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Masked ERP repetition priming in deaf and hearing readers

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Abstract

Deaf readers provide unique insights into how the reading circuit is modified by altered linguistic and sensory input. We investigated whether reading-matched deaf and hearing readers (n = 62) exhibit different ERP effects associated with orthographic to phonological mapping (N250) or lexico-semantic processes (N400). In a visual masked priming paradigm, participants performed a go/no-go categorization task; target words were preceded by repeated or unrelated primes. Prime duration and word frequency were manipulated. Hearing readers exhibited typical N250 and N400 priming effects with 50 ms primes (greater negativity for unrelated primes) and smaller effects with 100 ms primes. Deaf readers showed a surprising reversed priming effect with 50 ms primes (greater negativity for related primes), and more typical N250 and N400 effects with 100 ms primes. Correlation results suggested deaf readers with poorer phonological skills drove this effect. We suggest that weak phonological activation may create orthographic "repetition enhancement" or form/lexical competition in deaf readers.

Keywords

Deaf readers; ERPs; N250; N400; Masked priming

1. Introduction

Early deafness creates challenges for reading because deaf children cannot hear the language encoded by print. The linguistic experience of deaf children differs from hearing children who acquire spoken language auditorily prior to learning to read. Deaf children and adults tend to have weaker phonological abilities compared to their hearing peers, and growing evidence suggests that phonological skill is not a strong predictor of reading ability in deaf adults (e.g., Mayberry, del Giudice, & Lieberman, 2011; Emmorey, McCullough, & Weisberg, 2016). In addition, early deafness is associated with neuroanatomical changes in

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KE, PJH, and KJM conceptualized the study; KJM supervised data collection, PJH analyzed the data and wrote the first draft; KE, PJH, and KJM wrote, reviewed, and edited the final version.

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visual cortices (e.g., Allen, Emmorey, Bruss, & Damasio, 2013) and in visual processing (e.g., Bavelier et al., 2000; Proksch & Bavelier, 2002). These visual changes have been shown to impact sentence-level reading processes (e.g., Bélanger, Slattery, Mayberry, & Rayner, 2012: Bélanger, Lee, & Schotter, 2018).

Furthermore, recent studies suggest that deaf adults who are successful readers utilize a different set of early form-based processes during visual word comprehension compared to their reading-matched hearing peers (Emmorey, Midgley, Kohen, Sehyr, & Holcomb, 2017; Glezer et al., 2018; Sehyr, Midgley, Holcomb, Emmorey, Plaut, & Behrmann, 2020). For example, Emmorey et al. (2017) examined the N170 ERP component, which is hypothesized to reflect orthographic tuning to visual words, in deaf adults and hearing adults who were matched on reading skill but not phonological awareness. Hearing readers exhibited the expected left-lateralized N170 (greater negativity for words than symbol strings), while deaf readers exhibited a much more bilateral N170 response. Sehyr et al. (2020) recently replicated this finding using a passive word reading task. Glezer et al. (2018) provided further fMRI evidence indicating a more bilateral response in the visual word form area for skilled deaf readers. Importantly, linear mixed effects regression analyses examining the relation between reading ability and N170 amplitude indicated that this bilateral response to visual words is not maladaptive for deaf readers. Better reading ability and spelling ability (Sehyr et al., 2020) was associated with a larger N170 over right hemisphere temporo-occipital sites for deaf readers, but for hearing readers better reading ability was associated with a *smaller* right hemisphere N170 (Emmorey et al., 2017). These results support the "phonological mapping hypothesis" for hearing readers which proposes that the left-lateralized N170 emerges as a result of linking printed words to left hemisphere auditory language regions when mapping orthographic to phonological representations (McCandliss & Noble, 2003; Sacchi & Lazslo, 2016). Moreover, these results indicate that the optimal end-state for the reading system differs when access to auditory speech is significantly reduced during development due to hearing loss.

In addition to a different N170 distribution in deaf readers, both Emmorey et al. (2017) and Sehyr et al. (2020) found a smaller P1 for deaf readers (the PI is an early positive-going wave, peaking ~ 100 ms after stimulus onset and localized to occipital electrode sites). The amplitude of the P1 also correlated differently with reading ability for the two groups: more skilled deaf readers had a smaller P1, whereas more-skilled hearing readers had a larger P1 (Emmorey et al., 2017). These distinct patterns of early ERP effects suggest that the initial feedforward processing of orthographic information differs for deaf and hearing readers and is modulated differently by reading ability. Here we examined whether the different pattern of early ERP effects extends to pre-lexical form based processes reflected by the N250 and later lexico-semantic processes associated with the N400.

We used the visual masked priming (VMP) paradigm which has proven to be quite useful in dissecting the component processes of visual word recognition in both children and adults. In the VMP paradigm, information extracted from the brief masked prime is rapidly integrated with the information extracted from the subsequent target stimulus such that the prime and target are processed as a single perceptual event due to the blocking of recurrent neural processing by masking (Lamme et al., 1998; Lamme & Roelfsema, 2000). Using the

VMP paradigm, the N250 component has been shown to be sensitive to the degree of prime-target orthographic overlap and is thought to reflect the mapping of sublexical orthography onto whole-word representations (Holcomb & Grainger, 2007; Grainger, Kiyonaga, & Holcomb, 2006).

Repetition priming studies using the VMP paradigm indicate that the N250 component is sensitive to repetition priming (i.e., reduced negativity for repeated vs. unrelated prime words), but is insensitive to case, size, or font manipulations between the prime and target words (e.g., Chauncey, Holcomb, & Grainger, 2008). Such findings support the hypothesis that the N250 indexes abstract (form invariant) orthographic processing (see Grainger & Holcomb, 2009). A few behavioral studies have investigated masked priming with deaf and hearing readers and have found both similar and different effects. Cripps, McBride, and Forster (2005) found similar magnitude repetition priming for both groups, but only the hearing readers exhibited facilitation from pseudohomophone primes (bloo-BLUE; see also Bélanger, Baum, & Mayberry, 2012). Further, Cripps et al. (2005) reported that pseudohomophone primes resulted in an *inhibitory* effect for deaf readers, which suggests orthographic competition (see also Meade, Grainger, Midgley, Holcomb, & Emmorey, 2019).

Perea, Marcet, and Vergara-Martínez (2016) also reported evidence for differences in the early stages of visual word recognition for deaf and hearing readers using the VMP paradigm. This study examined physical identity vs. nominal (abstract) identity repetition priming. For hearing readers, physically identical prime-target pairs are responded to faster for non-word pairs (GEDA – GEDA < geda – GEDA), but not for real word pairs (REAL – REAL = real-REAL), which is hypothesized to be due to top-down lexical feedback for real words (e.g., Vergara-Martínez, Gomez, Jiménez, & Perea, 2015). In contrast, for deaf readers, both non-word and real-word pairs exhibited similar masked priming effects, which Perea et al. (2016) interpreted as reflecting less lexical phonological feedback for deaf readers. Gutierrez-Sigut, Vergara-Martínez, and Pera (2019) replicated this behavioral result for deaf readers, but their ERP data suggested a somewhat different explanation. Although the case difference for real-word pairs modulated the N/P150 (a component sensitive to feature-level processing), the N250 was insensitive to the case modulation for real word pairs, in contrast to non-word pairs. Gutierrez-Sigut argued that the N250 dissociation for words and non-words is evidence for early automatic lexical-semantic feedback that modulates orthographic processing in deaf readers. Overall, the existing research on masked priming with deaf readers suggests masked primes may be processed somewhat differently compared to hearing readers, perhaps reflecting differences in the strength of feedback from lexical phonological and semantic representations.

In the present study, we manipulated the duration of the masked priming word in part because this variable has been shown to influence ERP priming effects in hearing adults and children. For example, Eddy et al. (2014) showed that children produced clear and comparably large N250 priming effects for both short (50 ms) and longer (100 ms) duration primes while hearing adults produced robust N250s only when the primes where of short duration. Comparable N400 effects were seen in both groups for both prime durations suggesting that at the level of lexical semantics adults and children are processing words in an equivalent manner. The attenuation of the N250 for long duration primes in adults, but not in children, is consistent with prior evidence that the N250 starts to become refractory when the interval between the prime and target words is increased beyond the typical 60 to 70 ms used in most masked priming studies (see Grainger & Holcomb, 2009). Grainger and Holcomb have argued that the sensitivity of the N250 to the prime-target interval reflects an important property of low level form-based processing whereby the reading system has to quickly process orthographic information about the current word being attended and then rapidly reset in anticipation of the next word.

We hypothesized that deaf adult readers might show a different pattern of N250 effects as a function of prime duration because their orthographic skills are acquired with reduced phonological involvement which plausibly could impact the time course of pre-lexical orthographic processes. Specifically, the N250 has been found to be sensitive to phonological manipulations using short (50 ms) prime durations (e.g., Grainger et al., 2006), and the N250 is hypothesized to reflect a stage in visual word recognition when sublexical orthographic representations are mapped onto sublexical phonological representations (Grainger & Holcomb, 2009). If deaf readers do not robustly or automatically access sublexical phonological representations, then we may observe differences in the amplitude and/or time course of the N250, particularly for short prime durations. It is also possible that the visual processing changes that are associated with early deafness could impact masked priming effects at short durations.

Word frequency has also proven to have a potent influence on the time course of masked ERP priming effects, particularly on the N250. Grainger et al. (2012) showed that high frequency words, resulted in smaller N250 effects in adult (hearing) readers when the interval between prime and target onset is greater than 60 ms (in ERP masked priming the standard is 60–70 ms). Only with very short prime-target intervals (50 ms) did high frequency words produce N250 effects and even in this case the effects onset earlier than the standard N250. Grainger et al. argued that this earlier N250 time course to high frequency words reflects the increased efficiency of pre-lexical orthographic processing for these items and that the above mentioned “reset” mechanism operates more efficiently for high frequency words. Lower frequency (but known) words produced typical N250 and N400 priming effects which were not as sensitive to the prime-target interval (Grainger et al., 2012). Given the interpretation for altered early orthographic effects in deaf adult readers, it seems plausible that the time course of N250 priming might be different in deaf readers as a function of word frequency. In contrast, we do not expect to see clear group differences on the N400 in relation to word frequency since this component reflects later lexico-semantic influences that should be comparable in any competent reader.

1.1. The present study

To test these predictions, we measured the ERPs generated by target words in deaf and hearing adult readers (matched on overall reading ability) using the masked repetition priming paradigm. Following Grainger et al. (2012) ERPs on each trial were recorded to a series of visual stimuli displayed in rapid succession; this included a forward mask (a row of hash marks) presented for 300 ms, a prime word presented in lowercase letters for 50 ms or

100 ms, a backward mask consisting of a row of consonant strings for 20 ms and a target word in all uppercase letters for 300 ms (see Fig. 1). Participants engaged in a go/no-go semantic categorization task in which they were told to press a single button whenever they saw occasional probe words that named an animal (~15% of trials). The remaining non-probe (so-called critical trials) contained the experimental manipulations of word frequency (high vs. low), prime duration (50 ms vs. 100 ms) and priming (repeated vs. unrelated targets).

2. Methods

2.1. Participants

A total of sixty-eight volunteers participated in this experiment but of these, six were not included in analyses because of equipment failure (two) and excessive EEG artifact (four). Of the remaining 62, 31 were congenitally deaf adults (15 female; mean age = 29 years, range = 18–46 years) who were either native signers of ASL (born into deaf signing families; N = 22) or acquired ASL before age seven (N = 8); one deaf participant learned ASL after age seven. The other 31 participants were hearing adults (27 female; mean age = 22 years, range = 19–32 years) who were native speakers of English (none knew ASL). The deaf participants were severely to profoundly deaf (db loss ≥ 70 db), and all were congenitally or prelingually deaf. The mean number of years of education for the deaf participants was 17 (SD = 2.7) and for the hearing participants, it was 15 years (SD = 1.7). All participants had normal or corrected to normal vision. Three deaf and four hearing participants were left-handed.

2.2. Behavioral tests

All participants underwent an assessment battery that measured reading comprehension, vocabulary size, spelling ability, and phonological awareness. The battery included the following tests:

2.2.1. Peabody individual achievement test (PIAT) – revised; reading comprehension subtest (Markwardt, 1989)—In this subtest, participants read (silently) a sentence, then choose from four pictures the one that best matches the sentence. Items increase in difficulty throughout the test, and the test is discontinued if a participant produces seven consecutive responses containing five errors. The mean PIAT-R raw score for deaf readers was 85 (SD = 9.6), and the mean score for the hearing readers was 85 (SD = 9.2). The deaf and hearing groups did not differ in their reading comprehension ability, $t(60) = 0.07$, $p = .95$.

2.2.2. Peabody picture vocabulary test (PPVT-IV; Dunn & Dunn 2007) – adapted for print and deaf individuals—The standard version of the PPVT is given by the examiner saying an English word, and the participant points to the corresponding target picture (out of four). We use the adapted version of the PPVT created by Sarchet et al. (2014) to assess print vocabulary knowledge. In this version, each PPVT item consists of a display of the four picture choices with the target word printed in the center. The guidelines for administering the spoken version of the PPVT are followed. The mean score for deaf readers on the PPVT test was 198 (SD = 15.6), and for the hearing readers was 204 (SD = 11/2). The hearing readers scored marginally higher than the deaf readers, $t(60) = -1.81$, $p < .076$.

2.2.3. Spelling recognition test (Andrews and Hersch, 2010)—

The test contains 88 items, half correctly spelled and half misspelled. Misspellings change one to three letters of the word and often preserve the pronunciation of the base word (e.g., addmission, seperate). Items are printed in columns, and participants are instructed to circle items they think are incorrectly spelled. The recognition test score is the number of correctly classified items, both hits and correct rejections. The mean spelling score for deaf readers was 75 (SD = 7.4), and the mean spelling score for the hearing readers was also 75 (SD = 7.8). The deaf and hearing groups did not differ in their spelling ability, $t(60) = 0.08$, $p = .93$.

2.2.4. Phonological awareness test (Hirshorn et al., 2015)—

This test was specifically designed for profoundly deaf adults and does not require overt speech production. For one task, three pictures are displayed in a triangle formation, and participants select the “odd man out” – the item that has a different first sound or a different vowel (blocked conditions). In a second task, participants are shown two pictures (e.g., a bird and a toe) and are asked to combine the first sound of the word in the first picture with the rime of the word in the second picture to make a new word (e.g., bow). Participants type the new word that is created on a keyboard. The mean total accuracy for deaf readers on this phonological awareness test was 63% (SD = 14.1%), and the mean accuracy for the hearing readers was 91% (SD = 8.3%). The hearing readers scored significantly higher than the deaf readers, $t(60) = -9.52$, $p < .0001$.

2.3. ERP stimuli

The critical stimuli for this study were the same 120 five-letter words used in a previous experiment by Grainger et al. (2012). They ranged in HAL lexical frequency between 5.83 and 13.7 (English Lexicon Project; Balota et al., 2007). Sixty of these items were selected because they were comparatively lower in lexical frequency (mean log Hal frequency = 5.83, range 4.14–7.03) and the other 60 were chosen because they were comparatively higher in lexical frequency (mean log Hal frequency = 11.06, range 9.3–13.7). Grainger et al. reported in a separate rating study that included all 120 words (as well as an additional 60 very low frequency filler words) that the critical low frequency words were rated as being less familiar than the high frequency items (3.53 vs. 4.93 on a five-point scale). Importantly, all words were rated as being known by at least 9 of the 15 participants (hearing undergraduate students). The deaf readers from the current study performed a similar familiarity judgement task after participating in the ERP experiment using a four-point scale (0 = unknown, 3 = very familiar). Of the 60 low frequency words only 4% of the 1920 ratings were in the unknown category and of those no low frequency word was rated as unknown by more than five of the 31 deaf participants,

Words were arranged in pairs, and the first member of each pair was referred to as the prime and the second member as the target. From these pairs six stimulus lists were formed. In each list there were eight stimulus conditions made up of the factorial combination of word

Frequency (high vs. low), prime Duration (50 ms vs. 100 ms) and Priming (repeated vs. unrelated). The repeated condition refers to trials where the target was a full repetition of the prime (e.g., table - TABLE), and the unrelated condition refers to trials where the prime and target were unrelated words (e.g., space – TABLE). The 50 and 100 ms primes refer to the duration of the prime words. Each list was subdivided into three blocks of 20 items per condition. Across blocks each target word appeared once in each of the repeated (prime and target), unrelated prime, and unrelated target conditions, but no item was presented in more than one trial within a block as either a target or a prime. In this way, across the experiment, each participant saw each target word in all conditions and each word was shown an equal number of times. This scheme assures that average ERPs in the repetition and unrelated conditions are formed from exactly the same items (for both primes and targets) within participants.

Each list also contained 60 trials where an animal probe name appeared in the target position and 15 trials where an animal probe appeared in the prime position (mean log HAL frequency = 6.84, range 2.2–10.5). On probe trials half of the time a high-frequency non-animal filler word was paired with the animal name and the other half a low-frequency word was paired. Animal probes were used as “go” items in a go/no-go semantic categorization task in which participants were instructed to rapidly press a single button (response hand counterbalanced) with their thumb whenever they detected an animal probe name. Participants were told to read all other words passively without responding (i.e., critical stimuli did not require an overt response). The 15 probe items appearing in the prime position served as a measure of prime detectability, thus providing an objective measure of the effectiveness of the masking procedure. Prior to the experimental run, a practice block was run to familiarize the participant with the procedure.

All stimuli were presented in the center of a 24-inch gaming LCD monitor set to a refresh rate of 100 Hz and located approximately 125 cm directly in front of the participant. Stimuli were displayed as white letters on a black background in Arial font (25 × 50 pixel character cells). All word stimuli were presented within the fovea (less than 2° of horizontal and 1° of vertical visual angle).

Each trial began with a forward mask of eight hash marks (########) presented for a duration of 300 ms. The mask was immediately replaced at the same location on the screen by the prime word in lower case letters (e.g., table) and was displayed for either 50 ms (short primes) or 100 ms (long primes). The prime was then immediately replaced by a 20 ms backward mask of an upper-case consonant string of eight letters (e.g., CFTQABRM), which was in turn replaced by a 200 ms target word (e.g., TABLE) in capital letters. All target words were followed by a 700 ms blank screen which was replaced by a blink signal (- -) (see Fig. 1). Following Grainger et al. (2012) we used a consonant string backward mask to assure complete unawareness of the prime in the 50 ms condition. Participants were instructed to blink only during the 1800 ms that this stimulus was on the screen. The blink stimulus was followed by a blank screen for 500 ms, after which the next trail began.

2.4. EEG recording procedure

Participants were seated in a comfortable chair in a sound attenuated, darkened room. An electro-cap fitted with tin electrodes was used to record continuous EEG from 29 sites on the scalp including sites over left and right fronto-polar (FP1/FP2), frontal (F3/F4, F7/F8), frontal-central (FC1/FC2, FC5/FC6), central (C3/C4), temporal (T5/T6, T3/T4), central-parietal (CP1/CP2, CP5/CP6), parietal (P3/P4), and occipital (O1/O2) areas and five midline sites over the frontal pole (FPz), frontal (Fz), central (Cz), parietal (Pz) and occipital (Oz) areas (see Fig. 2). Four additional electrodes were attached: one below the left eye (to monitor for vertical eye movement/blinks - LE), one to the right of the right eye (to monitor for horizontal eye movements - HE), one over the left mastoid (reference) and one over the right mastoid (recorded actively to monitor for differential mastoid activity). All EEG electrode impedances were maintained below 5 kΩ (impedance for eye electrodes was less than 10 kΩ). The EEG was amplified by an SA Bioamplifier with a bandpass of 0.01 and 40 Hz and the EEG were continuously sampled at a rate of 250 Hz. Trials with blinks and eye movement artifacts were rejected before averaging.

2.5. Data analysis

Prior to averaging the EEG data we removed blink artifacts using ICA as recommend by Jung et al. (2000). After removing blink artifacts single trial EEG data time-locked to a point 100 ms pre-target onset and continuing for 700 ms were averaged at each of the 32 electrode sites. The resulting ERPs were baselined to the average of the 100 ms pre-target period and digitally bandpass filtered between 0.01 and 15 Hz. Only trials without residual EEG artifact were included in the averages. On average 2.5% (range 0–7%) of trials were rejected because of artifact. As is customary in our laboratory we inspected the average activity at the right mastoid across the conditions of interest to determine if differential mastoid activity due to our independent variables necessitated re-referencing to the average of the two mastoids. No such activity was noted so the data from the left mastoid reference was used for subsequent analysis.

Because the focus of masked priming is on the size of priming effects we measured mean amplitudes in differences waves calculated by subtracting repeated target ERPs from unrelated target ERPs.[1] Four difference waves were computed from the factorial manipulation of target word frequency (high vs. low) and prime duration (long vs. short). Three temporal windows were quantified based on those used in several previous ERP masked prime experiments: 100–200 ms (N/P150), 200–300 ms (N250) and 300–550 ms (N400) (Holcomb & Grainger, 2006; Grainger et al., 2006). In an initial omnibus set of analyses, we used a mixed-design ANOVA model with a between-subject factor of Group (hearing vs. deaf readers) and within-subject factors of target word Frequency (high vs. low), prime Duration (50 vs. 100 ms), Laterality (left vs. midline vs. right), and Anterior-Posterior electrode position (FP vs. F vs. C vs. P vs. O; see Fig. 2 for the analysis montage). Because our primary interest was in looking for differential group effects of repetition priming, we

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[1] Difference waves also have the advantage of removing the large effects of prime duration resulting from the differential temporal overlap of pre-target stimuli from the backward mask, prime word and forward mask that overlap with the target ERP. This makes comparisons of priming effects due to prime duration possible.

followed-up omnibus analyses where the priming effect differed as a function of Group by running within-group analyses separately for the hearing and deaf readers. The Geisser-Greenhouse correction was used for all repeated-measures factors with greater than 1 degree of freedom in the numerator.

3. Results

3.1. ERPs

Plotted in Figs. 3 and 4 are the ERPs from all Repeated and Unrelated targets (summed across word frequency and prime duration) for the hearing readers (Fig. 3) and deaf readers (Fig. 4). As can be seen there are small priming effects starting just after 100 ms (N/P150) which are followed by somewhat larger effects around 250 (N250) and 400 (N400) ms. Plotted in Figs. 5 and 6 are ERPs for hearing and deaf readers contrasting repeated with unrelated targets (i.e., the Priming effect) for the different prime Duration and word Frequency conditions.

3.1.1. 100–200 ms (N/P150)—In this initial window there was a significant priming effect as a function of AntPost distribution (F(4,240) = 2.41, p = .031), indicating that there was a small negative polarity priming effect at anterior sites, and a similarly small positive polarity effect at posterior sites. This effect did not interact with any of the other variables (all ps > 0.1). Occipital positivity and anterior negativity is typical of this earliest masked priming effect which did not differ as a function of Group.

3.1.2. 200–300 ms (N250)—In this second window there was a significant priming effect as a function of prime Duration (main effect of Duration: $F(1,60) = 4.99$, $p = .029$), indicating that the 100 ms duration produced more negative-going priming effects than the 50 ms duration (−0.39 vs. 0.08 μv). There were also differences in the size of the priming effect as a function of target word Frequency, $F(1,60) = 6.08$, $p = .0165$), with low frequency targets producing more negative-going priming effects than high frequency targets (−0.43 vs. 0.12 μv). Importantly, the prime Duration effect differed as a function of Group (Group × prime Duration interaction: $F(1,60) = 9.52$, $p = .003$), with deaf readers producing larger negative-going priming effects for the long prime duration condition (−0.62 vs. 0.48 μv) and hearing readers showing more negative-going priming for short duration primes (−0.15 vs. −0.33 μv). These patterns can be seen in the difference waves plotted in Fig. 7.

Follow-up analyses examining the two groups separately showed that hearing readers produced differential priming effects as a function of scalp site and word Frequency (word Frequency × AntPost × Laterality: $F(8,240) = 3.22$, $p = .008$) but not prime Duration. As can be seen in Figs. 5 and 7, while low frequency words produced robust N250 priming across the scalp (largest at midline frontal), high frequency words showed N250-like effects only at anterior sites. Deaf readers, on the other hand, revealed priming effects as a function of word Frequency, $F(1,30) = 5.38$, $p = .027$, and prime Duration, $F(1,30) = 12.70$, $p = .0012$. As can be seen in Figs. 6 and 7, while low frequency words tended to produce an N250-like negative polarity priming effect, high frequency words produced a marked positivity in this epoch, i.e., the opposite of a typical N250 effect. Similarly, for deaf readers long duration primes tended to produce typical negative-going priming effects while short duration primes were associated with a reversed polarity effect (Fig. 7).

3.1.3. 300–550 ms (N400)—There was again a significant priming effect as a function of prime Duration, $F(1,60) = 7.61$, $p = .0077$), with the 100 ms primes producing more negative-going priming effects than 50 ms primes (−0.54 vs. −0.04 μv). There was also a difference in the size of the priming effect as a function of AntPost scalp distribution, $F(4,240) = 5.62$, $p = .0064$, with central and parietal sites showing the largest priming effects (−0.52 and −0.43 μv) and frontal (FP) sites showing the smallest priming (−0.03 μv). The prime Duration by Group interaction continued into this epoch, $F(1,60) = 12.01$, $p = .001$, with deaf readers producing larger negative-going priming effects for the long prime duration condition (−0.71 vs 0.41 μv) and hearing readers showing comparable priming for the two prime durations (−0.37 vs. −0.49 μv). These patterns can be seen in the difference waves plotted in Fig. 7. There were no effects of word frequency in this epoch (all ps > 0.08).

Follow-up analyses in the hearing readers revealed that priming differed as a function of AntPost distribution (F(4,120) = 5.62, p = .0041), with the largest priming at central and frontal sites (−0.72 and −0.62 μv) and the smallest at frontal polar (FP) and occipital sites (−0.21 and −0.11 μv). There were no differences in priming as a function of word Frequency or prime Duration ($p > .50$) in hearing readers. Deaf readers, on the other hand, showed a significant effect of prime Duration, $F(1,30) = 15.33$, $p = .0005$, with a negative-going priming effect in the long duration prime condition and a positive-going priming effect in the short prime duration condition (−0.71 vs. 0.41 μv). As with the hearing readers, deaf readers did not show priming differences between high and low frequency target words in this epoch (p > .22).

3.2. Summary

Across two of our three epochs, hearing and deaf readers produced different patterns of repetition priming. While hearing readers revealed typical priming effects (unrelated more negative-going than repeated) in the N250 and N400 windows, deaf readers showed this typical pattern only for primes of longer duration (100 ms). For the short duration primes (50 ms) deaf readers showed a reverse priming effect with unrelated targets producing more positive-going waves than repeated targets, across both measurement windows. Both groups showed differential priming effects as a function of target word frequency, but only in the initial N250 epoch. In both groups low frequency words tended to generate larger negative-going priming effects than high frequency words.

3.3. Correlations

Although all 62 participants were competent readers, both groups exhibited a range of reading skills which allowed us to perform correlations between the mean amplitude of the ERP priming effect in both temporal epochs (N250 and N400) and measures of language skill from four behavioral tests. These included overall reading skill (PIAT), spelling skill (Andrews and Hersch, 2010), phonological skill (Hirshorn et al., 2015), and vocabulary skill

(PPVT; Sarchet et al., 2014). Only correlations surviving FDR correction are reported (Groppe et al., 2011).

In hearing readers, the only variable that showed a consistent pattern of correlation with ERP priming effects was print vocabulary skill, as measured by the adapted PPVT. The pattern of correlations can be seen in the correlation maps in Fig. 8 (left). The positive values (warm colors) of this correlation indicate that the standard N400 priming effect was smaller for hearing readers with higher PPVT scores (i.e., bigger vocabularies) and was larger for readers with lower PPVT scores. This pattern can also be seen in the voltage maps formed by separating participants into two groups with the highest and lowest PPVT scores. As can be seen in Fig. 8 (middle), the nine hearing readers with the lowest PPVT scores produced a robust N400 effect (larger N400 for unrelated than repeated targets), while the eight hearing readers with the highest PPVT scores revealed almost no evidence of a comparable N400 effect (Fig. 8, right). None of the other reading and language tests produced a consistent pattern of correlations with ERP Priming effects in the hearing readers.

In the deaf participants phonological skill varied as a function of the mean amplitude of the priming effect in the N250 epoch (200–300 ms) for high frequency words in the 50 ms prime duration condition. This correlation was negative at a number of electrode sites and suggests that deaf participants with higher phonological scores produced a more negative-going N250 priming effect, while deaf readers with the weakest phonological skills produced a large positive-going priming effect. The scalp distribution of these correlations can be seen in Fig. 9 (left), which reveals that the largest correlations were over left anterior-temporal and right occipital-parietal scalp sites. This relationship between phonological skill and N250 priming can also be seen in the voltage maps formed by separating participants into two groups at the extremes of phonological test scores (right two panels of Fig. 9). Here it is clear that the eight deaf readers with the highest scores (i.e., those with the best phonological skill) showed a more typical polarity N250 priming effect (larger N250s for unrelated compared to repeated targets) at right temporo-parietal sites, while the lowest scoring 10 deaf readers show the surprising reversed pattern (i.e., larger negativity for repeated than unrelated items) at left hemisphere temporo-frontal sites.

4. Discussion

Previous studies in hearing children and adults have shown a pattern of ERP masked priming effects that are sensitive to early sub-lexical (N250) as well as slightly later lexico-semantic (N400) processes involved in visual word recognition. With regards to the N250, there is evidence that this component is sensitive to both early orthographic processing as well as phonological processing (Grainger et al., 2006). Therefore, in the current study we hypothesized that deaf adult readers might show a different pattern of sub-lexical N250 effects because their orthographic skills are acquired with reduced phonological involvement which plausibly could impact both the processing nature and time course of pre-lexical visual word processing. If deaf readers do not robustly or automatically access sublexical phonological representations, we predicted that we would observe differences in the amplitude and/or time course of the N250, particularly when the duration of the prime word is short. We also predicted that since these deaf participants were all competent readers, the

N400 priming effects would show a similar pattern to those in hearing readers who were matched on reading comprehension.

At long prime durations (100 ms), where participants were aware of the prime word, both hearing and deaf readers produced the now typical pattern of masked priming ERP effects (e.g., Holcomb & Grainger, 2006), i.e., larger N250s and subsequent N400s to unrelated compared to repeated target words (see Fig. 7). However, at short prime durations (50 ms) which is the standard duration used in most masked priming studies, only the hearing readers produced the typical pattern of larger N250 and N400 negativities to unrelated than repeated target words. With 50 ms primes deaf readers revealed an unexpected reversed priming effect with larger negativities to repeated than unrelated target words especially in the N250 epoch (see Fig. 7). Furthermore, correlations between N250 amplitude and a measure of phonological skill suggested that the inverse N250 effect was due primarily to deaf readers with weaker phonological awareness (see Fig. 9). Hearing readers showed no relationship between phonological skill and the amplitude of priming effects in either the N250 or N400 time windows. What could be happening with 50 ms primes that differs from 100 ms primes for the deaf readers? Below we entertain several possible explanations for the reversed priming effect in deaf readers.

Previous studies using the visual masked priming paradigm with deaf readers have not reported a reversed N250 priming effect with short duration primes (Gutierrez-Sigut, Vergara-Martínez, & Perea, 2017, 2019; Meade et al., 2019, 2020). Two notable differences between these studies and our study is how the prime words were masked and the task used. Both Gutierrez-Sigut et al. (2017) and Meade et al. (2020) used a lexical decision task and a sandwich priming paradigm in which the mask is followed by a brief (30 or 50 ms) presentation of the target word before the prime word. However, neither of these studies assessed pure repetition priming. Gutierrez-Sigut et al. (2019) reported typical N250 and N400 identity priming effects in deaf readers, using the same pattern mask (#####) before (500 ms) and after (16.7 ms) the prime word (33.3 ms duration). In contrast, in our paradigm a string of upper case consonants constituted the second mask. It is possible that the use of consonant strings as the backward mask may have somehow altered how prime words were activated (or were processed visually) in the deaf participants with weaker phonological skill. Another difference is our use of a semantic judgment task. It is possible that by emphasizing the meaning of target words, we encouraged these deaf participants to shift attention away from lower level phonological processes.

Another possibility is that in deaf readers with the weakest phonological skills, phonological processing is sluggish and requires a longer duration for phonological representations to be activated. Slow or weak phonological activation could explain why when the prime is lengthened to 100 ms, sufficient time is now available to produce the more typical N250 priming pattern. Because hearing readers have more robust phonological skills, 50 ms duration primes are of adequate duration to activate phonological representations. In fact, at 100 ms the N250 in hearing readers has already started to wane, which is consistent with prior studies reporting that the N250 effect is refractory as the prime-target interval increases (see Grainger & Holcomb, 2009). However, this explanation leaves unanswered why at 50 ms deaf readers, especially those with poor phonological skills, show a significant *reversed* priming effect. This finding suggests that these readers are sensitive to the priming manipulation but that this sensitivity takes a very different form.

One possible source of this reversed pattern could be activity in purely orthographic representations that is manifest when there is no available phonological information to support typical priming effects. In the case of hearing readers this pattern would presumably never happen as orthographic processing is derivative of phonological processing. That is, hearing readers acquire a speech-based phonological system before learning to read and establishing associated orthographic representations. In contrast, deaf readers (particularly those with weak phonological skills) may develop orthographic representations that are associated with slowly activated and imprecise phonological representations. Many studies have found that deaf readers have stronger orthographic than phonological skills (e.g., Aaron et al., 1998; Kargin et al., 2012; Miller, 2005; Olson & Caramazza, 2004), and this could induce a greater reliance on visual processing of words such that short, repeated primes enhance visual word processing.

As such, increased negativity for targets with repeated 50 ms primes (vs. unrelated primes) may reflect a “repetition enhancement” effect for orthographic representations for deaf readers. This effect bears some resemblance to the unique N200 word repetition effect (greater negativity for repeated targets) reported for Chinese characters which do not have consistent sublexical mappings from orthographic to phonological representations (Du, Zhang, & Zhang, 2014; Zhang, Fang, Du, Kong, Zhang, & Xing, 2012). These authors suggest that this reversed N200 priming effect may be due to the greater emphasis on visual processing for Chinese characters compared to alphabetic scripts. In addition, this N200 effect appears to be associated with orthographic processing, rather than with semantic or phonological processing of Chinese characters (Du et al., 2014; Zhang et al., 2012). Although these studies did not use masked priming (among other differences), they nonetheless provide a clue as to the possible mechanism underlying the reversed N250 effect observed for deaf readers here. We speculate that the effect may reflect unique rapid, visual processing of words in deaf readers, where the subliminal (50 ms) prime enhances the neural response to the orthographic representation of the repeated target word. This hypothesis is consistent with studies reporting faster early visual processing by deaf individuals (e.g., Bottari et al., 2012), changes in visual attention associated with congenital deafness (e.g., Chen et al., 2010), and faster visual word recognition by deaf than hearing readers (e.g., Morford et al., 2019).

However, this account leaves open the question of what happens to the reversed orthographic effect when the slower phonological system is given enough time to become active. One possibility is that the supraliminal 100 ms prime allows for top-down information from phonological (and lexical) representations to suppress the neural response to the target word. In this case, decreased negativity for the target word could be due to reduced prediction error (e.g., Summerfield et al., 2008). Note that both repetition suppression (typical priming) and repetition enhancement (“reversed” priming) can occur within the same neuronal population (see Tartaglia, Mongillo, & Brunel, 2015).

A final possibility is that short duration primes give rise to a type of orthographic competition for deaf readers – especially those with poor phonological skills. As is standard in VMP we used lower-case prime words and upper-case targets. This might have resulted in the activation of two different (mismatching) visual representations especially in readers who rely more heavily on a purely visual code, The key here is that this mismatch would be present on both unrelated and repetition trials, but on repetition trials there would still be a match between prime and target at the lexical level. Thus, there is a conflict between the visual form level where the prime and target are coded as distinct and the lexical level where the prime and target encode the same representation. It is possible that this visual form/ lexical competition resulted in the reversed priming effect. But why doesn’t the same thing happen for hearing readers? Learning to read using phonology forces letter representations to be abstract, especially with regards to letter case since lower- and upper-case letters map onto the same sounds. However, in a weaker (or different) abstract letter coding system (especially one not based on sounds) there would be a greater visual mismatch between stimuli formed from lower-case as compared to the same upper-case letters (i.e., letter representations are less abstract, retaining information about case identity). In this case, the conflict would be between the visual forms that indicate that the prime and target are different, and the subsequent lexical forms which indicate that the words are the same. Note that in the case of unrelated pairs there is no form/lexical conflict since both levels of processing indicate that the prime and target are different. With long duration primes the visual forms might not have as potent an influence perhaps because the prime is processed explicitly or because there is more time to fully process the prime. Either way there would presumably be less direct competition between visual forms and lexical forms. A test between this hypothesis and the repetition enhancement notion would be to use primes and targets presented in the same case. According to the competition hypothesis there would no longer be a conflict between visual and lexical forms and thus deaf readers should produce typical N250 priming effects. However, if short duration primes regardless of case produce repetition enhancement, then we should see the same pattern of larger N250s for repeated compared to unrelated targets.

We also found effects of word frequency in both groups on the N250 but not the N400. Consistent with our prior work manipulating word frequency (Grainger et al., 2012), we found a typical widely distributed N250 priming effect for lower frequency words (larger negativity for unrelated prime-target pairs) in both groups, especially for the longer duration primes in the deaf group. For high frequency words, N250 priming was somewhat smaller and more anterior in distribution in hearing readers, but was completely reversed in polarity, especially at the short prime duration, for deaf readers. We have previously attributed the weaker N250 for high frequency words as reflecting the increased efficiency of pre-lexical orthographic processing for these items (Grainger et al., 2012) and that explanation would seem to hold for hearing readers in the current study as well. With respect to the larger reversed N250 for deaf readers for high frequency words, we suggest this finding is consistent with the competition hypothesis discussed above. Accordingly, because high frequency words are processed faster/more efficiently, competition between visual form and lexical processing might be expected to overlap more in time and therefore generate greater competition. This notion of form/lexical overlap is similar to the explanation for the lack of competition effects for long duration primes where there is presumably much less temporal overlap.

In contrast to the deaf readers, hearing readers showed an inverse relationship between the size of N400 priming and vocabulary skill – hearing readers with lower vocabulary scores on the PPVT tended to produce larger N400 effects and those with higher scores showed smaller N400s (see Fig. 8). This inverse correlation between N400 priming and the PPVT might seem difficult to explain. Why would participants with poorer vocabulary skill show larger N400 effects, especially since the N400 is usually interpreted as reflecting some aspect of lexico-semantic processing? One possibility for this finding is that prior studies have suggested that less skilled (hearing) readers tend to show larger N400 priming effects in sentence processing experiments (e. g., Holcomb et al., 1992). These studies have usually argued that poorer reading ability results in a greater reliance on context to aid comprehension and that better readers have more efficient bottom up processing that quickly resolves any lexical and semantic ambiguity during reading (leading to weaker N400 effects). If this idea is correct, then the inverse relationship between vocabulary size and lexico-semantic processing extends this efficiency explanation to the fast and automatic effects seen in masked priming.

If this explanation is correct, then why didn’t the deaf readers show a similar relationship between N400 effects and vocabulary size? One possibility is that vocabulary size in deaf readers is not as suitable a proxy for the efficiency of bottom-up visual word processing as it may be for hearing readers. Hearing readers with larger vocabularies might benefit from stronger/richer resonance between sublexical representations (*both* phonological and orthographic) and lexico-semantic representations, which in turn results in more efficient bottom-up processing. Alternatively, deaf readers with larger vocabularies might still rely more heavily on contextual factors because they acquire English as a second language. At least one prior study has suggested that even proficient bilinguals show larger effects of context than monolinguals (Weber-Fox and Neville, 2001). If deaf readers with different vocabulary sizes do not differ in their reliance on context, then we would not expect a relationship between N400 priming and PPVT scores.

In conclusion, these results extend previous studies that found laterality differences between reading-matched deaf and hearing adults in the N170 component (Emmorey et al., 2017; Sehyr et al., 2020). Although we did not find group differences in laterality, we observed differences in the impact of masked prime duration on the N250 and N400 components. With short (50 ms) primes, deaf readers exhibited unexpected reverse priming effects (greater negativities with repeated than unrelated primes), and a correlation analysis suggested that this reversed priming effect may be related to phonological processing. We suggest that both deafness (e.g., changes in visual attention) and less robust phonological representations give rise to either a repetition enhancement or form/lexical competition effect at short prime durations for deaf readers. With longer (supraliminal) primes, their slower phonological processing system can come on-line and top-down lexical information can suppress the response to the target word, resulting in the more typical ERP priming effect (greater negativity with unrelated than related primes) due to prediction error. However, this interpretation remains speculative and further research is needed to replicate these findings and to test our proposed explanations. Nonetheless, this study adds to a growing literature showing that the processes that underlie skilled reading differ for deaf and hearing adults.

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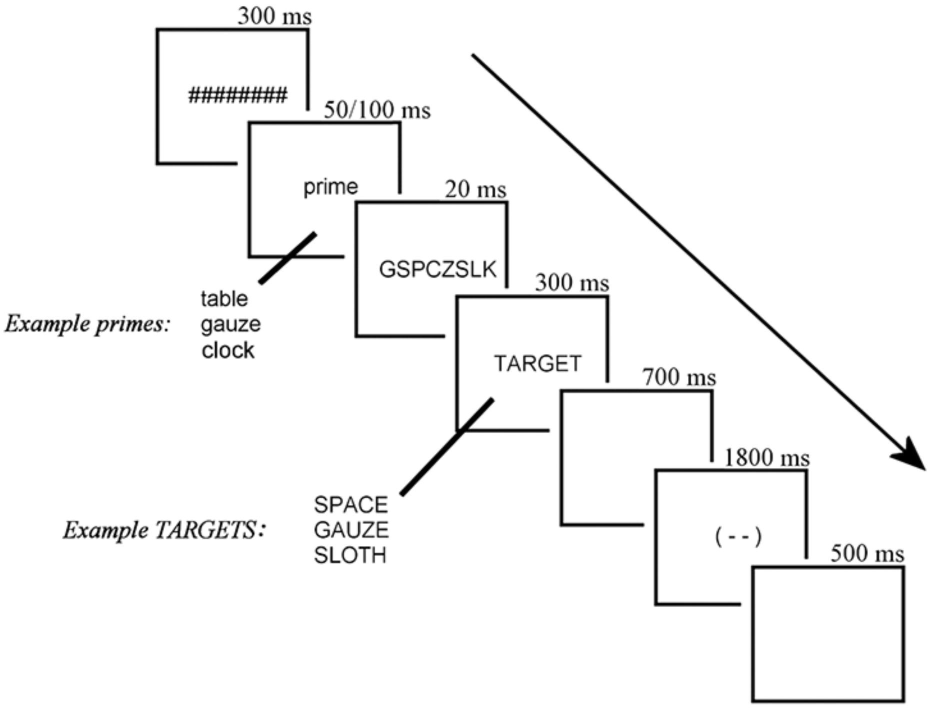

Fig. 1.

Schematic of a typical trial with examples of three conditions: unrelated (table-SPACE), repetition (gauze-GAUZE) and target animal probe (clock-SLOTH).

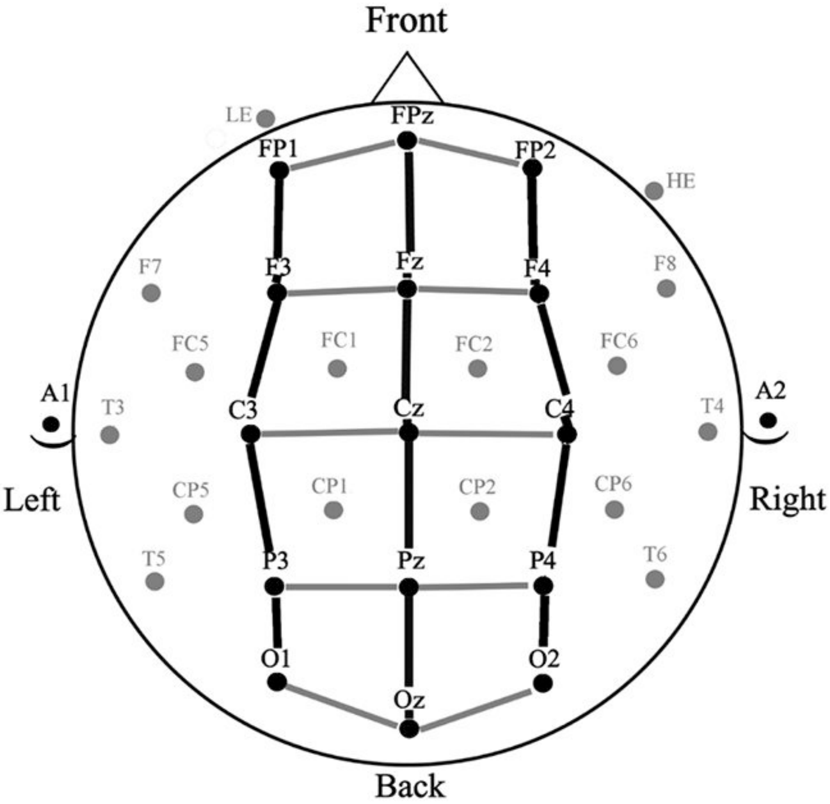

Fig. 2.

32 channel electrode montage including sites below the left eye (lower eye - LE) and to the right of the right eye (horizontal eye – HE). The 15 ANOVA analysis sites are labeled in black and the 3 lateral × 5 ant-post analysis grid is illustrated by the connecting lines.

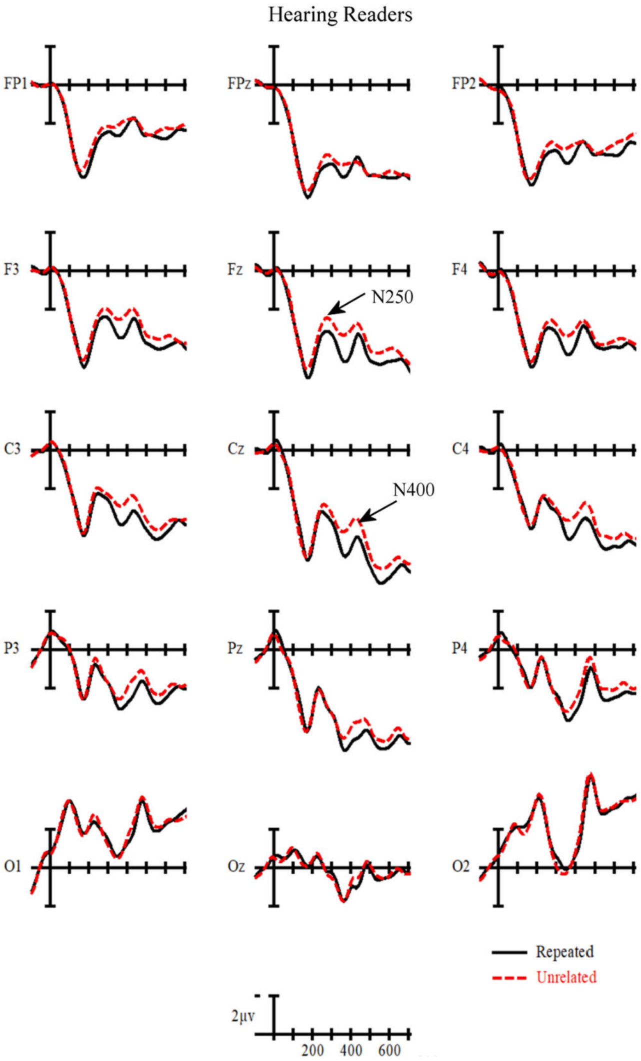

Fig. 3.

Grand average ERPs from 15 analysis electrodes time-locked to target words for the repeated (black solid) and unrelated (red dashed) conditions in hearing readers. In this and subsequent figures target onset is the vertical calibration bar and negative is plotted up.

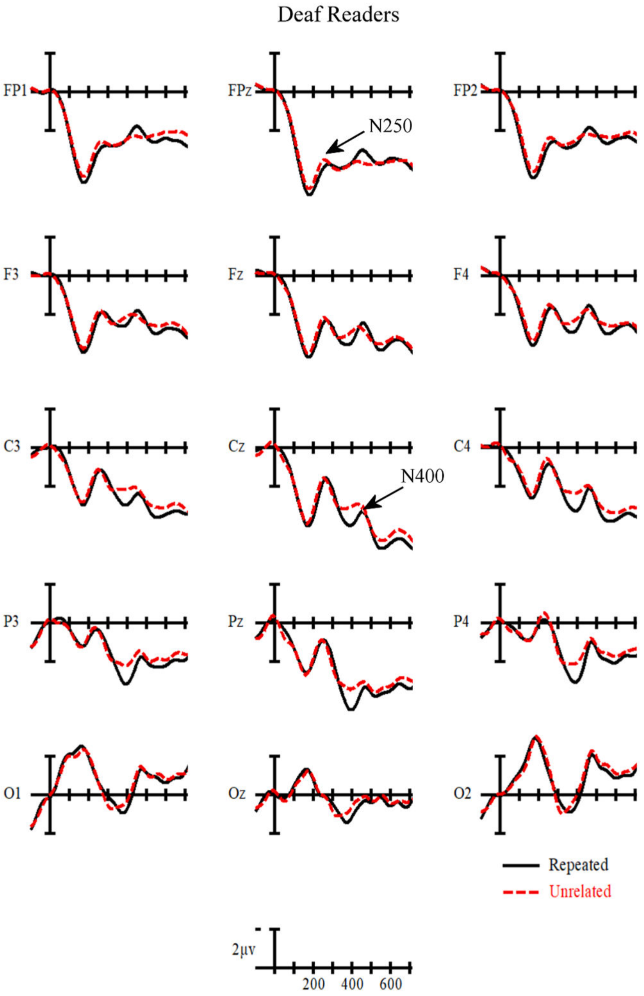

Fig. 4.

Grand average ERPs from 15 analysis electrodes time-locked to target words for the repeated (black solid) and unrelated (red dashed) conditions in deaf readers.

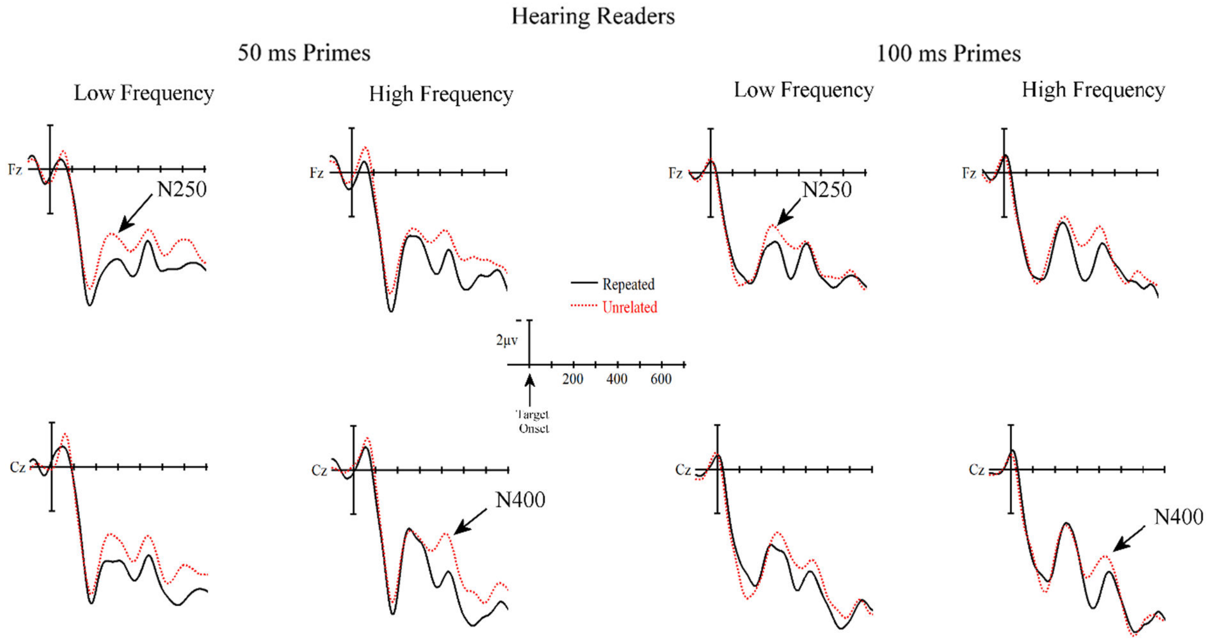

Fig. 5.

Grand average ERPs from two electrodes time-locked to target words for the repeated (black solid) and unrelated (red dashed) conditions in hearing readers. The four columns correspond to two prime durations and two target word frequency conditions.

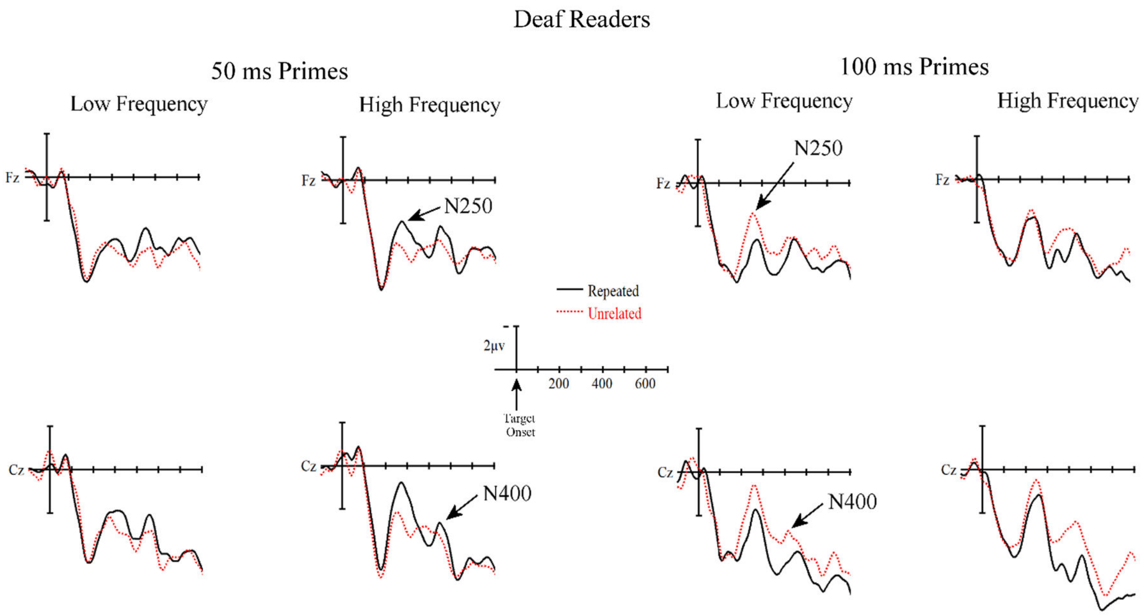

Fig. 6.

Grand average ERPs from two electrodes time-locked to target words for the repeated (black solid) and unrelated (red dashed) conditions in deaf readers. The four columns correspond to two prime durations and two target word frequency conditions.

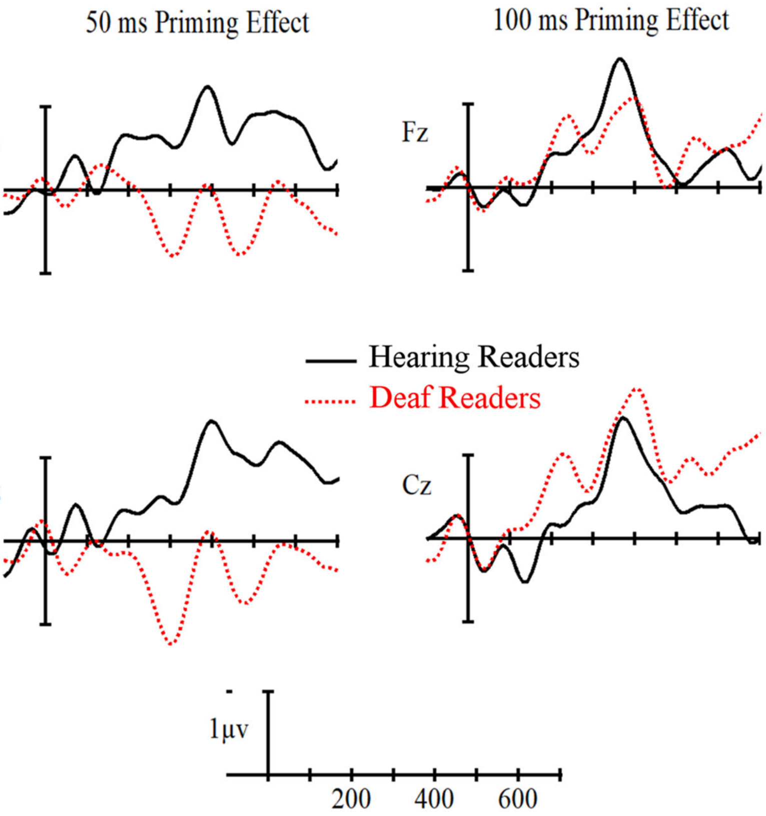

Fig. 7.

Difference waves computed by subtracting repeated target ERPs from unrelated target ERPs as a function of prime Duration and Group.

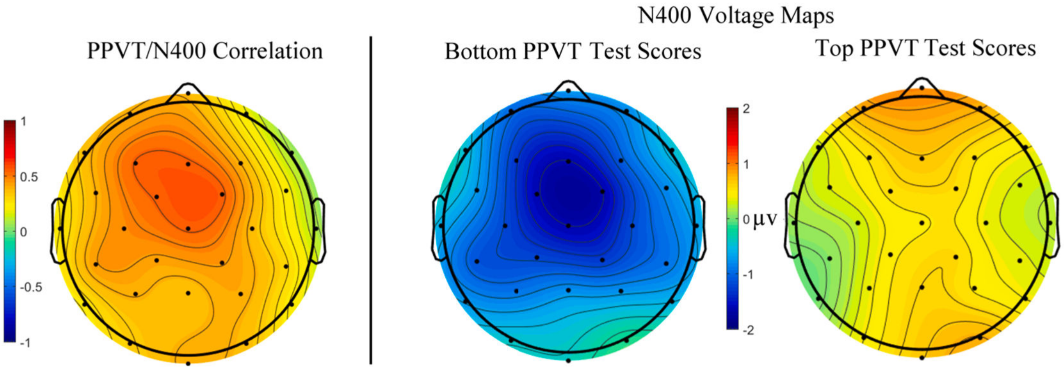

Fig. 8.

Correlation results showing that hearing readers with lower vocabulary scores (PPVT) had a larger N400 response. (Left) Map of correlations between mean amplitude 300–550 ms of the Priming effect with PPVT scores of each hearing participant. (Middle and right) Voltage maps of the N400 Priming effect (mean amplitude 300–550 ms for the Unrelated – Repeated target ERPs) for the nine hearing participants with the lowest PPVT scores (middle) and the eight highest PPVT scores (right).

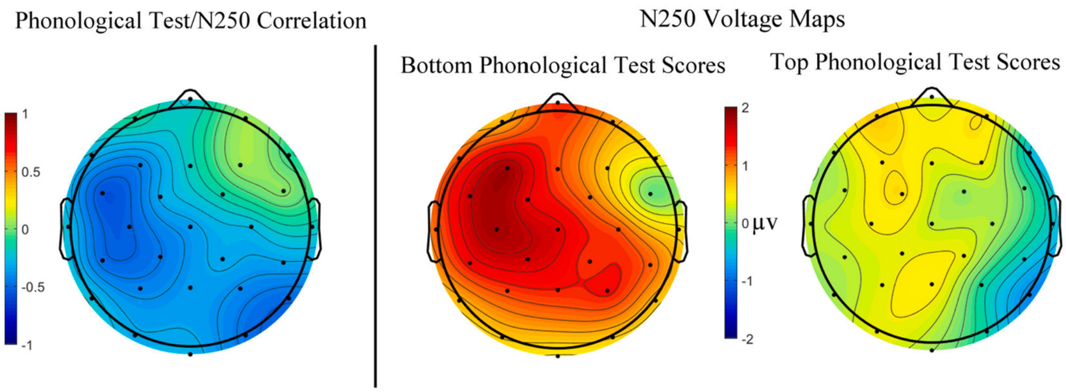

Fig. 9.

Correlation results showing that deaf readers with poorer phonological skills exhibited a reversed N250 in the 50 ms prime condition for high frequency words. (Left) Map of correlations between mean amplitude from 200 to 300 ms of the Prime effect with phonological test scores of each deaf participant. (Middle and right) Voltage maps of the Prime effect for the ten deaf readers who scored the lowest on the phonological test (middle) and the eight deaf readers who scored the highest on this test (right).