Neuropsychologia 177 (2022) 108420

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

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

Brittany Lee[a,*], Priscilla M. Martinez[b], Katherine J. Midgley[c], Phillip J. Holcomb[c], Karen Emmorey[c]

[a] Joint Doctoral Program in Language and Communicative Disorders, San Diego State University & University of California, San Diego, United States
[b] San Diego State University Research Foundation, United States
[c] San Diego State University, United States

ARTICLE INFO

Keywords:
ERPs
Deaf readers
Phonology
Orthography
Word processing

ABSTRACT

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

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

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

☆ This project was preregistered. Preregistration as well as data and materials are openly available at the project's Open Science Framework page: osf.io/9db3n. We have no conflicts of interest to disclose. Funding sources were not involved in study design; data collection, analysis, or interpretation; writing the research report; or the decision to submit the article for publication. Data and interpretations appearing in this manuscript were presented at the 61st Annual Meeting of the Psychonomic Society, the 28th Annual Meeting of the Society for the Scientific Study of Reading, and as part of Brittany Lee's doctoral dissertation.

* Corresponding author. Laboratory for Language and Cognitive Neuroscience, 6495 Alvarado Road, Suite 200, San Diego, CA, 92120, United States.
E-mail address: brittany.lee@yale.edu (B. Lee).

https://doi.org/10.1016/j.neuropsychologia.2022.108420
Received 26 May 2022; Received in revised form 28 September 2022; Accepted 7 November 2022
Available online 15 November 2022

Nielsen and Luetke-Stahlman, 2002), while others indicate they do not (Clark et al., 2016; Costello et al., 2021; Miller and Clark, 2011; Izzo, 2002; Mayberry et al., 2011; Farina et al., 2017; Bélanger et al., 2012; Bélanger et al., 2013).

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

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

One question that remains for hearing readers (and perhaps for deaf readers too) is how phonological and orthographic routes interact at the sublexical and lexical levels. For hearing readers, phonology may play a supporting role along the orthographic route to word recognition by tuning or stabilizing orthographic representations (Maurer and McCandliss, 2008; Sacchi and Laszlo, 2016), but this may not be the case for deaf readers (Emmorey et al., 2017). TL studies that also manipulate pronunciation allow us to examine this hypothesis. Pronounceable TL nonwords (barve) abide by the phonotactic and orthotactic rules of English, whereas unpronounceable TL nonwords (brvae) contain sound and letter combinations that are not permissible. Phonology and orthography are generally conflated in English, so studying pronounceability effects in readers that differ in their phonological awareness can help distinguish the unique contributions of phonological versus orthographic constraints on word recognition.

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

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

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

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

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

Third, we also conducted correlational analyses to determine if the size of the ERP effects or the behavioral measures (accuracy, RT) were modulated by reading ability, spelling ability, or phonological awareness. If pronounceability effects depend on access to phonology, they may correlate with phonological awareness for hearing readers but not (or to a lesser extent) for deaf readers. If pronounceability effects are based on orthographic sensitivity, the size of the ERP effects may correlate with spelling ability for both groups.

1. Methods

1.1. Participants

This study included 20 deaf participants (11 f; mean age 33 years) and 20 hearing participants (12 f; mean age 29 years). Deaf participants were severely or profoundly deaf and reported using ASL as their primary and preferred language. All deaf participants became deaf by the age of two, and 16 participants were deaf from birth. Five deaf participants were native signers (acquired ASL from birth), and 15 were early signers (acquired ASL before the age of seven). Hearing participants reported being monolingual English speakers with no exposure to another language before the age of seven. All participants were over the age of 18, reported no history of neurological disorders, and had normal or corrected-to-normal vision. Four deaf participants and three hearing participants were left-handed. One additional hearing participant and two deaf participants were run in the study but were excluded from analyses due to low accuracy on word trials (below 75% correct "yes" decisions), and three additional hearing participants were excluded due to a high proportion of critical trials contaminated by artifact (over 20%). All participants signed consent forms in accordance with the Institutional Review Board at San Diego State University and were compensated for their time.

Prior to the experiment, participants took behavioral tests for the purposes of group matching and planned correlational analyses. The deaf and hearing groups were matched on nonverbal intelligence as measured by the Kaufman Brief Intelligence Test - 2 (KBIT-2) (Kaufman and Kaufman, 2004), $t(38) = -0.07$, $p = 0.94$, and reading level as measured by the comprehension subtest of the Peabody Individual Achievement Test-Revised (PIAT-R) (Markwardt, 1989), $t(38) = 0.43$, $p = 0.67$ (see Table 1). Deaf readers were better spellers than hearing readers, as measured by a Spelling Recognition Test (Andrews and Hersch, 2010), $t(38) = 1.85$, $p = 0.01$. The hearing group had significantly better phonological awareness compared to the deaf group as measured by the Phonological Awareness Tests developed by Hirshorn et al. (2015), which were specially designed for testing deaf adults, $t(38) = 3.65$, $p < 0.001$.

Table 1
Nonverbal Intelligence and English Language Skills for Deaf and Hearing Participants (mean (SD)).

Group	Nonverbal Intelligence	Reading Comprehension	Spelling Recognition	Phonological Awareness
	Out of 46	Out of 100	Out of 88	Out of 100
Deaf Readers (N = 20)	38.75 (4.69)	87.55 (7.29)	77.60 (6.59)	70.68 (14.68)
Hearing Readers (N = 20)	38.85 (4.03)	85.63 (6.32)	70.45 (9.24)	85.95 (11.62)

1.2. Stimuli

The stimuli consisted of a total of 225 critical trials: 75 words, 75 pronounceable TL nonwords, and 75 unpronounceable TL nonwords. All words and nonwords contained five letters. Nonwords were created by transposing either the second and third letters or the third and fourth letters of the 75 real words. The pronounceability of nonwords was determined through a norming study taken by 20 hearing monolingual speakers on Mechanical Turk. Participants were asked to rate the nonwords using a four-point scale (1 = not pronounceable at all, 4 = totally pronounceable). Nonwords with ratings of 1 from at least 80% of the participants were deemed unpronounceable, and nonwords with ratings of 4 from at least 80% of the participants were deemed pronounceable. Only words (e.g., brave) whose letter transpositions yielded both a pronounceable (e.g., barve) and unpronounceable (e.g., brvae) nonword were selected for critical trials in the experiment. Twenty-five filler words were added to achieve a 2:3 ratio of words to nonwords. Thus, participants saw a total of 250 trials, but only the 225 critical trials were analyzed. A complete list of stimuli is available at osf.io/9db3n.

In order to make the lexical decision more difficult, for each trial, the stimulus was displayed for 70 ms and followed by a mask for 300 ms. The mask was made up of jumbled letter fragments. Stimulus duration was determined though a pilot study to ensure both groups would be able to perceive the stimuli and yield comparable error rates on the lexical decision task. Frankish and Turner (2007) used a 40 ms stimulus duration, which yielded 94% accuracy on words and 60% accuracy on nonwords. Our pilot study indicated that similar accuracy on words (92% for deaf readers; 93% for hearing readers) and nonwords (65% for deaf readers; 47% for hearing readers) could be achieved with a 70 ms stimulus duration in our study. A blank screen was then displayed until the participant responded. A purple fixation cross was displayed for 1500 ms between trials, followed by a white fixation cross for 500 ms to indicate that the next trial was coming up.

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

1.3. Procedure

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

Following the experiment, participants completed an offline stimulus visibility task. Five-letter real words were presented with the same masking as in the experiment at durations between 20 and 150 ms by increments of 10 ms, with five trials at each duration. Hearing participants read the words aloud, and deaf participants provided the ASL translation for words that they were able to perceive. This task ensured that all participants able to perceive stimuli presented at 70 ms (the duration chosen for the experiment).

1.4. EEG methods

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

1.5. Analyses

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

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

2. Results

2.1. Behavioral results

2.1.1. Post-experiment stimulus visibility task

The post-experiment stimulus visibility task indicated that all participants were we able to perceive stimuli with a 70 ms duration. We also calculated both the minimum duration at which each participant accurately named at least one stimulus, as well as the minimum duration at which they named stimuli accurately across all five trials. On average, the lowest possible duration perceived was 23 ms for deaf participants and 30 ms for hearing participants, $t(38) = -2.1$, $p = 0.04$. The lowest duration that was perceived consistently across trials by deaf participants was 29 ms and 40 ms by hearing participants, $t(38) = -1.96$, $p = 0.06$. Ten of the deaf participants perceived 100% of the stimuli across all durations compared to only five of the hearing participants.

2.1.2. Lexicality

Behavioral results are presented in Fig. 1. For the lexicality analysis, there was a main effect of Group, $F(1, 38) = 8.54$, $p = 0.01$, $\eta_p^2 = 0.18$, with deaf participants (82%) responding more accurately overall compared to hearing participants (72%). There was also a main effect of Lexicality, $F(1, 38) = 138.47$, $p < 0.001$, $\eta_p^2 = 0.78$, with participants

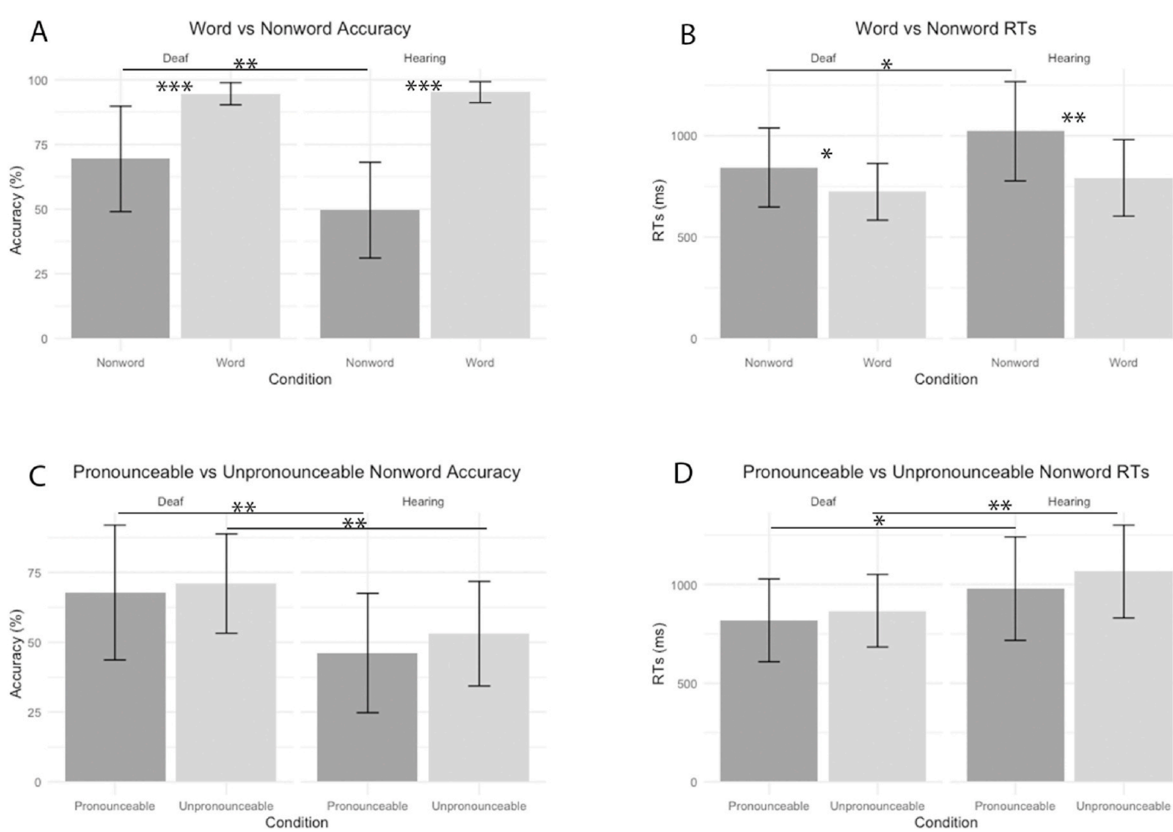

Fig. 1. behavioral effects of lexicality and pronounceability on accuracy and RTs for deaf and hearing readers.

responding more accurately to words (95%) compared to nonwords (60%). Finally, there was a Group × Lexicality interaction, $F(1, 38) = 11.5$, $p < 0.002$, $\eta_p^2 = 0.23$. The difference in accuracy between words and nonwords was greater in the hearing group, who were only performing at chance on nonword trials.

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

2.1.3. Nonword pronounceability

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

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

2.2. ERP results

2.2.1. Lexicality

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

2.2.2. Nonword pronounceability

The pronounceability ERP effects for all participants are shown in Fig. 3. There was no effect of pronounceability on the N250 component, all *ps* > 0.09. However, the omnibus test for the N400 effect yielded a main effect of Pronounceability, with pronounceable nonwords producing greater negativities than unpronounceable nonwords, particularly at more posterior sites, $F(1, 38) = 14.56$, $p = 0.001$, $\eta_p^2 = 0.28$, Pronounceability × Anterior/Posterior, $F(4, 152) = 7.01$, $p < 0.001$, $\eta_p^2 = 0.16$. There were no interactions with Group.

2.3. Correlations

Pearson correlations were used to identify associations between various reading skills, behavioral measures, and ERP effects. ERP difference waves were calculated (mean amplitude of nonwords minus words for the Lexicality effect and pronounceable nonwords minus unpronounceable nonwords for the Pronounceability effect) for each of the 15 analyzed sites. Correlations were performed with measures of reading ability, spelling ability, and phonological awareness for the N250 Lexicality effect, the N400 Lexicality effect, and the N400 Pronounceability effect as well as accuracy and RTs on the lexical decision task. Correlations were corrected for multiple comparisons using false discovery rate (FDR) corrections (Groppe et al., 2011). We conducted separate FDR analyses for each ERP window and behavioral test (e.g., the *p*-values for the 15 correlations between N250 lexicality mean amplitude and spelling ability in one FDR analysis).

For hearing readers, spelling ability was strongly correlated with lexical decision accuracy ($r = 0.57$, $p = 0.02$) and with nonword rejection accuracy ($r = 0.55$, $p = 0.02$). For deaf readers, spelling ability was also strongly correlated with lexical decision accuracy ($r = 0.68$, $p =$

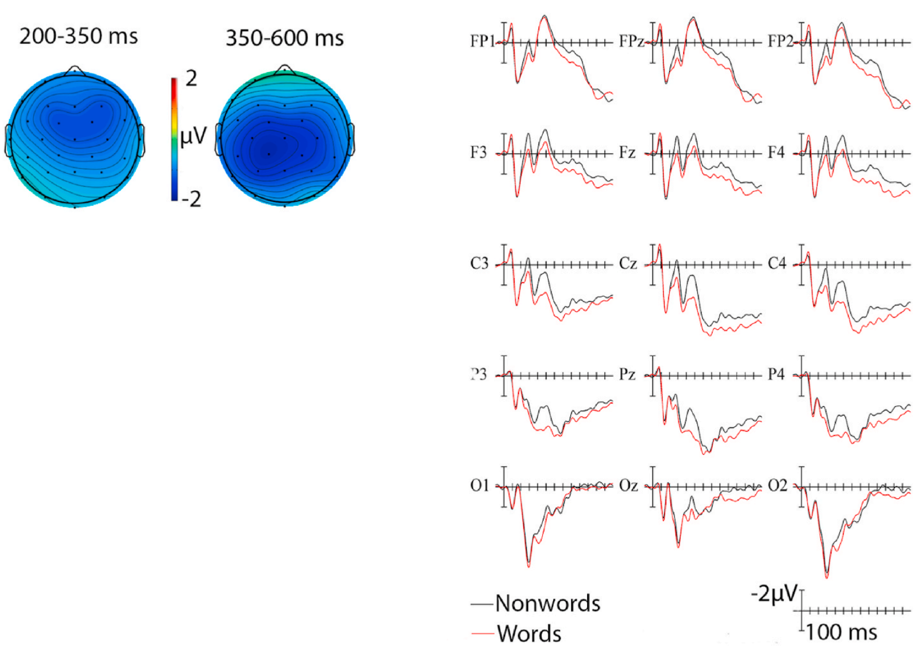

Fig. 2. Lexicality N250 and N400 effects for deaf and hearing readers combined.

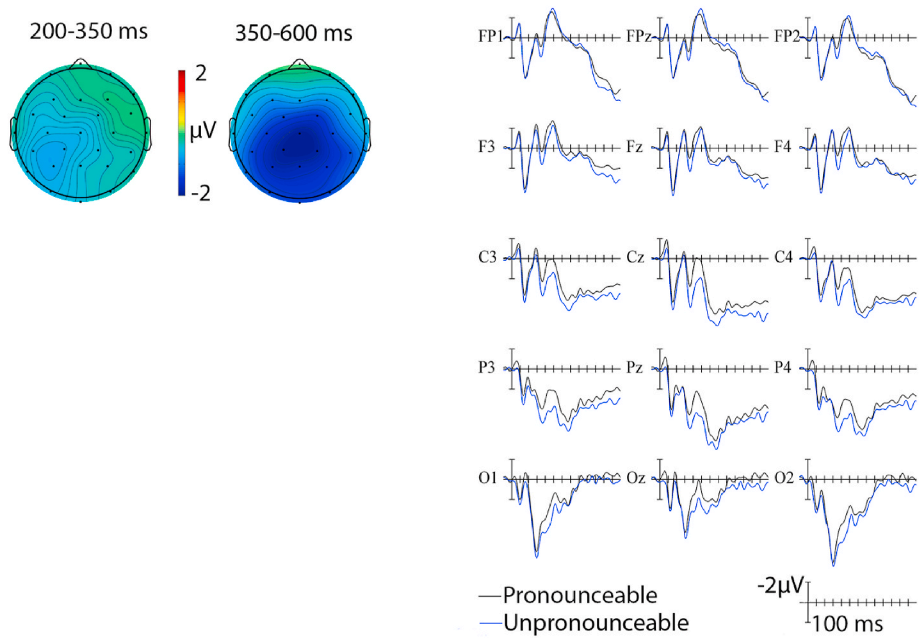

Fig. 3. Pronounceability N250 and N400 effects for deaf and hearing readers combined.

0.001) and with nonword rejection accuracy ($r = 0.65$, $p = 0.002$) (see Fig. 4). Spelling ability was negatively correlated with RTs for nonword trials in the deaf group only ($r = -0.54$, $p = 0.01$). None of the ERP effects correlated with reading ability, spelling ability, or phonological awareness for either group, all $ps > 0.25$.

Fisher transformations were performed to compare correlations between groups. An observed z value of 0.50 confirmed that there was no significant difference in the correlation between spelling ability and lexical decision accuracy for the deaf and hearing groups. Similarly, an observed z value of 0.45 confirmed that there was no significant difference in the correlation between spelling ability and nonword rejection accuracy for the deaf and hearing groups.

3. Discussion

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

Half of the TL nonwords in this experiment were pronounceable (i.e., orthotactically/phonotactically legal) and half were unpronounceable (i.e., orthotactically/phonotactically illegal). Behaviorally, both deaf and hearing readers responded more accurately to unpronounceable nonwords compared to pronounceable nonwords. This result goes in the opposite direction of the pronounceability effect in Frankish and Turner (2007) and may be due to a speed-accuracy trade off in our experiment, since participants were also slower to respond to unpronounceable than pronounceable nonwords. Pronounceable nonwords are more word-like, so they showed greater activation as plausible candidates for lexical access and participants were more likely to quickly and incorrectly conclude that they were words. Unpronounceable nonwords are less word-like, so they showed less activation, which may have led to slower RTs, and participants were more likely to accurately reject them. It is also possible that methodological differences across experiments led to the discrepancy in results (e.g., differences in masks, stimulus duration and presentation, etc.). Deaf readers were faster and more accurate in their nonword decisions than hearing readers, but they were similar in their (in)sensitivity to nonword pronounceability.

In terms of ERPs, we observed similar lexicality effects on the N250

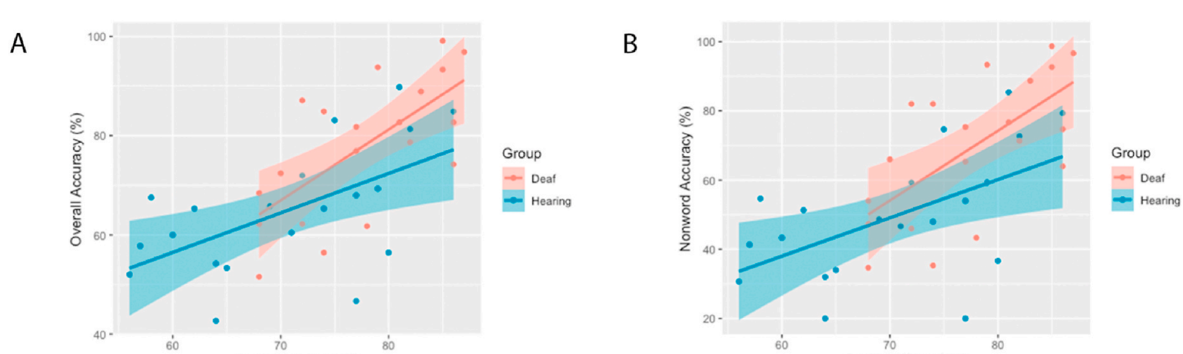

Fig. 4. Correlations between accuracy and spelling ability in deaf and hearing readers.

and N400 (greater negativities for nonwords than words) for both deaf and hearing readers. Because there was no evidence of an interaction between Group and Lexicality, we conducted Bayesian null hypothesis analyses (e.g., Rouder et al., 2009) to statistically examine whether there was evidence in favor of the null hypothesis (i.e., that there was no difference in the Lexicality effect between groups). Cz was selected as a representative electrode for the effect, and results showed only weak evidence favoring the null hypothesis over the alternative hypothesis (BF01 = 2.43 in the N250 window and BF01 = 2.31 in the N400 window) (Kass and Raftery, 1995). It is therefore difficult to conclude whether there were truly no differences in the lexicality effect for deaf compared to hearing readers in the current study. However, Gutierrez-Sigut et al. (2022) reported no group differences in the lexicality effect for deaf and hearing readers, and we had no a priori reason to expect that this effect would differ between the two groups.

There were no ERP N250 effects of pronounceability, but there was an N400 effect, with pronounceable nonwords eliciting larger amplitude negativities than unpronounceable nonwords for both groups. Contrary to our hypothesis that pronounceability is driven by sublexical orthotactic and phonotactic structure, it appears that these constraints affected lexical-level processing for both deaf and hearing readers. We again performed Bayesian null hypothesis analyses for the group interaction in the N400 window for the Pronounceability effect with Cz as a representative electrode. Results showed moderate evidence favoring the null hypothesis (i.e., that there was no difference in the pronounceability effect between groups) over the alternative hypothesis (BF01 = 3.30); the null hypothesis was three to four times more likely to hold than the alternative hypothesis. This result supports our conclusion that the pronounceability effect did not differ for deaf and hearing readers. Because deaf and hearing readers differ in their phonological awareness, the lack of group differences leads us to believe that the pronounceability N400 effect was driven by sensitivity to lexical-level orthotactic structure. This result is consistent with the lack of correlation between phonological awareness and ERP or behavioral effects and with the correlations between spelling and accuracy for deaf and hearing readers. Fisher transformations showed no significant difference in these correlations between groups, suggesting that orthography played an important role for both deaf and hearing readers.

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

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

Another possible explanation for the larger amplitude N400s for pronounceable compared to unpronounceable nonwords is that pronounceable nonwords are more plausible candidates for lexical access. Because they conform to orthographic and phonological constraints of English, they are more word-like and are more likely to be mistaken for words. They may incite activation that is unresolved when no lexical entry is found, resulting in larger amplitude N400s compared to unpronounceable nonwords. In contrast, unpronounceable nonwords were more accurately rejected because they clearly violate such constraints and may be treated similarly to random consonant strings, which have been shown to generate smaller N400s than words or pronounceable nonwords (Holcomb and Neville, 1990). Because they are less plausible candidates for lexical access, they demand less activation, and thus the N400 response is less pronounced. Unpronounceable nonwords may show smaller amplitude N400s not because they are being processed as real words (i.e., they were autocorrected), but because that they are so *unlike* words that they do not generate a big N400.

Finally, an important finding of this study is that deaf readers were far faster (by 172 ms) and more accurate (by 19%) at classifying nonwords compared to hearing readers, even though English is their second language. These behavioral results are consistent with a number of studies that show faster lexical and semantic word decisions for deaf compared to hearing readers (Clark et al., 2016; Morford et al., 2017, 2019; Villwock et al., 2021). Deaf readers may have had an advantage in processing TL nonwords because they may have advantages in visual attention and processing (see Pavani and Bottari, 2012 for review). Data from the post-experiment stimulus visibility test revealed greater sensitivity for the deaf group, with lower and less variable visibility thresholds, despite being slightly older (M = 32 years; SD = 6) than the hearing group (M = 28 years; SD = 7), $t(38) = 2.18$, $p = 0.04$. This difference in visibility threshold suggests that deaf participants may have had more robust or earlier visual access to the stimuli compared to hearing participants. There is also evidence that deaf readers are more sensitive to the visual features of words (i.e., outline shape) compared to hearing readers (Gutierrez-Sigut et al., 2022). Although speculative, one possible explanation for faster and more accurate responses among deaf readers in the current study could be that they may need less visual information to process visual word forms compared to hearing readers.

Faster lexical decisions for deaf readers could also be due to more efficient orthographic-semantic links (Bélanger and Rayner, 2015; Emmorey et al., 2016; Costello et al., 2021; Gutierrez-Sigut et al., 2019; Meade et al., 2019; Morford et al., 2017). In bypassing the phonological route to word recognition, deaf readers avoid activation of phonological competitors for lexical access. Thus, the orthographic route to word recognition is more efficient (Grainger and Ziegler, 2011) and may accelerate word reading and lexical decisions. In the current study, the deaf group had better spelling ability than a hearing group with comparable reading abilities, and spelling ability was negatively correlated with RTs for nonword trials in the deaf group (i.e., better spellers responded faster). These two possible explanations (enhanced early visual processing and efficient orthographic-semantic links) are not mutually exclusive. It should also be noted that hearing readers of languages with opaque orthographies like English may rely more on a direct orthographic-to-semantic route for visual word recognition compared to hearing readers of languages with transparent orthographies like Spanish, for whom the orthographic-to-phonological route is more accessible. However, skilled deaf readers do not rely on a phonological mediation in languages with opaque (e.g., Bélanger et al., 2013; Mayberry et al., 2011) or transparent orthographies (e.g., Bélanger et al., 2012; Costello et al., 2021; Fariña et al., 2017). We might therefore expect to see greater differences between deaf and hearing groups in pronounceability effects and stronger correlations with phonological awareness in hearing readers if this study were repeated in a language with a transparent orthography.

In conclusion, this study investigated how lexicality and pronounceability affect word processing for deaf and hearing readers. As expected, we found classic behavioral and ERP effects of lexicality that were similar across groups. Counter to our predictions, effects of pronounceability also appeared similar across groups and were seen in the N400 rather than the N250 window. Although the ERP data indicated that words and nonwords were processed similarly across groups, behavioral differences indicated that deaf readers had an advantage in making lexical decisions and in rejecting TL nonwords. We suggest that this advantage may be due to a heightened sensitivity to the visual-orthographic make up of words and tighter orthographic-to-semantic connections for deaf readers that support an orthographic route to word recognition that is not phonologically mediated. Future studies may wish to further explore how visual and orthographic processes interact to support efficient word processing and reading skill in deaf readers.

Credit author statement

Brittany Lee: data curation, methodology, investigation, formal analysis, validation, visualization, writing – original draft preparation, writing – review and editing, **Priscilla M. Martinez**: data curation, investigation, writing – original draft preparation, **Katherine J. Midgley**: data curation, methodology, formal analysis, funding acquisition, project administration, resources, software, supervision, validation, writing – review and editing, **Phillip J. Holcomb**: data curation, methodology, formal analysis, funding acquisition, project administration, resources, software, supervision, validation, writing – review and editing, **Karen Emmorey**: conceptualization, methodology, funding acquisition, project administration, resources, supervision, validation, writing – review and editing.

Data availability

The data are available on OSF through the link provided.

Acknowledgments

The authors wish to thank Cindy O'Grady Farnady, Mathieu Declerck, and all the participants, without whom this project would not have been possible. We gratefully acknowledge funding from National Science Foundation grants BCS-1651372 and BCS-1756403. BL was also supported by National Institutes of Health National Institute on Deafness and Other Communication Disorders award T32 DC017703.

References

Andrews, S., Hersch, J., 2010. Lexical precision in skilled readers: Individual differences in masked neighbor priming. J. Exp. Psychol. Gen. 139 (2), 299. https://doi.org/10.1037/a0018366.

Aparicio, M., Gounot, D., Demont, E., Metz-Lutz, M.N., 2007. Phonological processing in relation to reading: an fMRI study in deaf readers. Neuroimage 35 (3), 1303–1316. https://doi.org/10.1016/j.neuroimage.2006.12.046.

Bélanger, N.N., Baum, S.R., Mayberry, R.I., 2012. Reading difficulties in adult deaf readers of French: phonological codes, not guilty. Sci. Stud. Read. 16 (3), 263–285. https://doi.org/10.1080/10888438.2011.568555.

Bélanger, N.N., Mayberry, R.I., Rayner, K., 2013. Orthographic and phonological preview benefits: parafoveal processing in skilled and less-skilled deaf readers. Q. J. Exp. Psychol. 66 (11), 2237–2252. https://doi.org/10.1080/17470218.2013.780085.

Bélanger, N.N., Rayner, K., 2015. What eye movements reveal about deaf readers. Curr. Dir. Psychol. Sci. 24 (3), 220–226. https://doi.org/10.1177/0963721414567527.

Carreiras, M., Perea, M., Vergara, M., Pollatsek, A., 2009a. The time course of orthography and phonology: ERP correlates of masked priming effects in Spanish. Psychophysiology 46 (5), 1113–1122. https://doi.org/10.1111/j.1469-8986.2009.00844.x.

Carreiras, M., Vergara, M., Perea, M., 2009b. ERP correlates of transposed-letter priming effects: the role of vowels versus consonants. Psychophysiology 46 (1), 34–42. https://doi.org/10.1111/j.1469-8986.2008.00725.x.

Chambers, S.M., 1979. Letter and order information in lexical access. J. Verb. Learn. Verb. Behav. 18 (2), 225–241. https://doi.org/10.1016/s0022-5371(79)90136-1.

Clark, M.D., Hauser, P.C., Miller, P., Kargin, T., Rathmann, C., Guldenoglu, B., et al., 2016. The importance of early sign language acquisition for deaf readers. Read. Writ. Q. 32 (2), 127–151. https://doi.org/10.1080/10573569.2013.878123.

Costello, B., Caffarra, S., Fariña, N., Duñabeitia, J.A., Carreiras, M., 2021. Reading without phonology: ERP evidence from skilled deaf readers of Spanish. Sci. Rep. 11 (1), 1–11. https://doi.org/10.1038/s41598-021-84490-5.

Eddy, M.D., Grainger, J., Holcomb, P.J., Gabrieli, J.D., 2016. Orthographic and phonological processing in developing readers revealed by ERPs. Psychophysiology 53 (12), 1776–1783. https://doi.org/10.1111/psyp.12763.

Emmorey, K., McCullough, S., Weisberg, J., 2016. The neural underpinnings of reading skill in deaf adults. Brain Lang. 160, 11–20. https://doi.org/10.1016/j.bandl.2016.06.007.

Emmorey, K., Midgley, K.J., Kohen, C.B., Sehyr, Z.S., Holcomb, P.J., 2017. The N170 ERP component differs in laterality, distribution, and association with continuous reading measures for deaf and hearing readers. Neuropsychologia 106, 298–309. https://doi.org/10.1016/j.neuropsychologia.2017.10.001.

Emmorey, K., Lee, B., 2021. The neurocognitive basis of skilled reading in prelingually and profoundly deaf adults. Language and Linguistics Compass 15 (2), e12407. https://doi.org/10.1111/lnc3.12407.

Farina, N., Dunabeitia, J.A., Carreiras, M., 2017. Phonological and orthographic coding in deaf skilled readers. Cognition 168, 27–33. https://doi.org/10.1016/j.cognition.2017.06.015.

Frankish, C., Turner, E., 2007. SIHGT and SUNOD: the role of orthography and phonology in the perception of transposed letter anagrams. J. Mem. Lang. 56 (2), 189–211. https://doi.org/10.1016/j.jml.2006.11.002.

Grainger, J., 2008. Cracking the orthographic code: an introduction. Lang. Cognit. Process. 23 (1), 1–35. https://doi.org/10.1080/01690960701578013.

Grainger, J., Holcomb, P.J., 2009. Watching the word go by: on the time-course of component processes in visual word recognition. Language and Linguistics Compass 3 (1), 128–156. https://doi.org/10.1111/j.1749-818x.2008.00121.x.

Grainger, J., Kiyonaga, K., Holcomb, P.J., 2006. The time course of orthographic and phonological code activation. Psychol. Sci. 17 (12), 1021–1026. https://doi.org/10.1111/j.1467-9280.2006.01821.x.

Grainger, J., Ziegler, J., 2011. A dual-route approach to orthographic processing. Front. Psychol. 2, 54. https://doi.org/10.3389/fpsyg.2011.00054.

Groppe, D.M., Urbach, T.P., Kutas, M., 2011. Mass univariate analysis of event-related brain potentials/fields I: a critical tutorial review. Psychophysiology 48 (12), 1711–1725. https://doi.org/10.1111/j.1469-8986.2011.01273.x.

Gutierrez-Sigut, E., Vergara-Martinez, M., Perea, M., 2022. The impact of visual cues during visual word recognition in deaf readers: an ERP study. Cognition 218, 104938. https://doi.org/10.1016/j.cognition.2021.104938.

Gutierrez-Sigut, E., Vergara-Martínez, M., Perea, M., 2019. Deaf readers benefit from lexical feedback during orthographic processing. Sci. Rep. 9 (1), 1-13. https://doi.org/10.1038/s41598-019-48702-3.

Hanson, V.L., Fowler, C.A., 1987. Phonological coding in word reading: evidence from hearing and deaf readers. Mem. Cognit. 15 (3), 199–207. https://doi.org/10.3758/bf03197717.

Hanson, V.L., McGarr, N.S., 1989. Rhyme generation by deaf adults. J. Speech Lang. Hear. Res. 32 (1), 2–11. https://doi.org/10.1044/jshr.3201.02.

Hirshorn, E.A., Dye, M.W.D., Hauser, P., Supalla, T.R., Bavelier, D., 2015. The contribution of phonological knowledge, memory, and language background to reading comprehension in deaf populations. Front. Psychol. 6, 1153. https://doi.org/10.3389/fpsyg.2015.01153.

Holcomb, P.J., Neville, H.J., 1990. Auditory and visual semantic priming in lexical decision: a comparison using event-related brain potentials. Lang. Cognit. Process. 5 (4), 281–312. https://doi.org/10.1080/01690969008407065.

Izzo, A., 2002. Phonemic awareness and reading ability: an investigation with young readers who are deaf. Am. Ann. Deaf 147, 18–28. https://doi.org/10.1353/aad.2012.0242.

Kass, R.E., Raftery, A.E., 1995. Bayes factors. J. Am. Stat. Assoc. 90, 773–795. https://doi.org/10.1080/01621459.1995.10476572.

Kaufman, A.S., Kaufman, N.L., 2004. Kaufman Brief Intelligence Test, second ed. American Guidance Service, Inc, Circle Pines, MN.

Ktori, M., Kingma, B., Hannagan, T., Holcomb, P.J., Grainger, J., 2014. On the time-course of adjacent and non-adjacent transposed-letter priming. J. Cognit. Psychol. 26 (5), 491–505. https://doi.org/10.1080/20445911.2014.922092.

MacSweeney, M., Goswami, U., Neville, H., 2013. The neurobiology of rhyme judgment by deaf and hearing adults: an ERP study. J. Cognit. Neurosci. 25 (7), 1037–1048. https://doi.org/10.1162/jocn_a_00373.

Markwardt, F.C., 1989. Peabody Individual Achievement Test-Revised: PIAT-R. Circle Pines. American Guidance Service.

Massol, S., Midgley, K.J., Holcomb, P.J., Grainger, J., 2011. When less is more: feedback, priming, and the pseudoword superiority effect. Brain Res. 1386, 153–164. https://doi.org/10.1037/e512592013-686.

Massol, S., Grainger, J., Midgley, K.J., Holcomb, P.J., 2012. Masked repetition priming of letter-in-string identification: an ERP investigation. Brain Res. 1472, 74–88. https://doi.org/10.1016/j.brainres.2012.07.018.

Mayberry, R.I., Del Giudice, A.A., Lieberman, A.M., 2011. Reading achievement in relation to phonological coding and awareness in deaf readers: a meta-analysis. J. Deaf Stud. Deaf Educ. 16 (2), 164–188. https://doi.org/10.1093/deafed/enq049.

Meade, G., Grainger, J., Midgley, K.J., Holcomb, P.J., Emmorey, K., 2019. ERP effects of masked ortho- graphic neighbour priming in deaf readers. Language, Cognition and Neuroscience 34, 1016–1026. https://doi.org/10.1080/23273798.2019.1614201.

Meade, G., Grainger, J., Midgley, K.J., Holcomb, P.J., Emmorey, K., 2020. An ERP investigation of ortho- graphic precision in deaf and hearing readers. Neuropsychologia 146, 107542. https://doi.org/10.1016/j.neuropsychologia.2020.107542.

Maurer, U., McCandliss, B.D., 2008. The development of visual expertise for words: the contribution of electrophysiology. In: Grigorenko, E.L., Naples, A.J. (Eds.), Single-word Reading: Behavioral and Biological Perspectives. Taylor & Francis, pp. 43–63. https://doi.org/10.4324/9780203810064.

Miller, P., Clark, M.D., 2011. Phonemic awareness is not necessary to become a skilled deaf reader. J. Dev. Phys. Disabil. 23 (5), 459. https://doi.org/10.1007/s10882-011-9246-0.

Morford, J.P., Occhino-Kehoe, C., Piñar, P., Wilkinson, E., Kroll, J.F., 2017. The time course of cross-language activation in deaf ASL-English bilinguals. Bilingualism 20 (2), 337. https://doi.org/10.1017/s136672891500067x.

Morford, J.P., Occhino, C., Zirnstein, M., Kroll, J.F., Wilkinson, E., Piñar, P., 2019. What is the source of bilingual cross-language activation in deaf bilinguals? J. Deaf Stud. Deaf Educ. 24 (4), 356–365. https://doi.org/10.1093/deafed/enz024.

Nielsen, D.C., Luetke-Stahlman, B., 2002. Phonological awareness: one key to the reading proficiency of deaf children. Am. Ann. Deaf 147 (3), 11–19. https://doi.org/10.1353/aad.2012.0213.

O'Connor, R.E., Forster, K.I., 1981. Criterion bias and search sequence bias in word recognition. Mem. Cognit. 9 (1), 78–92. https://doi.org/10.3758/bf03196953.

Pavani, F., Bottari, D., 2012. Visual abilities in individuals with profound deafness a critical review. In: Murray, M.M., Wallace, M.T. (Eds.), The Neural Bases of Multisensory Processes. CRC Press/Taylor & Francis. https://doi.org/10.1201/9781439812174-28.

Perea, M., Carreiras, M., 2006. Do transposed-letter similarity effects occur at a prelexical phonological level? Q. J. Exp. Psychol. 59 (9), 1600–1613. https://doi.org/10.1080/17470210500298880.

Perea, M., Carreiras, M., 2008. Do orthotactics and phonology constrain the transposed-letter effect? Lang. Cognit. Process. 23 (1), 69–92. https://doi.org/10.1080/01690960701578146.

Perfetti, C.A., Sandak, R., 2000. Reading optimally builds on spoken language: implications for deaf readers. J. Deaf Stud. Deaf Educ. 5 (1), 32–50. https://doi.org/10.1093/deafed/5.1.32.

Pollatsek, A., Perea, M., Carreiras, M., 2005. Does conal prime CANAL more than cinal?. Masked phonological priming effects in Spanish with the lexical decision task. Mem. Cognit. 33 (3), 557–565. https://doi.org/10.3758/bf03193071.

Rouder, J.N., Speckman, P.L., Sun, D., Morey, R.D., Iverson, G., 2009. Bayesian t tests for accepting and rejecting the null hypothesis. Psychonomic Bull. Rev. 16, 225–237. https://doi.org/10.3758/pbr.16.2.225.

Sacchi, E., Laszlo, S., 2016. An event-related potential study of the relationship between N170 lateralization and phonological awareness in developing readers. Neuropsychologia 91, 415–425. https://doi.org/10.1016/j.neuropsychologia.2016.09.001.

Sehyr, Z.S., Petrich, J., Emmorey, K., 2017. Fingerspelled and printed words are recoded into a speech-based code in short-term memory. J. Deaf Stud. Deaf Educ. 22 (1), 72–81. https://doi.org/10.1093/deafed/enw068.

Vergara-Martínez, M., Perea, M., Gómez, P., Swaab, T.Y., 2013. ERP correlates of letter identity and letter position are modulated by lexical frequency. Brain Lang. 125 (1), 11–27. https://doi.org/10.1016/j.bandl.2012.12.009.

Villwock, A., Wilkinson, E., Piñar, P., Morford, J.P., 2021. Language development in deaf bilinguals: deaf middle school students co-activate written English and American Sign Language during lexical processing. Cognition 211, 104642. https://doi.org/10.1016/j.cognition.2021.104642.

Zimman, H., Osmond, S., Emmorey, K., Holcomb, P.J., Midgley, K.J., 2019. Preliminary ERP Evidence for Different Rapid Feedforward Orthographic and Phonological Masked-Priming Effects. Presented at Cognitive Neuroscience, San Francisco, 2019.