negativities than those preceded by substitution primes (black lines) when the transposition was adjacent. Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 1 µV. The scalp voltage maps to the right show the distribution of the effects (substitution-TL) within the N250 and N400 windows that were analyzed for each group.

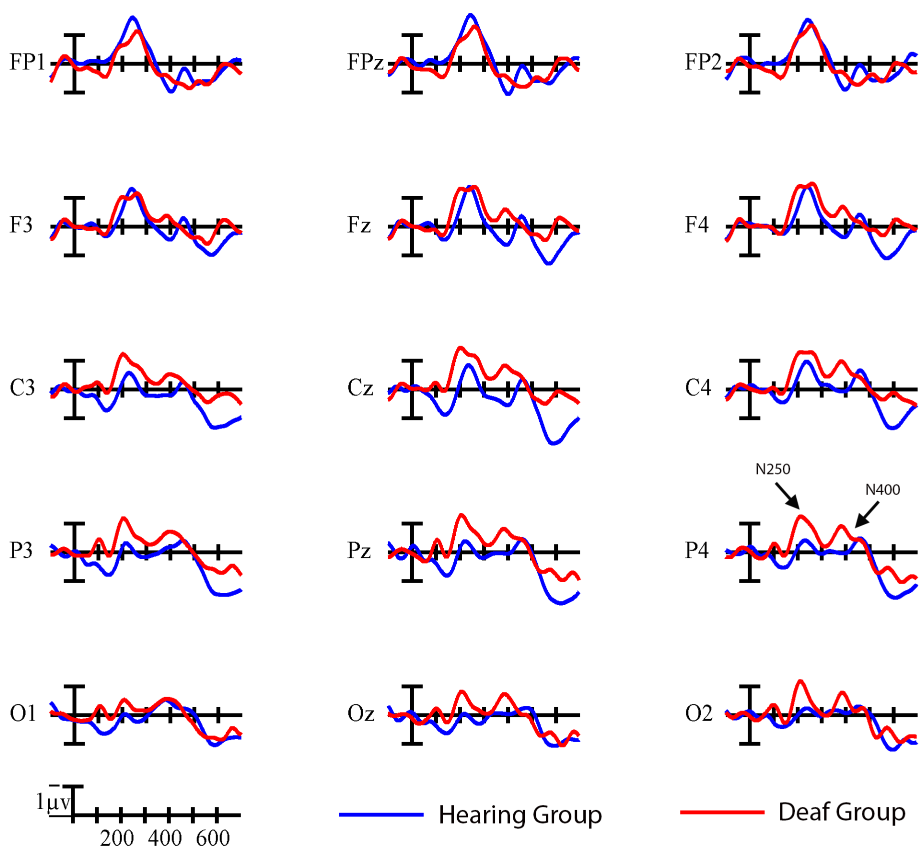

Figure 4.3. Difference waves (substitution-TL) show the relative size of the adjacent TL priming effect over time for the hearing group (blue line) and deaf group (red line). Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 1 µV.

4.4.1.4. N400. There were no significant effects within the N400 window in the omnibus analysis, all *ps* > .07. The absence of significant priming effects held for both the hearing group, all *ps* > .22, and the deaf group, all *ps* > .06 (see Figures 4.2 and 4.3).

4.4.2. Non-adjacent TL priming

4.4.2.1. RTs. A significant main effect of Prime in the omnibus analysis indicated that words preceded by non-adjacent TL primes elicited faster responses than those preceded by non-adjacent substitution primes, $F(1,42) = 9.36$, $p = .004$, $\eta_p^2 = .18$. The effect did not significantly differ between groups, Group × Prime, $F(1,42) = .17$, $p = .679$, $\eta_p^2 = .00$. In follow-up analyses by group, priming was significant for the deaf group, $F(1,21) = 9.81$, $p = .005$, $\eta_p^2 = .32$, but not for the hearing group, $F(1,21) = 2.52$, $p = .127$, $\eta_p^2 = .11$.

4.4.2.2. Accuracy. There was no effect of non-adjacent TL priming in the omnibus analysis or in separate follow-ups by group, all *p*s > .18.

4.4.2.3. N250. In the omnibus analysis, targets preceded by non-adjacent TL primes elicited smaller amplitude N250s than those preceded by non-adjacent substitution primes, especially over right hemisphere electrodes, Prime × Laterality, $F(2,84) = 5.68$, $p = .013$, $\eta_p^2 = .12$. Neither the main effect of Group nor any interactions involving that factor were significant, all *p*s > .16. In the planned follow-up analyses, there were no significant results involving Prime for the hearing group, all *p*s > .11, or the deaf group, all *p*s > .06 (see Figures 4.4 and 4.5).

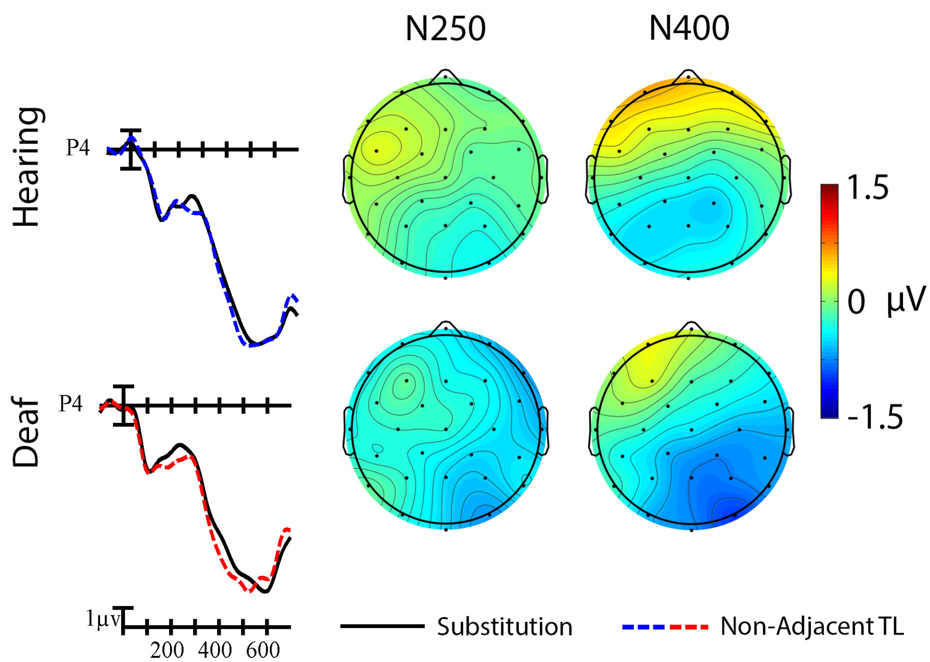

Figure 4.4. The effect of non-adjacent TL priming for the hearing (top) and deaf (bottom) groups. Grand average waveforms on the left illustrate the time course of the effect at representative right posterior site P4. Targets preceded by TL primes (colored lines) elicited smaller amplitude negativities than those preceded by substitution primes (black lines) when the transposition was non-adjacent. Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 1 µV. The scalp voltage maps to the right show the distribution of the effects (substitution-TL) within the N250 and N400 windows that were analyzed for each group.

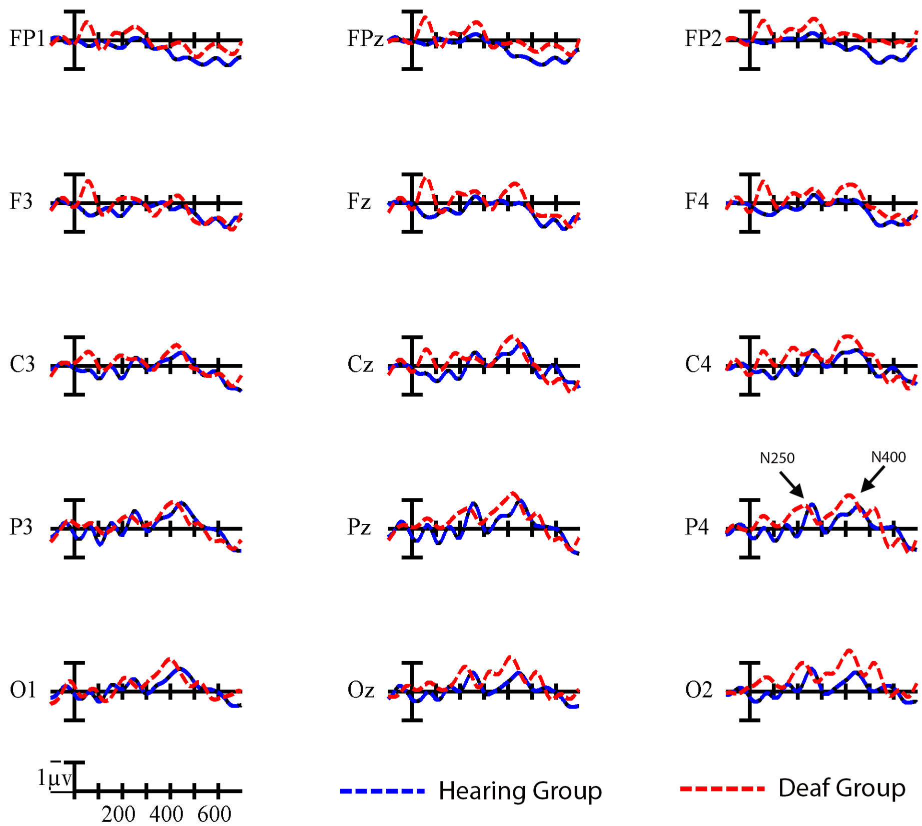

Figure 4.5. Difference waves (substitution-TL) show the relative size of the non-adjacent TL priming effect over time for the hearing group (blue line) and deaf group (red line). Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 1 µV.

4.4.2.4. N400. In the omnibus analysis, targets preceded by non-adjacent TL primes elicited smaller amplitude N400s than those preceded by non-adjacent substitution primes, especially over posterior electrodes, Prime × Anterior/Posterior, $F(4,168) = 9.95$, $p < .001$, $\eta_p^2 = .19$. Neither the main effect of Group nor any interactions involving that factor were significant, all *ps* > .13. In the planned follow-up with the hearing group, a significant Prime × Anterior/Posterior interaction indicated that the priming effect in the expected direction was strongest over posterior electrodes (with a slight reversal over anterior sites), $F(4,84) = 5.28$, $p = .014$, $\eta_p^2 = 20$ (see Figures 4.4 and 4.5). In the deaf group, there was evidence of a similar distribution, Prime × Anterior/Posterior, $F(4,84) = 4.82$, $p = .020$, $\eta_p^2 = .19$ (see Figures 4.4 and

4.5). The effect in the deaf group was also right lateralized, Prime × Laterality, $F(2,42) = 4.31$, $p = .040$, $\eta_p^2 = .17$.

4.5. Discussion

To examine whether or not phonology contributes to the precision with which orthographic representations are accessed or represented, we compared adjacent and non-adjacent TL priming effects between groups of hearing and deaf readers who were matched for age and spelling ability. We reasoned that TL primes should be less effective at activating target words that are represented more precisely compared to those that are represented less precisely (see Meade et al., submitted). If phonology is the primary mechanism by which orthographic representations are tuned, then hearing readers who have robust access to spoken phonology should have a more precise orthographic system, and therefore smaller TL priming effects. In contrast, if orthographic precision is primarily determined by orthographic factors (e.g., orthographic neighborhood density, morphology), then the groups would be expected to have similar levels of precision and similar TL priming effects. The results are more consistent with the latter hypothesis; we found virtually no evidence for any differences between groups in the size of either electrophysiological or behavioral TL priming effects. Both groups showed a similar pattern of TL priming for adjacent transpositions that was more prominent within the N250 window followed by TL priming for non-adjacent transpositions that was more prominent within the N400 window.

The finding that the size of TL priming effects is similar overall between groups suggests that the precision of the orthographic representations and the way in which they were accessed was similar for deaf and hearing readers. The existing evidence regarding how phonology impacts effects of orthographic similarity in deaf versus hearing readers is contradictory. Perea, Marcet, and Vergara-Martínez (2016) argued that deaf readers' weak top-down feedback from lexical phonology makes their orthographic processing different from hearing readers. However, their comparison of case-matched (e.g., REAL-REAL) and case-mismatched (e.g., real-REAL) identity primes does not allow for a strong dissociation between feedback from phonology versus orthography (see Gutiérrez-Sigut, Vergara-Martínez, & Perea, 2019 for ERP evidence of orthographic feedback in deaf readers using the same paradigm). Moreover, the authors compared data acquired from deaf readers against an established finding in the literature, so some factor other than hearing status (and access to phonology) might have confounded the results. In contrast, in a comparison of TL priming effects between skilled deaf and hearing readers who were carefully matched on behavioral measures of reading ability, Fariña et al. (2017) found that both groups were slower and less accurate to reject TL nonwords (e.g., *mecidina*, formed from the Spanish word *medicina*) than substitution nonwords (e.g., *mesifina*) in a lexical decision task. This result suggests that the deaf and hearing readers were similarly sensitive to the relationship between the TL nonwords and the orthographic representations of the corresponding base words, which hindered their ability to reject the TL nonwords. We also recently presented evidence from the masked neighbor priming paradigm to suggest that orthographic precision is surprisingly similar between deaf and hearing readers (Meade, Grainger, Midgley, et al., 2019). The present results support the latter conclusion using a different approach that more directly taps into orthographic precision.

It is worth emphasizing that these data cannot be used to refute the role that phonology may or may not play in tuning orthographic representations in hearing readers. Rather, they indicate that deaf readers achieve a high level of orthographic precision in spite of their altered access to phonology. It is possible that the access to phonology that deaf readers have through speechreading is sufficient to tune their orthographic representations. However, a recent randomized controlled trial found that speechreading training did not benefit word reading for young deaf readers (Pimperton et al., 2019). This finding raises doubts as to the relationship between phonological skills and reading acquisition in deaf children. It is perhaps more likely that deaf readers are using some means other than spoken phonology to tune orthographic representations. American Sign Language (ASL) is the primary means of communication for the deaf readers in this study; it is therefore conceivable that their orthographic representations benefit from associations with fingerspelling (e.g., Emmorey & Petrich, 2012; Stone, Kartheiser, Hauser, Petitto, & Allen, 2015). Another possibility is that readers acquire orthotactic regularities through reading experience and that this knowledge benefits the tuning of orthographic representations. Recent work illustrates that morphology might be one such source of orthographic regularity that benefits reading acquisition (see Rastle, 2019 for a recent review). Deaf readers can readily access the structure provided by morphology, but it might also play a critical role for hearing readers of languages with deeper orthographies. Regardless of the mechanism, the end result of orthographic tuning appears to be similar in both hearing and deaf readers.

More generally, the processes that hearing and deaf readers engage in to recognize visual words appeared to be virtually identical in this study; we failed to find any overall differences between groups (i.e., irrespective of the priming manipulation). This result may be surprising given that English is the less dominant language (L2) for the deaf readers, and L2 word recognition is typically characterized by slower responses and smaller amplitude N400s (e.g., Declerck, Snell, & Grainger, 2018; Midgley, Holcomb, & Grainger, 2009; Soskey, Holcomb, &

Midgley, 2016). However, unlike the hearing unimodal bilinguals in these studies, deaf bimodal bilinguals read in only one of their languages (ASL has no written form).

There has also been some suggestion in the literature that deaf and hearing readers respond differently to visual words. Deaf readers tend to be faster than their hearing counterparts in studies with single word presentation (e.g., Fariña et al., 2017; Morford, Occhibo-Kehoe, Piñar, Wilkinson, & Kroll, 2017), but the opposite effect has emerged across masked priming studies (Bélanger, Baum, & Mayberry, 2012; Cripps, McBride, & Forster, 2005; Meade, Grainger, Midgley, et al., 2019). This pattern led us to hypothesize previously that the enhanced visual reactivity in deaf readers (e.g., Bottari, Caclin, Giard, & Pavani, 2011) might make them more sensitive to the rapid succession of visual stimuli in the masked priming paradigm (see Meade, Grainger, Midgley, et al., 2019). Even though deaf readers were numerically slower on average in the masked sandwich priming paradigm here, following the overall pattern in the literature, the effects of group across analyses were far from significant. In contrast, the absence of a difference in N400 amplitude between deaf and hearing readers appears to be relatively consistent across studies (e.g., Gutiérrez-Sigut et al., 2017; Meade, Grainger, Midgley, et al., 2019).

Finally, only a few ERP studies have included the non-adjacent TL manipulation, so these results are informative with respect to how the distance between the transposed letters modulates the timing of the TL priming effect. In both groups, the bulk of the adjacent TL priming effect occurred within the N250 window, which echoes the onset of similar effects in previous studies (e.g., Grainger et al., 2006; Ktori et al., 2014). There was some hint of a non-adjacent TL priming effect within the N250 window, but it was more prominent within the N400 window. Largely consistent with this pattern, Ktori and colleagues (2014) found earlier and longer lasting effects of TL priming when the transpositions were adjacent compared to when they were non-adjacent in hearing readers. Thus, adjacent TL priming is stronger than non-adjacent TL priming, and this difference can be reflected in amplitude, timing, or both. The greater TL effects seen with adjacent transpositions can be readily accommodated by models that explain TL effects as the result of positional noise, such as the overlap model (Gómez et al., 2008). This pattern also fits with the proposal that TL effects reflect the combined impact of positional noise in fine-grained orthographic representations and the flexibility of coarse-grained orthographic representations in the dual-route model (Grainger & Ziegler, 2011; Ktori et al., 2014).

In conclusion, our investigation of orthographic precision in deaf readers does not support the hypothesis that phonology is critical for determining how orthographic information is represented and processed. Instead, our findings suggest that the precision of orthographic representations is likely to be primarily determined by orthographic factors that would have a similar impact in hearing and deaf readers. One such factor could be orthographic regularities across words, including morphology (see Rastle, 2019). Another prominent candidate is orthographic neighborhood density, with more dense neighborhoods forcing the reading system to use more precise representations (e.g., Grainger, 2008; Lally et al., 2019; Meade et al., submitted). Either of these orthographic pressures could conceivably have a similar impact on deaf and hearing readers and lead to the nearly identical pattern of TL priming results observed here.

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Chapter 5: General Discussion

The primary goal of this dissertation was to build an empirical foundation for understanding the role that precision plays in the orthographic system. Precision was defined as the specificity with which letters are assigned to positions within words. To index precision, I measured differences in the size of behavioral and electrophysiological TL priming effects across representations within the same reader and across readers; words that are represented more precisely are less susceptible to activation by TL primes and should yield smaller TL priming effects. In Chapter 2, I presented novel data to suggest that words from high-density orthographic neighborhoods are represented more precisely than words from low-density orthographic neighborhoods. In Chapter 3, I demonstrated that bilinguals represent words in their two languages with varying levels of precision. Across two groups of bilinguals, I found that words in the less-dominant language are represented more precisely. In Chapter 4, I turned to understanding the role of phonology in modulating precision across readers. However, I did not find strong evidence for differences in precision between deaf and hearing readers who were matched for spelling ability. In what follows, I outline the theoretical ramifications of these data when considered together.

The first important implication of the results presented here is that models must incorporate a mechanism by which precision differs across words within the same reader. Previous TL priming studies have manipulated sublexical variables but have rarely considered how these effects might be modulated by lexical-level factors. In the few existing models that allow for this variability across word forms, the function of precision could not be more different. Whereas models like the lexical quality hypothesis associate precision with the optimal end state of representations, others like the dual-route model associate it with beginning reading and reading aloud. The bilingual data from Chapter 3 converge with evidence from a previous study in which frequency was manipulated (Vergara-Martínez, Perea, Gómez, & Swaab, 2013) to refute the idea that precision is the end goal of the system; if this were the case, then representations that have been encountered more often should have been less susceptible to activation by TL primes. The results are more consistent with a system in which better developed representations have increased flexibility rather than increased precision.

In the original instantiation of the dual-route model, the coarse- and fine-grained processing pathways were proposed to serve different functions. The "good enough" representations along the coarse-grained route were thought to be optimized for silent reading, whereas the phonological encoding along the fine-grained route was associated with reading aloud. The present results suggest that both pathways are utilized in silent reading and that the relative strength of connections along the two routes is influenced by a number of factors. Based on Chapter 3, one such factor could be exposure, with words that are encountered less often having stronger connections along the fine-grained route. Based on Chapter 2, another factor is orthographic neighborhood density. Words that are easy to confuse because they have many orthographic neighbors might also benefit from stronger connections along the fine-grained route. Finally, preliminary comparisons across Chapters 2 and 3 indicate that the task in which participants are engaged also modulates the manifestation of precision. It is worth noting here that these theoretical implications only hold to the extent that TL priming is a reliable index of orthographic precision. Ongoing work that is not included in the dissertation examines this assumption by exploring other paradigms that might tap into orthographic precision and could provide complementary evidence.

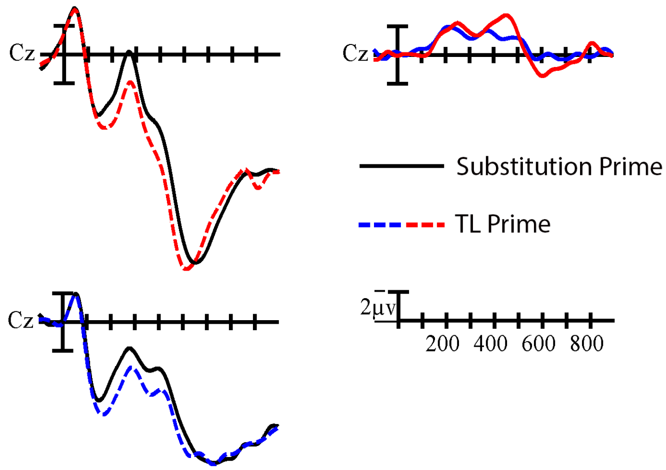

Figure 5.1. Effects of TL priming at representative site Cz for participants from Chapter 2 with the highest (red) and lowest (blue) scores on a spelling recognition measure. The two figures to the left are grand average waveforms for all words preceded by substitution primes (solid) versus TL primes (dotted). On the right, the difference waves (substitution-TL) for each group are superimposed. Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 2 µV.

Turning to the question of what factors modulate orthographic precision across readers, the data presented here do not provide a straightforward answer. In a previous review of the literature, I argued that phonology might contribute to tuning of orthographic representations (Meade, 2020). By extension, I expected that readers who have more robust access to spoken phonology and better phonological skills would have more precise orthographic representations. The remarkable similarity in TL priming effects between deaf and hearing readers who were matched for spelling ability in Chapter 4 contested the argument that phonology plays a fundamental role in tuning orthographic representations. Building on the work on individual differences in visual word processing by Sally Andrews and colleagues (e.g., Andrews & Hersch, 2010; Andrews & Lo, 2012), another possibility is that spelling and reading ability are primary determinants of orthographic precision. To examine this, I conducted post-hoc analyses of the TL priming effects in Chapter 2 with spelling skill as an additional factor. The individuals who participated in this study had a wide range of spelling skill, as indexed by the spelling recognition measure introduced by Andrews and Hersch (2010). In Figure 5.1, I have plotted the

ERP priming effects for the quartiles (N=12) who scored highest and lowest on this measure. Unsurprisingly given how similar the N250 effects for the two groups appear visually, there were no significant interactions including Group and Prime. Interestingly, the difference in the N400 priming effect across skill levels parallels the pattern that I found in bilinguals in Chapter 3; participants who scored higher on the spelling measure appear to show a larger N400 TL priming effect. This difference is not significant, perhaps due to the small sample size and limited power for finding the between-participant interaction. Overall then, it is difficult to conclude that either phonology or spelling ability contribute to orthographic precision in the samples that I measured. However, I caution the reader to interpret these null effects with prudence. Future studies addressing this question might benefit from a more sensitive measure of orthographic precision that increases variability in the size of the effects across individuals or a more exhaustive battery of behavioral measures that accurately captures the abilities of each reader.

5.1. Final Conclusions

To conclude, the results presented in this dissertation demonstrate that precision varies across orthographic representations, but that it is not positively related to exposure or proficiency. Rather, they suggest that precision plays a role in tuning newer representations and is then optimized to maximize the efficiency of word recognition. One example of the latter is maintaining high levels of precision for words that would be easily confused with other representations if more flexible representations were used. This is but one example; future investigations will likely reveal other organizing principles and will lend additional insight into the skills that explain variability in precision across readers.

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