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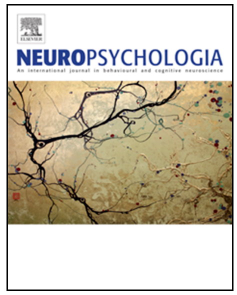

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Running Head: ORTHOGRAPHIC PRECISION IN DEAF READERS

An ERP investigation of orthographic precision in deaf and hearing readers

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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 was 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 that phonological tuning is not required to represent orthographic information in a precise manner.

Keywords: orthographic precision, deaf readers, transposed-letter priming, ERPs

1. 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. Take the overlap model, which posits that letter identities are normally distributed across positions (Gómez, Ratcliff, & Perea, 2008). In this model, 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 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. 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, 2020). 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 recordings, which have 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). This paradigm is commonly used in studies that include a non-adjacent condition since these TL priming effects are difficult to detect in the standard masked priming paradigm. 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.

1.1. 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 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 assesses a greater level of flexibility in orthographic processing. 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. A final possibility is that deaf readers rely more on orthographic processing than their hearing counterparts, which might change how they process the brief presentation of the target preview or prime.

2. Methods

2.1. 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 (ASL) 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 raw 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), $t(42) = 4.22$, $p < .001$.[1] 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 also excluded for high artifact rejection rates (N=6) and experimenter error (N=1).

2.2. Stimuli

The critical stimuli consisted of 160 word targets, all of which had singular noun meanings in English (see Table 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,

[1] After correcting for multiple comparisons, there were no significant correlations between reading and spelling ability and the size of the priming effects that we report below, all *p*s > .40.

all *ps* > .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 1. Example Stimuli

	Adjacent	**Non-Adjacent**
Substitution	*teuster-TOASTER*, chidven- *CHICKEN*	*toustor- TOASTER* *cticfen-CHICKEN*
TL	*taoster-TOASTER*, *chikcen-CHICKEN*	*toestar-TOASTER*, *ckichen-CHICKEN*

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.

2.3. 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.

2.4. 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. 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.

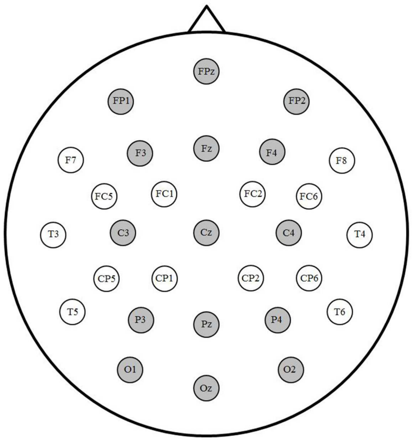

Figure 1. Sites highlighted in gray were included in analyses.

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). 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.

3. Results

Behavioral results for the word trials are presented in Table 2. For comparison, the overall mean reaction time for pseudoword target trials was 718 ms (SD 125 ms) for the hearing group and 732 ms (SD 163 ms) for the deaf group. Overall accuracy for pseudoword target trials was 91.5% (SD 5.0%) in the hearing group and 88.2% (*SD* 11.1%) in the deaf group.

Table 2. Behavioral responses [Mean (SD)]

		Reaction times (ms)		**Accuracy (%)**	
		Hearing	**Deaf**	**Hearing**	**Deaf**
Adjacent	Substitution	612 (93)	628 (108)	95.1 (4.9)	93.5 (5.5)
	TL	589 (93)	607 (114)	96.1 (4.6)	94.7 (3.9)
	Priming Effect	*23 ms*	*21 ms*	*-1.0%*	*-1.2%*
Non-Adjacent	Substitution	622 (90)	638 (114)	93.9 (5.2)	93.2 (4.4)
	TL	612 (104)	624 (122)	94.8 (4.4)	93.8 (3.9)
	Priming Effect	*10 ms*	*14 ms*	*-0.9%*	*-0.6%*

3.1. Adjacent TL priming

3.1.1. RTs. A significant main effect of Prime indicated that targets preceded by adjacent TL primes elicited faster responses than those preceded by adjacent substitution primes, $F1(1,42) = 55.56$, $p < .001$, $\eta_p^2 = .57$, $F2(1,159) = 31.28$, $p < .001$, $\eta_p^2 = .16$. The main effect of Group was only significant in the by-item analysis, $F1(1,42) = 0.31$, $p = .581$, $\eta_p^2 = .01$, $F2(1,159) =$

10.73, p = .001, η_p^2 = .06, and indicated that the deaf group was slightly slower than the hearing group. Finally, the effect of adjacent TL priming on RTs did not differ between groups, Group × Prime, $F1(1,42) = .07$, p = .788, η_p^2 = .00, $F2(1,159) = .02$, p = .897, η_p^2 = .00. Bayesian hypothesis testing (Kass & Raftery, 1995) confirmed that a model including only Prime is more likely to account for the data than the full model that also includes Group and the two-way interaction (BF_{01} = 4.28).[2]

3.1.2. Accuracy. A significant main effect of Prime indicated that targets preceded by adjacent TL primes elicited more accurate responses than those preceded by adjacent substitution primes, $F1(1,42) = 5.05$, p = .030, η_p^2 = .11, $F2(1,159) = 4.31$, p = .040, η_p^2 = .03. The main effect of Group was only significant in by-item analyses, $F1(1,42) = 1.18$, p = .283, η_p^2 = .03, $F2(1,159) = 42.71$, $p < .001$, η_p^2 = .21, and indicated that the deaf group had slightly lower accuracy than the hearing group. The magnitude of the adjacent TL priming effect did not significantly differ between groups, Group × Prime, $F1(1,42) = .06$, p = .814, η_p^2 = .00, $F2(1,159) = 0.07$, p = .789, η_p^2 = .00. In accordance with this, Bayesian hypothesis testing suggested that a model including only Prime is more likely to account for the data than the full model that also includes Group and the two-way interaction (BF_{01} = 4.85)

3.1.3. 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, η_p^2 = .22. The effect was strongest at right hemisphere and anterior sites, Prime × Laterality, $F(2,84) = 4.47$, p = .023, η_p^2 = .10, Prime × Anterior/Posterior, $F(4,168) = 6.99$, p = .004, η_p^2 = .14. Neither the main effect of Group nor any of the interactions involving that factor reached significance, all ps > .10. Bayesian hypothesis

[2] All Bayesian analyses were conducted in JASP with default priors (Morey & Rouder, 2015; Rouder, Morey, Speckman, & Province, 2012; JASP Team, 2020).

testing on mean amplitude at representative electrode Fz (see Figure 2) confirmed that a model including only Prime is more likely to account for the data than the full model that also includes Group and the two-way interaction (BF_{01} = 3.22). 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 2 and 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 2 and 3).

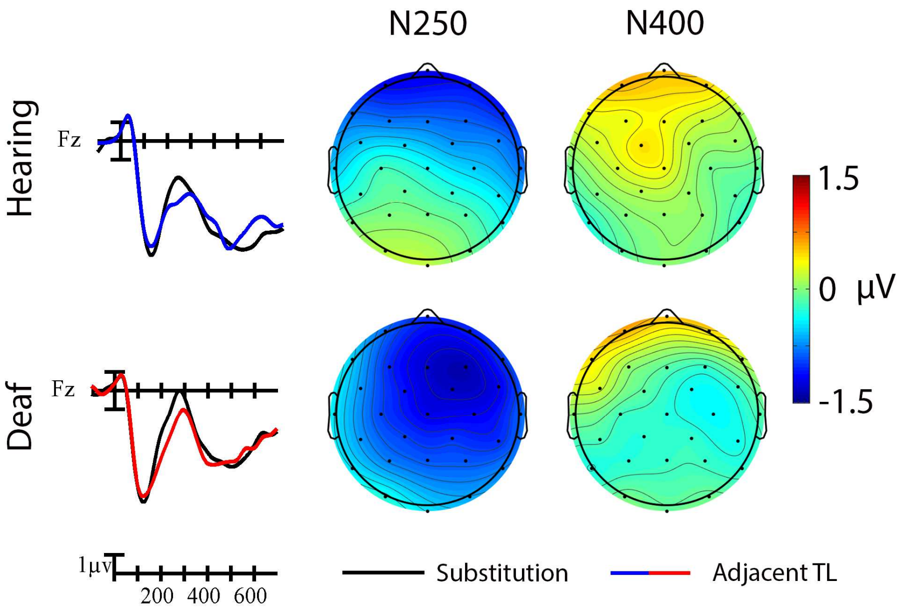

Figure 2. The effect of adjacent TL priming for the hearing (top) and deaf (bottom) groups. Grand average waveforms on the left illustrate the time course of the effect at representative anterior site Fz. Targets preceded by TL primes (colored lines) elicited smaller amplitude negativities than those 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.

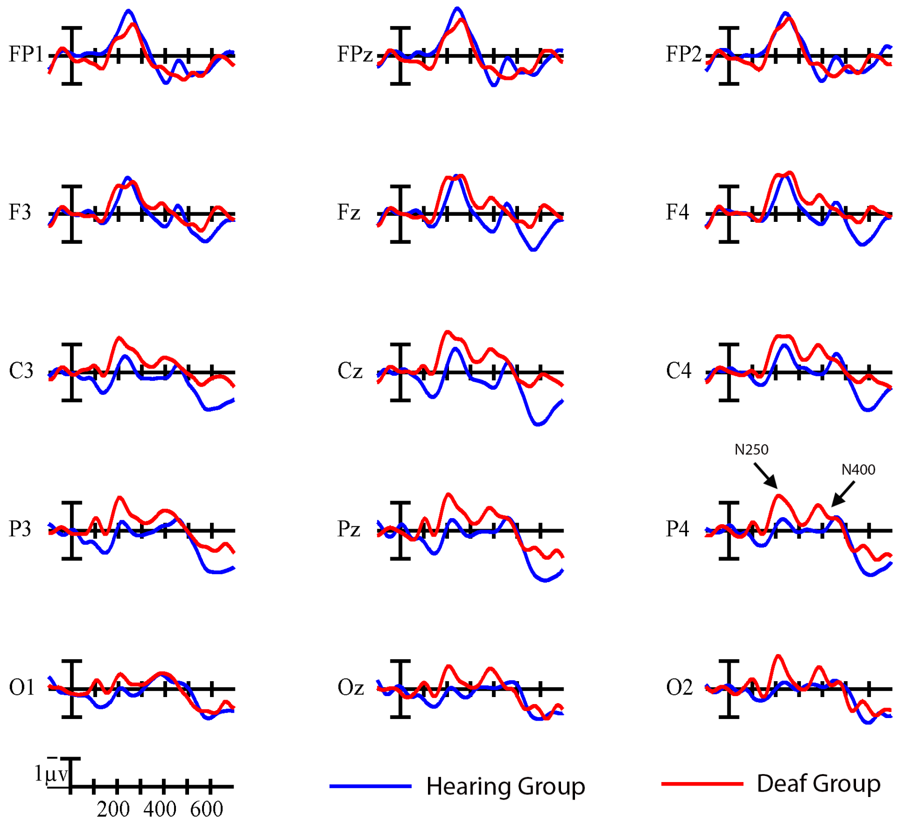

Figure 3. Difference waves (substitution-TL) show the relative size of the adjacent TL priming effect over time for the hearing group (blue line) and deaf group (red line). Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 1 µV.

3.1.4. 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 2 and 3).

3.2. Non-adjacent TL priming

3.2.1. 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, $F1(1,42) = 9.36$, $p = .004$, $\eta_p^2 = .18$, $F1(1,159) = 4.43$, $p = .037$, $\eta_p^2 = .03$. As in the adjacent analyses, the main effect of Group was only significant in the by-item analyses and indicated that the hearing group was slightly faster than the deaf group, *F1*(1,42) = 0.20, *p* = .66, η_p^2 = .00, *F2*(1,159) = 14.17, *p* = .002, η_p^2 = .08. The size of the effect did not significantly differ between groups, Group × Prime, *F1*(1,42) = .17, *p* = .679, η_p^2 = .00, *F2*(1,159) = 0.44, *p* = .508, η_p^2 = .00. Bayesian hypothesis testing confirmed that a model only including Prime was a more likely fit for the data relative to the full model that also included Group and the two-way interaction (BF_{01} = 3.92).

3.2.2. Accuracy. There were no effects of non-adjacent TL priming on accuracy, all *p*s > .13.

3.2.3. 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, η_p^2 = .12. Neither the main effect of Group nor any interactions involving that factor were significant, all *p*s > .16. Bayesian hypothesis testing confirmed that a model including only Prime was a more likely fit for mean N250 amplitude data at representative site P4 (see Figure 4) than the full model that also included Group and the two-way interaction (BF_{01} = 9.27). 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 and 5).

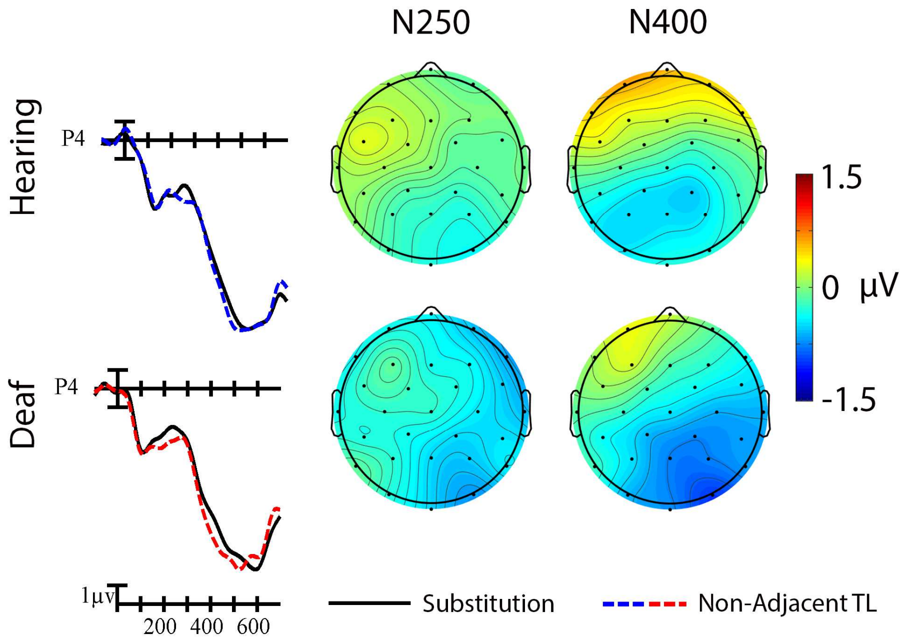

Figure 4. The effect of non-adjacent TL priming for the hearing (top) and deaf (bottom) groups. Grand average waveforms on the left illustrate the time course of the effect at representative right posterior site P4. Targets preceded by TL primes (colored lines) elicited smaller amplitude negativities 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.

3.2.4. 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 *p*s > .13. Bayesian hypothesis testing confirmed that a model including only Prime was a more likely fit for mean N400 amplitude data at representative site P4 (see Figure 4) than the full model that also included Group and the two-way interaction ($BF_{01} = 3.93$). 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 and 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 and 5). The effect in the deaf group was also right lateralized, Prime × Laterality, $F(2,42) = 4.31$, $p = .040$, $\eta_p^2 = .17$.

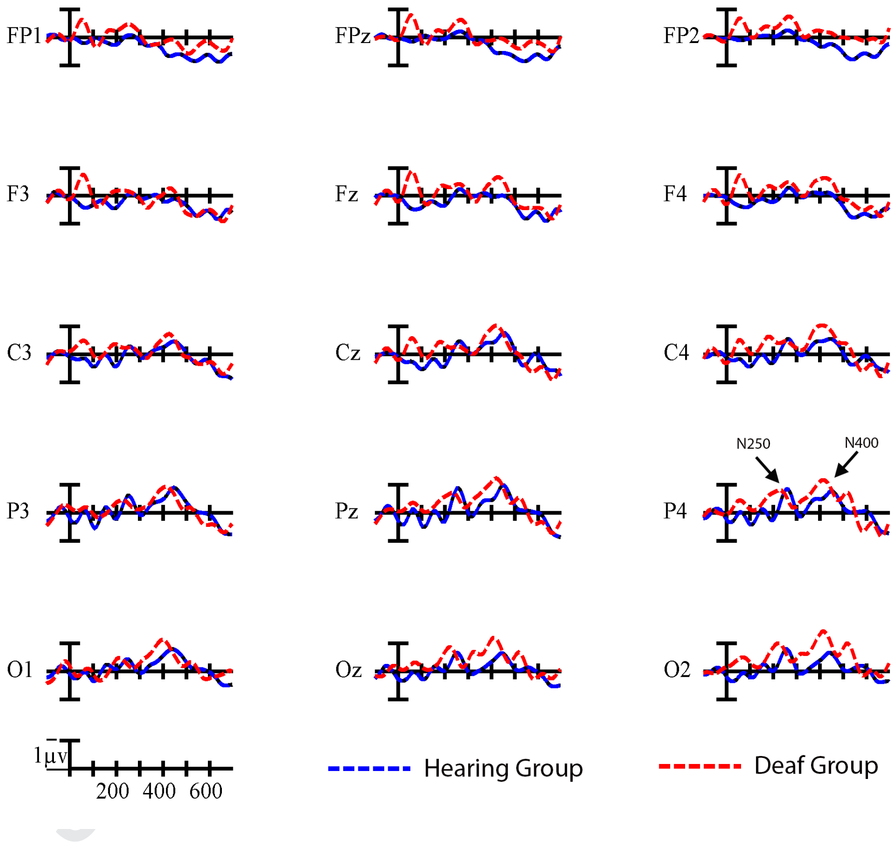

Figure 5. Difference waves (substitution-TL) show the relative size of the non-adjacent TL priming effect over time for the hearing group (blue line) and deaf group (red line). Each vertical tick marks 100 ms and negative is plotted up. The vertical line marks target onset and the calibration bar marks 1 µV.

4. 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), which 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. Given that American Sign Language (ASL) is the primary means of communication for the deaf readers in this study, it is 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, and 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 the hearing and deaf readers tested here.

More generally, the processes that hearing and deaf readers engage in to recognize visual words appeared to be virtually identical in this study; we found minimal evidence of 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 distracted by the rapid succession of visual stimuli in the masked priming paradigm (see Meade, Grainger, Midgley, et al., 2019). There was some evidence for that hypothesis here; deaf readers were slower (and less accurate) than hearing readers, but the effects were only significant in by-item analyses. This pattern is especially noteworthy given that our masked sandwich priming paradigm involved a brief preview of the target before the prime and target. In contrast to behavioral differences, 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, duration, 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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- Adjacent and non-adjacent transposed-letter priming assessed orthographic precision
- Deaf and hearing participants were matched for age and spelling ability
- No significant differences between groups in behavioral, N250, or N400 priming
- Adjacent priming occurred earlier than non-adjacent priming in both groups
- Spoken phonology is not a requirement for orthographic tuning