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The impact of visual cues during visual word recognition in deaf readers: An ERP study

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ABSTRACT

Although evidence is still scarce, recent research suggests key differences in how deaf and hearing readers use visual information during visual word recognition. Here we compared the time course of lexical access in deaf and hearing readers of similar reading ability. We also investigated whether one visual property of words, the outline-shape, modulates visual word recognition differently in both groups. We recorded the EEG signal of twenty deaf and twenty hearing readers while they performed a lexical decision task. In addition to the effect of lexicality, we assessed the impact of outline-shape by contrasting responses to pseudowords with an outline-shape that was consistent (e.g., mofor) or inconsistent (e.g., mosor) with their baseword (motor). Despite hearing readers having higher phonological abilities, results showed a remarkably similar time course of the lexicality effect in deaf and hearing readers. We also found that only for deaf readers, inconsistent-shape pseudowords (e.g., mosor) elicited larger amplitude ERPs than consistent-shape pseudowords (e.g., mofor) from 150 ms after stimulus onset and extending into the N400 time window. This latter finding supports the view that deaf readers rely more on visual characteristics than typical hearing readers during visual word recognition. Altogether, our results suggest different mechanisms underlying effective word recognition in deaf and hearing readers.

1. Introduction

Expert reading in alphabetic languages requires general language skills and efficient word recognition through rapid orthographic and phonological decoding (Gough & Tunmer, 1986). After appropriate instruction of grapheme-phoneme correspondences (Castles, Rastle, & Nation, 2018), and with enough practice, most hearing children recognise words rapidly and effortlessly. However, this is not the case for most deaf people, who find reading a challenging task. Indeed, current reading instruction only takes most deaf readers as far as a reading level equivalent to that of a 10-year-old (see, e.g., English: Traxler, 2000; Spanish: Sánchez & García-Rodicio, 2006)—this has a negative impact not only on their academic achievement but also on their social and emotional wellbeing (McArthur & Castles, 2017).

Given that phonological processing plays a key role for skilled reading in hearing people (see, e.g., Frost, 2012), the low reading attainment in many deaf people has often been attributed to their difficulties in phonological processing (see, e.g., Perfetti & Sandak, 2000). However, recent research supports a partially different view. The idea is that deaf readers can achieve a more efficient lexical access during reading using the visual-orthographic route rather than a phonologically based route (for a recent review, see Emmorey, 2020; Emmorey & Lee, 2021). Consistent with this proposal, we recently showed that, for deaf readers of Spanish, more efficient use of the visual-orthographic route correlated with better reading skills; in contrast, increased automatic phonological processing did not (see Gutierrez-Sigut, Vergara-Martinez, & Perea, 2017; Gutierrez-Sigut, Vergara-Martinez, & Perea, 2019). These findings can be accounted for by Bélanger and Rayner's (Bélanger & Rayner, 2015) word-processing efficiency hypothesis. This account proposes that skilled deaf readers "have tighter connections between orthography and semantics" (p. 224) than hearing readers. Bélanger and Rayner also proposed that deaf readers are "extremely attuned to the visual-orthographic makeup of words and quickly detect precise word forms" (p. 224). Indeed, deaf

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readers can extract more information than hearing readers from a given fixation during sentence reading (i.e., they skip more words, re-read fewer words, and refixate words less often; see also Traxler et al., 2021, for recent converging evidence).

Let's assume that deaf readers are indeed more attuned than hearing readers to the visual-orthographic features of words. In this case, we might expect clear differences between deaf readers and hearing readers of matched reading ability in aspects of lexical access linked to visual-orthographic processing. However, the literature is mixed. While most prior studies of visual word recognition have not found differences in orthographic processing between deaf and hearing participants (e.g Bélanger, Baum, & Mayberry, 2012; Bélanger, Mayberry, & Rayner, 2013; Cripps, McBride, & Forster, 2005; Fariña, Duñabeitia, & Carreiras, 2017; Meade, Grainger, Midgley, Holcomb, & Emmorey, 2019, 2020), recent neuroimaging research has shown subtle differences in deaf and hearing readers' responses to word stimuli, suggesting a larger prominence of visual-orthographic processing in deaf readers. Specifically, Emmorey, Midgley, Kohen, Sehyr, and Holcomb (2017) found that words elicited stronger left lateralization of the N170 event related potential (ERP) component in hearing than in deaf readers. Similarly, Glezer et al. (2018) found fine-grained orthographic tuning bilaterally for deaf readers but only left lateralized for hearing readers. Furthermore, Emmorey, Holcomb, and Midgley (2021) recently found a reversed priming ERP effect in deaf readers but not in hearing readers in response to case mismatch between prime and target words at short prime durations (see also Perea, Marcet, & Vergara-Martínez, 2016 for similar perceptual-visual effects in deaf readers). These recent findings point to nuanced differences in visual word recognition between deaf and hearing readers that can be assessed using highly sensitive paradigms.

In the present study, we first compared the processes underlying lexical access in deaf and hearing readers of similar reading ability by investigating the effect of lexicality (words vs. pseudowords) in an Event-Related Potentials (ERPs) lexical decision task experiment. The effect of lexicality (measured as the difference between responses to words and pseudowords) has been linked to orthographic knowledge (see e.g., Coch, 2015; Coch & Holcomb, 2003; Cuetos & Suárez-Coalla, 2009; Zoccolotti, De Luca, Di Filippo, Judica, & Martelli, 2008). Thus, the lexicality effect allows us to evaluate whether deaf and hearing readers are equally sensitive to the lexical principles of written language. Secondly, we investigated deaf and hearing readers' sensitivity to the "visual-orthographic makeup of words" by examining the responses to two types of pseudowords that only varied on the outline-shape of their base word. Specifically, we compared pseudowords with an outline-shape congruent with the base word (e.g., the pseudoword *mofor* is congruent with the outline-shape of its base word *motor* [engine]) or incongruent (e.g., the pseudoword *mosor*). Finally, we investigated whether the degree of sensitivity to outline word shape is associated with reading and phonological skills.

In the rest of the Introduction, we first summarize the behavioural and electrophysiological signatures of the lexicality effect. We focus on its relationship with orthographic knowledge, which is the basis of our first research aim. Second, we evaluate the impact of visual-orthographic features (i.e., the word outline-shape) on lexical access, which is the basis for our second research question.

1.1. The lexicality effect

The behavioural and electrophysiological correlates of the lexicality effect in visual word recognition in adult skilled readers are well-known (see, e.g., Grainger & Holcomb, 2009; Stone & Van Orden, 1989; Swaab, Ledoux, Camblin, & Boudewyn, 2012a; Wagenmakers et al., 2004). Behaviourally, the finding of faster RTs obtained for words vs. pseudowords in lexical decision tasks is interpreted as an index of familiarity (words are familiar letter-strings) and accessibility of lexical-semantic information stored in long-term memory (nonwords do not have an entry in the mental lexicon). The best-known electrophysiological correlate of the lexicality effect is a larger N400 amplitude in response to pseudowords than words (also see, e.g., Hauk, Coutout, Holden, & Chen, 2012 for early effects of lexical status), a result thought to reflect increased efforts during lexical access as readers struggle to find a matching lexical entry (see, e.g., Kutas & Federmeier, 2011). Interestingly, the advantage of reading words over pseudowords has been linked to orthographic knowledge: the lexicality effect increases as a function of understanding the conventions of the writing system (Conrad, Harris, & Williams, 2013; Cuetos & Suárez-Coalla, 2009). For example, Zoccolotti et al. (2008) showed that, in children, the advantage in response times for words over pseudowords increased from first to eight grade as words' representations consolidate in the mental lexicon (see also Cuetos & Suárez-Coalla, 2009; Job, Peressotti, & Cusinato, 1998; Orsolini, Fanari, Tosi, De Nigris, & Carrieri, 2006; Seymour, Aro, Erskine, & Network, 2003). That is, as more words are incorporated into the vocabulary, detailed orthographic representations are built and linked to lexical memory (Perfetti, 2007; Zarić, Hasselhorn, & Nagler, 2021).

Similarly, it is generally assumed that the increase in the N400 elicited by pseudowords observed for more experienced readers reflects an increase in the refinement of the word processing system (Coch, 2015; Coch & Holcomb, 2003). In their study with young readers, Coch and Holcomb (2003) found that pseudowords elicited a larger N400 than known words in high- but not in low-ability readers. These findings indicate that being less experienced with word stimuli, low-ability young readers were reading less automatically than their high-ability peers. Therefore, the electrophysiological correlates of the lexicality effect can be used to assess the similarity of the neurocognitive systems underlying word recognition in different groups of readers.

To the best of our knowledge, the present study is the first that directly contrasts the behavioural and electrophysiological correlates of the lexicality effect in deaf and hearing readers of comparable reading ability. To maximise the chances of observing differences related to orthographic knowledge in adult readers, we chose pseudowords that only differed in one letter from their base words (e.g., the pseudoword *mosor* vs. the Spanish word *motor*) (see Vergara-Martínez, Perea, Gómez, & Swaab, 2013 for a similar approach and discussion of the prior literature, p. 2). Similar to what we have observed before in a group of deaf readers (Gutierrez-Sigut, Vergara-Martínez, & Perea, 2019) and the previous literature in hearing readers, we expect faster response times and lower amplitude N400s for words than pseudowords for both groups. Given their equivalent reading ability, similar time courses of lexical access between both groups would suggest that the development of orthographic knowledge could support efficient word recognition in deaf readers despite them having a lower ability at a phonological task. Conversely, differences in the timing, size or distribution of the effects would reflect differences in the neurophysiological underpinnings of word recognition.

1.2. On the use of visual-orthographic features: the effect of outline word shape

During visual word recognition, most researchers assume that readers can rapidly access abstract letter/word representations. Indeed, neurally-inspired models of printed word recognition (Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger, Rey, & Dufau, 2008) assume that perceptual elements (e.g., color, font, size, or letter-case) do not play a role after the initial perceptual stages. In behavioural studies, the visual features' limited role is typically reflected in facilitation from identity primes independently of them sharing or not visual features with the target. For example, Bowers, Vigliocco, and Haan (1998) found a similar degree of facilitation in a behavioural masked priming experiment for English words that were similar and dissimilar in upper- and lower-case (e.g., compare kiss-KISS vs. edge-EDGE), indicating that access to abstract letter identity overrides perceptual similarity (for similar findings in adult and beginner readers in other languages see: Arabic Perea, Mallouh, & Carreiras, 2013; French Jacobs, Grainger, & Ferrand, 1995; and Spanish Perea, Jiménez, & Gomez, 2015). At the electrophysiological level, Vergara-Martínez, Gómez, Jiménez, and Perea (2015) found differences between words preceded by masked identity primes displayed in the same case or a different case in a perceptual component (N/P150; VILLA-VILLA vs. villa-VILLA) that vanished by 200 ms post-stimulus onset. That is, when the initial contact to abstract letter identities is achieved (<200 ms), visual features do not further facilitate word processing.

When looking specifically at outline word shape (e.g., comparing crown [flat word] vs. bishop [non-flat word]), previous research has shown that word recognition times of normo-typical readers, both adult and children, from 4th grade on, are not affected by this visual cue (Lavidor, 2011; Perea & Panadero, 2014). However, the scenario is different for individuals with dyslexia. In a lexical decision task, Lavidor (2011) found that adult dyslexic readers, but not typical readers, responded faster to words with a distinctive physical appearance (i.e., non-flat words such as *bishop*) than to flat words (e.g., *crown*). Likewise, Perea & Panadero, 2014 contrasted response times of typical adult and young readers as well as young dyslexic readers to two types of pseudowords that, while differing in just one letter from their base word, had a consistent outline-shape (e.g., *viotin* vs. word base *violin*) or an inconsistent outline-shape (e.g., *viocin*). They found that only young dyslexic readers were sensitive to the outline-shape (worse performance to *viotin* [base word violin] than to *viocin*). The larger difficulty in resolving lexical ambiguity for "viotin" pseudowords compared to "viocin" pseudowords can be explained by the increased effort in differentiating "viotin" and "violin" (base word), due to larger perceptual overlap. This suggests poor letter representations in young readers with developmental dyslexia. These results have been interpreted within the framework of interactive models of word recognition, where top-down feedback from the phonological and lexical levels support more precise letter representations (see Carreiras, Armstrong, Perea, & Frost, 2014). In this context, readers with poorer phonological representations are likely to have less precise orthographic representations and hence are likely to be more influenced by visual cues that play a limited role in visual word recognition for expert readers (e.g., font, outline-shape, size, etc.)

Similar to dyslexic readers, deaf readers have underspecified phonological representations. Their poor phonological representations are not likely to fully contribute to improving orthographic precision. This reduced contribution from phonological representations might result in deaf readers also being more sensitive to visual features that, in the context of hearing skilled reader's visual word recognition, are supposed to play a minor role. For instance, in an analysis of spelling errors in deaf readers, Padden (1993) found a high rate of confusions among letters of the same height (t, d, and b) or among letters with descenders (p, q, and g), reflecting attempts to reproduce the overall shape of words. Similarly, Perea et al. (2016) found an advantage of nominally and physically identical priming condition (EDGE-EDGE) over the nominally identical priming condition (edge-EDGE) in deaf but not in hearing readers' behavioural responses, suggesting differences in visual-orthographic processing between the groups (see Gutierrez-Sigut, Vergara-Martínez, & Perea, 2019, for similar behavioural results).

Thus, the second aim of the present experiment is to contrast the behavioural and electrophysiological responses of deaf and hearing readers with similar reading ability but different phonological skills (i.e., lower syllable counting accuracy in the deaf group) to two types of pseudowords. For half of the pseudoword targets, an ascending or descending consonant (e.g., t in motor [engine]) was replaced by another ascending or descending consonant (congruent-shape pseudoword: e.g., *mofor*). For the other half, the replacement resulted in an incongruent-shaped pseudoword (e.g., *mosor*). In line with Perea & Panadero, 2014 results, we expect no differences in processing of both pseudoword types in hearing readers. Critically, if deaf readers have developed precise orthographic representations regardless of their poorer phonological representations, we would expect no differences between the two types of pseudowords. Conversely, if deaf readers are more reliant than hearing readers on visual information, we would expect larger interferences in the correct no-responses to congruent-shape (e.g., *mofor)* compared to incongruent-shape pseudowords (*mosor)*.

Finally, in order to assess the relationship between reading and phonological skill and the effect of outline shape, we performed correlational analyses. First, if less-skilled deaf readers are less finely tuned to the visual-orthographic properties of words, we would expect a negative correlation between the size of the outline-shape effect and reading ability. Second, if better phonological skills help stabilize the orthographic representation, which allows discarding the outline-shape information, we would expect a negative correlation between the size of the outline-shape effect and performance in a phonological task (syllable counting).

In sum, in the present experiment, we aim to track down the time course of lexical access in deaf readers, investigating the similarities and differences in processing between deaf and hearing readers of similar reading ability. We also aim to elucidate whether one visual property of words, outline-shape, modulates visual word recognition in deaf readers. Finally, we explore whether reading and phonological skills are correlated to differences in processing due to outline-shape.

2. Methods

2.1. Participants

Twenty-three congenitally deaf participants were recruited for this experiment. Data from 3 participants had to be rejected due to an excessive number of movements and other artefacts (more than 60% of the trials). The remaining 20 participants (8 female) were profoundly deaf and skilled signers. Six participants were native signers of Spanish sign Language (LSE), eight were early signers (learn sign language before the age of 6), and six were late signers. Their ages ranged from 21 to 54 years (M = 39, SD = 9.3). In addition to the deaf participants, twenty hearing participants (10 female) were selected for the study from the same communities and with similar socioeconomic status (e.g. type of job, highest education level achieved). They did not know sign language. Their ages ranged from 20 to 53 years (M = 38, SD = 8.4). All participants were right-handed, had no neurological or psychiatric impairment history, and had normal (corrected-to-normal) vision.

All participants were tested on reading ability (measured with TECLE; Carrillo & Marín, 1997) and phonological processing during an explicit phonological task (syllable counting). Participant's performance in both tasks was correlated (see Table 1). Deaf and hearing participants did not differ significantly in reading ability. However, deaf readers were significantly less accurate than hearing readers in the syllable counting task.

This study was approved by the Research Ethics Committee of the University of Valencia. This research was conducted according to the relevant guidelines, and all participants gave written informed consent before the experiment. Information necessary for the informed consent was given to deaf participants both in writing and in LSE.

Table 1
Mean scores for off-line measures of reading and phonological abilities for each group separately as well results of independent samples *t*-test for each of the measures.

	Deaf Mean (SD)	Hearing Mean (SD)	*t* (38)	*p*
Reading (% correct)	68.3 (29)	79.5 (17)	−1.47	0.149
Phonological processing (% correct)	74.4 (13)	86.5 (8)	3.54**	0.001

2.2. Materials and design

A set of 160 words (average length = 6.8 letters, range: 5–8) were selected for the experiment. The mean frequency of these words was 42 per million (range: 1–384) in the Spanish ESPAL database (Duchon, Perea, Sebastián-Gallés, Martí, & Carreiras, 2013). The mean number of one-letter substitution neighbours for these words was 3 (range: 0–20). From these, 120 contained one ascending or descending letter in an internal position and were the base words for the pseudowords in the experiment. We created 240 pseudowords by replacing the ascending or descending consonant letter from the base words. For half of the pseudoword targets, an ascender consonant (e.g., *t* in the word *motor*) was replaced by another ascending consonant (consistent-shape pseudoword: e.g., *mofor*). For the other half, the replacement resulted in an inconsistent-shape pseudoword (e.g. *mosor*). The mean log bigram frequency in the two sets of pseudowords was virtually the same (2.3 in each set, $p > .50$), both sets of pseudowords also had the same syllable structure as their base words. We created 3 lists of counterbalanced items in a Latin square manner (*motor* would be presented in list 1, *mofor* in list 2 and *mosor* in list 3). The remaining 40 words were flat (did not contain any ascending or descending letters) and were presented in all three counterbalancing lists—as a result, each participant was presented with 80 words and 80 pseudowords.

In addition, eight words and eight pseudowords (4 flat and 4 containing an ascending letter) were used as practice items. The complete list of experimental materials can be found in Appendix A.

2.3. Procedure

Participants were seated comfortably in a darkened room. All stimuli were presented on a high-resolution monitor that was positioned slightly below eye level, 85–90 cm in front of the participant. The size of the stimuli and distance from the screen allowed for a visual angle of less than 3.6 degrees horizontally. Stimuli were presented in the center of the screen, in white 24-pt Courier font against a dark-gray background. The participants viewed a fixation cross (+) for 500 ms, followed by a 100 ms blank and, next, by the target stimulus, which remained on the computer screen until the participant responded or 2000 ms had elapsed. After participants' response, the drawing of an eye stayed on screen for 2000 ms to allow for blinks, followed by a blank screen of a random duration between 700 and 1000 ms. Participants were asked to decide as fast and accurately as possible if the target stimulus was a real Spanish word or not. They pressed one of two response buttons (SÍ [YES] /NO). The hand used for each response was counterbalanced across participants. RTs were measured from target onset until the participant's response. Each participant was randomly assigned to one of the three counterbalanced lists. The order of stimuli presentation from each list was randomized for each participant. The session lasted approximately 20 min.

2.4. EEG recordings and analysis

The electroencephalogram (EEG) was recorded from 33 Ag/AgCl active electrodes (four of them around the eyes to record the electrooculogram) referenced to the right mastoid. The recording was re-referenced offline to the average of left and right mastoids. Signals were sampled continuously with a sampling rate of 250 Hz, and band-pass filtered offline between 0.01 and 30 Hz. Initial analysis of the EEG data was performed using the ERPLAB (Lopez-Calderon & Luck, 2014) for EEGLAB (Delorme & Makeig, 2004). Epochs of 550 ms post-target onset, with a 100 ms baseline were analysed. Trials with eye movements, blinks, muscle activity or other artefacts were rejected (all participants had more than 20 valid trials in each condition—there were no significant differences in the number of rejected trials between conditions, *ps* > 0.3).

To precisely characterize the time course and scalp distribution of lexical processing during single word recognition in deaf and hearing readers, and in order to inform the selection of larger analysis windows, we first performed a massive univariate analysis for the lexicality effect. ERP responses to words vs pseudowords were compared (e.g.,*motor* vs. *mosor*) for each group of participants (deaf vs. hearing readers) separately. Specifically, we performed repeated measures two-tailed *t*-tests at each sampling point between 100 and 550 ms at 23 scalp electrodes (i.e. Fp1, FC1, FC5, C3, CP1, CP5, P3, P7, T7, O1, Fz, Cz, Pz, Fp2, FC2, FC6, C4, CP2, CP6, P4, P8, T8 and O2; total of 3051 comparisons; see Fig. 1). The Benjamini and Yekutieli (2001) procedure for control of the false discovery rate (FDR: i.e., mean proportion of significant test results that are false discoveries or Type I errors) was applied to assess the significance of each test using an FDR level of 5%. For the deaf readers, this analysis showed significant early differences, between approximately 150 and 200 ms, at central and central-right electrodes (i.e., Cz, Pz, FC2, C4, CP2, and P8). Further significant differences between words and pseudowords were consistent with the timings and central distribution of the N400. Initially, between 300 and 400 ms, the differences were restricted to central electrodes bilaterally (Fz, Cz, FC1, C3, CP1, P3, FC2, C4 and CP2). The difference between words and pseudowords were widely distributed from 400 ms until the end of the epoch. For the hearing readers, the results of this analysis showed short-lived differences between words and pseudowords approximately between 250 and 300 ms that were strong at posterior-right electrodes (CP6, P8, and O2). This analysis also showed widely distributed differences between words and pseudowords starting around 400 ms until the end of the epoch.

To directly contrast ERPs of hearing and deaf participants for the lexicality and outline-shape effects independently, we used the results of this univariate analysis to guide the selection of 4 large time windows (150–200 ms, 250–300 ms, 300–400 ms, and 400–550 ms) and the selection of 6 representative fronto-central, central and centro-parietal electrodes (FC1, FC2; C3, C4; and CP1,CP2, respectively; see Gutierrez-Sigut, Vergara-Martínez, & Perea, 2017, Gutierrez-Sigut, Vergara-Martínez, & Perea, 2019; Laszlo & Federmeier, 2014 for similar data-driven approaches). We then included the mean voltage amplitude of each time window at each electrode in separate mixed ANOVAs including the factors Group (Deaf vs. Hearing), hemisphere (left vs. right), A-P distribution (anterior, central and posterior electrode sites), and either Lexicality (word vs. pseudoword) or Outline-shape (congruent vs. incongruent). Effects of hemisphere, A-P distribution, and Group factors are only reported when they interact with the experimental manipulation. Interactions between factors were followed up with simple-effects tests.

3. Results

The mean lexical decision times and percentage of correct responses per condition are displayed in Table 2. Note that incorrect responses (2.8%) and lexical decision times above and below the 2.5 SDs of the average per participant and condition (2.5%) were excluded from the latency analysis.

3.1. Lexicality

Fig. 1 shows the scalpmaps, the results of the univariate analysis and the ERP waves of the words (black) and pseudowords (red) in one representative electrode for the deaf (left) and hearing (right) readers. The ERPs in the target epoch produced an initial negative component peaking around 50 ms, which was followed by a slightly larger negative peak around 100 ms, and then by a larger and slower positivity (P2) ranging between 130 and 300 ms. Following these early potentials, a large and slow negativity peaking around 400 ms can be seen widely distributed across the scalp.

3.1.1. Behavioural results

Repeated measures ANOVAs with the factors Lexicality (words vs.

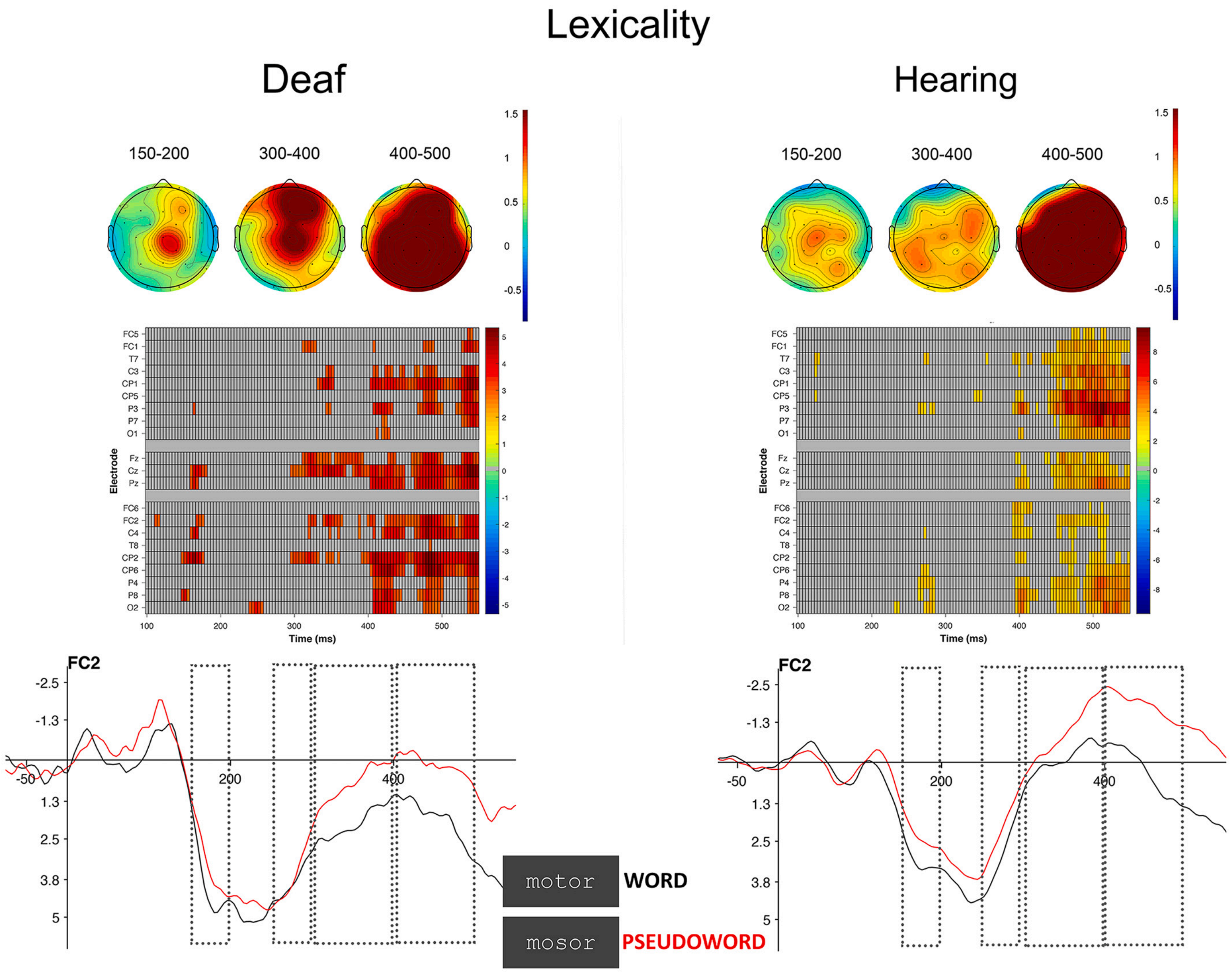

Fig. 1. Time course of the effect of lexicality in deaf (left side of the image) and hearing (right side), including from top to bottom: a) the topographic distribution of the lexicality effect (difference in voltage amplitude between the ERP responses to words and pseudowords), b) the results of the univariate analysis, and c) the grand average ERPs in one representative electrode for each group.

Table 2
Average percentage of accurate responses and average response times for each group in each of the type of stimuli tested.

	Accuracy		RTs	
	Deaf Average (SD)	Hearing Average (SD)	Deaf Average (SD)	Hearing Average (SD)
Words	94.6 (8.9)	98 (2.4)	745 (202)	780 (137)
Incongruent outline-shape pseudowords	90.5 (12.5)	93.1 (9)	944 (156)	1069 (208)
Congruent outline-shape pseudowords	89.4 (13.8)	93.8 (8.1)	943 (187)	1071 (226)

incongruent outline-shape pseudowords) and Group were performed separately for the latency and accuracy data (subjects [F1] and items [F2] analyses were performed for both).

The latency analysis revealed a main effect of lexicality, $F1(1,38) = 98.91$, $p < .001$; $F2(1238) = 638.64$, $p < .001$. The main effect of group was not significant in the F1 analysis, $F1(1,38) = 2.48$, $p = .123$; $F2(1238) = 73.12$, $p < .001$ and the interaction was only marginally significant in the F1 analysis, $F1(1,38) = 3.4$, $p < .073$; $F2(1238) = 6.52$, $p = .011$. Response times were significantly faster for words than for pseudowords in both deaf and hearing readers (all $ps < 0.001$).

The accuracy analysis also revealed a main effect of lexicality, $F1(1,38) = 8.71$, $p = .005$; $F2(1238) = 7.004$, $p = .009$. The main effect of group and the interaction were not significant (all *ps* > 0.15).[1]

3.1.2. ERP results

We performed repeated-measures ANOVAs (see EEG recording an analysis section for details) including the factors Hemisphere, A/P distribution, Lexicality and Group separately on each time window of interest.

150–200 ms. There was a significant main effect of Lexicality, $F(1,38) = 7.7$, $p = .009$. The interaction between Lexicality and Group was not significant, $F(2,76) < 1$. No other interactions with Lexicality were significant (all *ps* > 0.10).

250–300 ms. There was a significant main effect of Lexicality, $F(1,38) = 4.2$, $p = .047$. No other effects or interactions were significant, (all *Fs* < 1).

300–400 ms. There was a significant main effect of Lexicality, $F(1,38) = 10.9$, $p = .002$. The interaction between Lexicality and Group was not significant, $F(2,76) < 1$. No other interactions with Lexicality were significant (all *ps* > 0.41).

400–550 ms. There was a significant main effect of Lexicality, $F(1,38) = 30.6$, $p < .001$. The interaction between Lexicality and Group was not significant, $F(2,76) < 1$. No other interactions with Lexicality were significant (all *ps* > 0.1).

3.1.3. Correlations with reading ability

The size of the behavioural effect of lexicality was not correlated with reading ability in neither group (all *ps* > 0.1). The same was true for the ERP lexicality effects: there were no significant correlations with reading ability at any of the selected electrodes in any of the time windows of interest in neither of the groups (all *ps* > 0.1).

3.2. Effect of outline-shape

Fig. 2 shows the scalpmaps and the ERP waves of the congruent outline-shape pseudowords (blue) and incongruent outline-shape pseudowords (red) in one representative electrode for the deaf (left) and hearing (right) readers.

3.2.1. Behavioural results

Repeated-measures ANOVAs with the factors Outline-shape (congruent vs incongruent) and group were performed separately for the latency and accuracy data (subjects [F1] and items [F2] analyses were performed for both).

The latency analysis revealed a main effect of group, $F1(1,38) = 4.29$, $p = .045$; $F2(1238)$ 97.67, $p < .001$, showing that the deaf readers were faster than the hearing readers (mean 943 vs. 1070 respectively) regardless of the type of pseudoword. The main effect of outline-shape and the interaction were not significant (all *Fs* < 1). The accuracy analysis did not show any significant effects (all *ps* > 0.112).

3.2.2. ERP results

We performed repeated-measures ANOVAs (see EEG recording an analysis section for details) including the factors Hemisphere, A/P distribution, Lexicality and Group separately on the same electrode sites and time windows used in the Lexicality analysis.

150–200 ms. There was a significant main effect of Outline-shape, $F(1,38) = 8.19$, $p = .007$, that was qualified by an interaction between Outline-shape, A/P distribution and Group, $F(2,76) = 3.89$, $p = .035$. There were no significant differences for hearing readers at any of the electrode sites (all *ps* > 0.12). In deaf readers, congruent outline-shape pseudowords elicited a significantly more positive ERP than incongruent pseudowords at anterior, $F(1,38) = 7.69$, $p = .009$), and posterior electrodes, $F(1,38) = 11.38$, $p = .002$), the difference did not reach statistical significance at central electrodes, $F(1,38) = 3.43$, $p = .073$). No other interactions with Outline-shape were significant (all *ps* > 0.13).

250–300 ms. There were no significant effects or interactions, (all *ps* > 0.07).

300–400 ms. There was a significant interaction between Outline-shape, A/P distribution and Group, $F(2,76) = 4.98$, $p = .010$. There were no differences for hearing readers at any of the electrode sites (all *ps* > 0.23). In deaf readers incongruent outline-shape pseudowords elicited a significantly more negative ERP than congruent pseudowords at anterior electrode sites, $F(1,38) = 4.24$, $p = .047$), the difference was only marginally significant at posterior electrodes, $F(1,38) = 3.45$, $p = .071$), and did not reach significance at central electrodes, $F(1,38) = 1.12$, $p = .297$). The main effect of Outline-shape and the remaining interactions with Outline-shape were not significant (all *ps* > 0.14).

400–550 ms. The interaction between Outline-shape, A/P distribution and Group was only marginally significant, $F(2,76) = 3.74$, $p = .075$. Planned comparisons showed that there were no differences for hearing readers at any of the electrode sites (all *ps* > 0.24). In deaf readers incongruent outline-shape pseudowords elicited a significantly more negative ERP than congruent outline-shape pseudowords at posterior electrode sites, $F(1,38) = 4.27$, $p = .046$). The difference was only marginally significant at anterior electrodes, $F(1,38) = 3.34$, $p = .076$), and did not reach significance at central electrodes, $F(1,38) = 2.75$, $p = .105$). The main effect of Outline-shape and the remaining interactions with Outline-shape were not significant (all *ps* > 0.14).

3.2.3. Correlations with behaviour

The size of the behavioural effect of outline-shape (RTs to congruent minus RTs to incongruent outline-shape pseudowords) was negatively correlated with reading ability and with phonological processing in deaf readers (see Table 3). This is, more skilled deaf readers—and those with better phonological skills—were less influenced by the outline-shape of the pseudowords than less skilled deaf readers. The effect of outline-shape on accuracy was not correlated to the reading-related measures. There were no significant correlations in hearing readers (see Table 3).

The ERP effect of outline-shape was not correlated with reading ability nor phonological processing at any of the selected electrodes in any of the time windows of interest in neither in deaf (all ps >0.17) nor in hearing readers (all ps >0.22).

4. Discussion

We designed a lexical decision experiment to compare the time course of the lexicality effect in adult deaf and hearing readers of Spanish with similar reading ability. We also investigated the electrophysiological correlates of processing a visual feature such as the word's outline-shape. Results showed an equivalent lexicality effect in both groups, as well as a larger sensitivity to outline-shape in deaf than in hearing readers. We will discuss these two findings in order.

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[1] Note that words were compared to incongruent-shape pseudowords to avoid a confounding with the potential effects of visual similarity that could be specific to deaf participants—this issue will be addressed by our second research question. However, as requested by a Reviewer, we also conducted a three-way ANOVA including words and both types of pseudoword. Unsurprisingly, the results are virtually the same for both types of pseudowords. For the latency data, the results from this analysis show a main effect of Lexicality, $F1(2,76) = 63.3$, $p < .001$; $F2(1357) = 344.6$, $p < .001$. Responses were faster for words than for both incongruent- and congruent shape pseudowords (all *ps* < 0.001). There were no significant differences between both types of pseudowords (both *ps* $= 0.181$). The main effect of group did not reach significance in the by-subject analysis, $F1(1,38) = 3.14$, $p = .084$; $F2(1357) = 73.12$, $p < .001$, and the interaction was not significant in the by-subject analysis, $F1(2,76) = 2.3$, $p < .113$; $F2(1238) = 3.61$, $p = .028$. The accuracy analysis also revealed a main effect of lexicality, $F1(2,76) = 8.35$, $p \leq 0.001$; $F2(1357) = 5.24$, $p = .006$. Responses were more accurate for words than for either type of pseudoword (all *ps* < 0.005), but there was no significant difference between both types of pseudoword (*ps* > 0.05). The main effect of group and the interaction were not significant (all *ps* > 0.2).

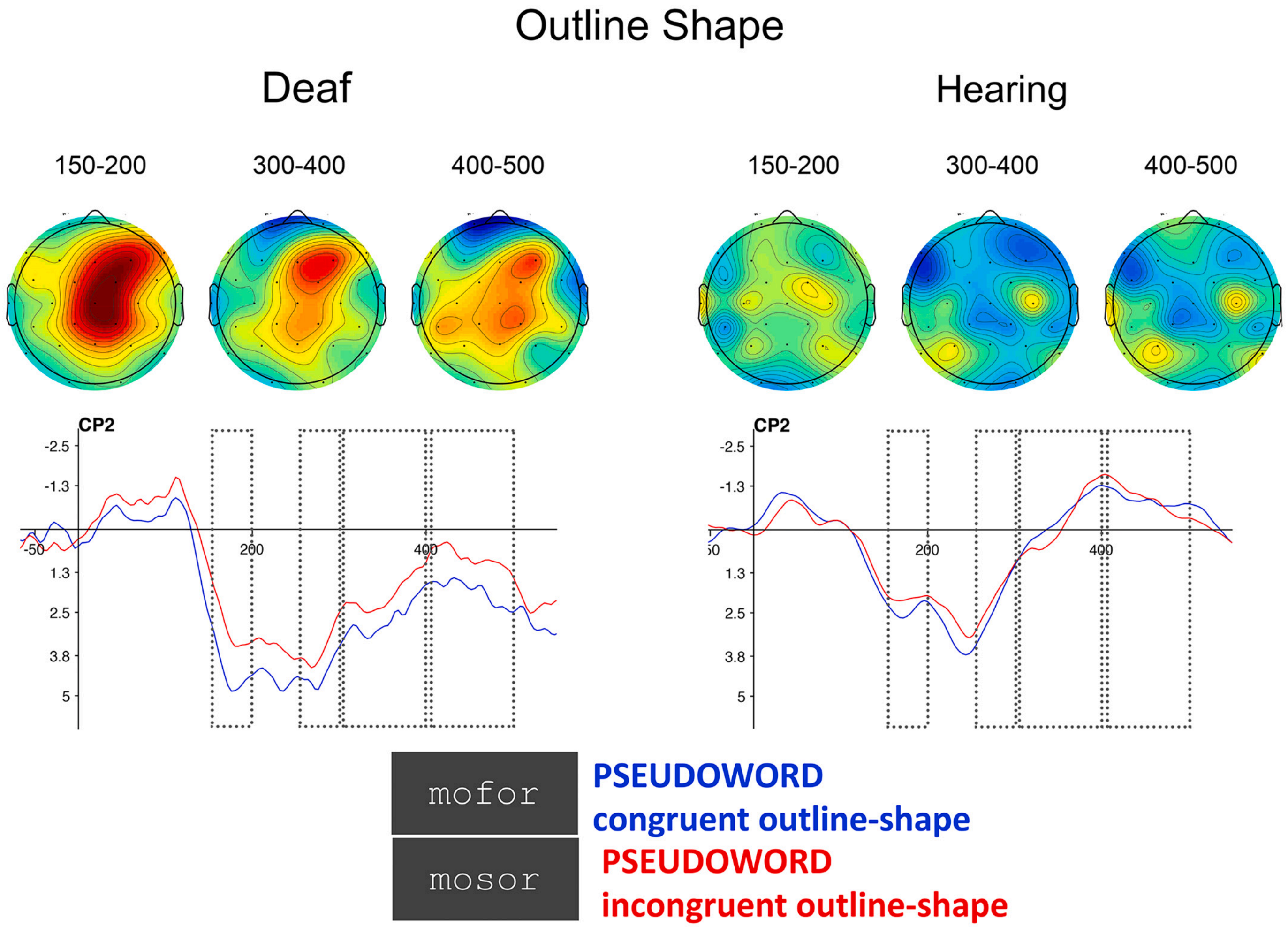

Fig. 2. Time course of the effect of outline-shape in deaf (left side of the image) and hearing (right side), including the topographic distribution of the effect and the grand average ERPs in one representative electrode for each group.

Table 3
Pearson correlations (r) between the offline measures of reading and RTs and accuracy during the behavioural task.

	Deaf		Hearing	
	Reading ability	Phonological processing	Reading ability	Phonological processing
RTs	−0.54**	−0.59**	0.08	0.15
Accuracy	0.33	0.45	0.21	0.30

* $p < .05$; * $p < .01$; ** *$p < .001$.

4.1. The time course of lexical processing in deaf and hearing readers

We directly compared the behavioural and electrophysiological correlates of the lexicality effect in deaf and hearing adult readers. Importantly, both groups were matched in reading ability although the hearing group performed significantly better in an explicit phonological task. Consistent with previous findings with deaf and hearing readers separately, we found a lexicality effect in both the behavioural (response times and accuracy) and the electrophysiological measures for both groups. Regarding the time course of the ERPs, the larger negativities for the pseudowords than for the words were present early on, between 150 and 200 ms post stimulus onset (see e.g. Hauk et al., 2012 for effects of lexicality starting before 200 ms post stimulus onset) in the centrally distributed electrodes where they are typically observed (see e.g. Swaab, Ledoux, Camblin, & Boudewyn, 2012b). The present data confirms and expand our previous finding (Gutierrez-Sigut et al., 2019) of a robust lexicality effect in deaf readers of Spanish in an experiment using a completely different paradigm (masked priming). More importantly, the direct comparison of the deaf and hearing groups' responses showed no significant differences between the groups neither at the behavioural nor at the electrophysiological level. Note that although the earlier effect of lexicality (150–200 ms post stimulus onset) seemed robust only for the deaf participants (as indicated by the univariate analyses), the differences between the groups at that time window were far from significant. Later differences between words and pseudowords were consistent with an N400 effect and, again, the between-group comparisons showed that the timing and size of the effect were comparable for deaf and hearing readers.

Altogether, our behavioural and ERP findings point to similar sensitivity to lexical principles of written language in deaf and hearing adult readers. Interestingly, this similarity occurs despite significant differences in performance in an explicit phonological task (i.e., higher syllable counting accuracy for hearing than deaf readers). A similar pattern has been reported in hearing children that have not yet developed in full the grapheme-phoneme relationships (Cuetos & Suárez-Coalla, 2009; Job et al., 1998; Orsolini et al., 2006; Seymour et al., 2003). For example, Cuetos and Suárez-Soalla (2009) found behavioural lexicality effects in children at the end of their kindergarten year who had just acquired awareness of the graphemes but had not mastered the grapheme to phoneme conversion rules yet. The authors argued that an early stage of acquisition of grapheme-phoneme conversion mechanisms is not a necessary steppingstone to advance from phonological decoding to the orthographic stage of reading, even in transparent languages such as Spanish. We propose that the present results can be interpreted in the same way. Deaf readers, in the absence of fully specified phonological representations of the words, use orthographic knowledge to facilitate lexical access and therefore for reading. This is not to say that deaf readers are unable to use phonological information from written words. We have recently shown that deaf readers of Spanish with a wide range of reading skills automatically activate phonological codes during word recognition (Gutierrez-Sigut, Vergara-Martínez, Marcet, & Perea, 2018; Gutierrez-Sigut et al., 2017; see also Sehyr, Petrich, & Emmorey, 2016, who found a phonological similarity effect of the same magnitude in deaf and hearing signers in a serial word-recall task, despite significantly different performance in an explicit phonological task). However, our recent work also showed that this automatic use of phonology has a less significant role for deaf than hearing readers explaining reading skill (i.e. the size of the phonological effect was correlated with reading ability for hearing but not for deaf readers). Deaf participants in the present study showed an average accuracy of 75% percent correct responses in the syllable counting task. This accuracy level is above the expected for a random response, but it is still lower than the score for the hearing group. This pattern suggests a partially specified phonological representation of words for deaf readers, which previous neuroimaging studies with similar participants have identified as coarse-grained (e.g. Glezer et al., 2018). However, the coarse-grained phonological representations of our deaf readers do not seem to hinder accurate lexical access during visual word recognition, as shown by the similarity between hearing and deaf readers regarding the lexicality effect. One might argue that deaf readers achieve the present outcome by relying more on orthographic knowledge. This interpretation is consistent with Glezer et al.'s (2018; see also Emmorey & Lee, 2020; Sehyr et al., 2016) proposal that deaf readers' phonological coding during implicit word reading tasks is coarser grained than that of their hearing counterparts (Glezer et al., 2018) and that fine-grained orthographic processing might hold a heavier weight during lexical access in deaf readers.

4.2. *The effect of outline-shape in deaf and hearing readers*

The second aim of the present study was to examine whether a visual-orthographic cue, such as the outline-shape, had a differential effect in deaf and hearing readers. Furthermore, we explored the links of visual-orthographic processing with reading and phonological skills. We found that the behavioural measures were not sensitive enough to capture subtle differences in processing between both groups. That is, neither response times or accuracy showed a benefit of outline-shape—defined as faster times or less errors at rejecting incongruent than congruent outline-shape pseudowords. However, the high sensitivity of the ERP measures allowed us to detect an increased negativity for incongruent outline-shape pseudowords (e.g. mosor, base word motor) when compared to the congruent outline-shape pseudowords (e.g. mofor) for deaf readers only. In other words, deaf—but not hearing—ERP responses were modulated by the congruency with the outline-shape of the base word.

Consistent with previous findings, hearing readers accessed the abstract orthographic representation early during processing and, consequently, showed no differences at any stage of processing between pseudowords that were visually similar to their base words and those with an incongruent outline-shape. This finding suggests that: (1) both types of pseudoword stimuli activate the underlying word representation to a similar degree, and (2) outline-shape is not relevant as a visual feature to be mapped onto the lexical representations stored in memory.

In a comprehensive review, Grainger and Holcomb (2009) summarised the literature on masked priming research with hearing readers, showing that the mapping of visual features (e.g., words size, font, etc.) onto abstract letter identities and word representations is resolved within the initial 200 ms after word presentation. Furthermore, recent research has revealed that, in hearing readers, low spatial-frequency visual characteristics such as word shape could be processed faster than high spatial-frequency visual information (Bar et al., 2006). In the same vein, low spatial frequency information has been found to play a reduced role in word recognition when compared to high spatial-frequency visual features (see also Winsler, Holcomb, Midgley, & Grainger, 2017). Indeed, Winsler et al. (2017) found that high spatial-frequency visual features accounted for most of the ERP effects in masked priming experiments, while low spatial-frequency information such as word shape did not. This later finding could explain why the outline-shape was not an important visual element used by hearing readers when responding to pseudowords in the present study.

In contrast, pseudoword processing in deaf readers was modulated by a visual feature such as outline-shape from approximately 150 ms after stimulus onset until the end of the N400 time window. Specifically, pseudowords with an outline-shape similar to their basewords elicited reduced negativities compared to the incongruent outline-shape pseudowords, indicating an increased sensitivity of deaf readers when compared with hearing readers to visual features like shape. This result is consistent with previous behavioural findings in deaf readers (Padden, 1993; Perea et al., 2016). Likewise, our ERP findings go in line with results from Emmorey et al., (2017), who reported differences in word recognition between deaf and hearing readers arising as early as 50 ms into word recognition. Crucially, the differences were clear at the N170 ERP component, which is thought to reflect reader's tunning to printed stimulus due to experience seeing words. Specifically, Emmorey et al. (2017) found reduced left lateralization of the N170 component for deaf than for hearing readers at parietal electrodes—which were closer to areas of the brain linked to phonological processing—but not at occipital electrodes which were likely to reflect early visual processing. Furthermore, phonological awareness was more strongly correlated to the size of the N170 component in hearing than deaf readers.

Given these previous results, one possibility is that our deaf readers have not developed orthographic representations precise enough to quickly override perceptual similarity upon access. In other words, their representation of the abstract letter identity may not be robust enough for them to unequivocally access that specific letter (and not access other letter that share visual features such as shape). This can be interpreted in relation to their reduced phonological skills, as acquiring phonological representations contribute to stabilize early orthographic processing during reading development. It is widely accepted that fully formed phonological representations favour strong orthographic representations (see Perea et al., 2016, for discussion). Moreover, previous behavioural experiments have shown that dyslexic readers, due to their poor phonological representations, are more sensitive to visual features that do not play a fundamental role for successful word recognition in expert readers (e.g., Lavidor, 2011; Perea & Panadero, 2014). The correlation between phonological skill and the difference in response times to the congruent- and incongruent-shape pseudowords found here can be interpreted within this view, as it was deaf readers with lower phonological skills who had slower responses to the congruent than the incongruent-shape pseudowords. This correlation suggests that, due to the high sensitivity to visual cues like word outline-shape, the size of lexical access effects decreases as phonological knowledge increases. In the same line, Emmorey et al. (2021) recently reported greater sensitivity to case mismatch between primes and targets in deaf than hearing readers. They proposed that deaf reader's sensitivity to conflicting visual information (identity priming where the prime is in lower case, and the target is in upper case) under conditions that do not allow for top-down influence of phonological processing (i.e. short prime duration) might be indicative of a weaker abstract letter coding system in deaf readers. However, the authors also raise the possibility that deaf readers' abstract letter coding system is different rather than just weaker or less efficient. It is also worth noticing that in the present study the electrophysiological signature of pseudoword processing in deaf readers reveals that deaf readers are more sensitive than hearing readers to subtle visual similarities. However, this occurs despite a remarkably similar lexicality effect between the groups and deaf readers being faster at correctly identifying both congruent and incongruent-shape items as pseudowords. The fact that deaf readers were faster than hearing readers at rejecting pseudowords is consistent with numerous previous studies showing faster lexical decision times (e.g., Fariña et al., 2017) and faster reading times (see, e.g., Bélanger & Rayner, 2015) of deaf participants than their hearing counterparts. Faster lexical decision times, together with wider perceptual spans for deaf than hearing readers (Bélanger, Slattery, Mayberry, & Rayner, 2012), suggest that visual processing is highly efficient in deaf readers. In this context, our ERP findings suggest that the high reliance on visual features in deaf readers is not necessarily detrimental. Instead, they could reflect fine-grained visual-orthographic processing that supports word recognition (Bélanger & Rayner, 2015). Therefore, a second possibility is that visual word recognition in deaf readers might be just different as pointed out by Emmorey et al. (2021) and that it relies more on visual/orthographic processing than it typically does for hearing readers. We acknowledge that more research is needed onto the precise visual mechanisms that deaf readers use to access word meaning and its effectiveness towards facilitating access to meaning.

5. Conclusion

In summary, the present lexical decision ERP experiment revealed a remarkably similar time course of the lexicality effect in deaf and hearing readers despite deaf readers being less skilled using phonology. At the same time, ERP responses showed that deaf readers were more sensitive to visual features such as the word outline-shape than hearing readers. Taken together, these results suggest that fine-grained visual processing and the development of orthographic knowledge via exposure to words could support efficient word recognition in deaf readers regardless of a lower phonological skill. Further research is needed to fully understand the precise visual mechanisms used by deaf readers.

Author contributions

Conceived and designed the experiment: E.G., M.P., M.V.; Performed the experiments: E.G., M.V..; Analysed the data: E.G.; Interpretation of the findings: E.G., M.P., M.V.; Contributed to writing the manuscript: E. G., M.P., M.V.

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Appendix A. Experimental materials

Base word: acierto, alemana, asiento, aventura, cadenas, cansado, celoso, circuito, color, concreto, conocido, cordero, cuarenta, eficacia, encuesta, escalera, espacio, existir, incendio, islas, manejo, mariposa, medicina, milenio, moderna, morada, navaja, nosotros, oriente, recinto, relevo, rescate, revista, salario, seguro, silencio, superior, vejez, victoria, visitar, agencia, anterior, aumentar, cabecera, calor, carbono, cientos, circular, columna, condena, consuelo, corteza, cubano, encanto, enfermo, escritor, especie, imaginar, infancia, maduro, mantener, masaje, mejorar, minuto, moneda, motivo, negociar, ondas, otoño, recuerdo, relieve, resistir, rotura, saliva, sendero, similar, uniforme, ventana, vieja, vivienda, aguas, aprecio, aumento, cabeza, canela, cazador, cintura, colonia, comedor, conducir, contener, criterio, cuñado, encargo, envidia, escuela, estar, imperio, informe, maestro, marcador, materia, mensaje, misterio, montaña, nadie, negocio, oreja, realizar, reforma, remedio, retiro, ruido, secreto, separar, superar, urgencia, viaje, visita, volumen.

Pseudoword ascender: acierlo, atemana, asienlo, avenfura, calenas, cansafo, cetoso, circuifo, cobor, concrefo, conocifo, corfero, cuarenfa, edicacia, encuesfa, escatera, esgacio, exislir, incenfio, isfas, manepo, marigosa, meficina, mitenio, molerna, morafa, navapa, nosobros, orienfe, recinfo, refevo, rescafe, revisla, satario, sepuro, sifencio, sugerior, vepez, vicforia, visibar, apencia, anlerior, aumenlar, calecera, cador, carfono, cienfos, circufar, cobumna, confena, consuedo, corbeza, cufano, encanfo, endermo, escrilor, esgecie, imapinar, indancia, mafuro, manfener, masape, meporar, minufo, monela, mobivo, nepociar, onlas, oloño, recuerlo, refieve, resislir, rofura, sadiva, senlero, simidar, unilorme, venfana, viepa, vivienla, apuas, agrecio, aumenfo, cateza, caneba, cazalor, cinlura, cobonia, comefor, conlucir, confener, crilerio, cuñalo, encarpo, envilia, escueba, esfar, imgerio, inlorme, maesfro, marcalor, maferia, mensape, misferio, monlaña, nafie, nepocio, orepa, readizar, reborma, remelio, reliro, ruilo, secrebo, segarar, suyerar, urpencia, viape, visiba, votumen.

Pseudoword flat: aciervo, avemana, asienco, avenvura, carenas, cansavo, cecoso, circuiro, coror, concrevo, conociro, corvero, cuarenva, ericacia, encuesna, escacera, esmacio, exismir, incenvio, isvas, manemo, marimosa, mevicina, misenio, monerna, morava, navama, nosocros, orienve, recinco, rezevo, rescave, revisca, samario, semuro, sivencio, sunerior, vevez, vicnoria, visivar, avencia, anverior, aumenrar, canecera, camor, carzono, cienvos, circuvar, cocumna, convena, consuemo, corseza, cuzano, encanvo, envermo, escrisor, esnecie, imasinar, incancia, mazuro, mansener, masaze, mesorar, minuvo, monesa, momivo, nevociar, onvas, ovoño, recuervo, revieve, resisvir, rovura, saciva, senvero, simicar, univorme, vencana, viesa, vivienva, avuas, acrecio, aumenco, cameza, caneca, cazanor, cincura, cosonia, comevor, convucir, concener, criverio, cuñaco, encarzo, enviria, escueva, esvar, imcerio, invorme, maescro, marcanor, maveria, mensaze, misverio, monvaña, nazie, nesocio, oreza, reasizar, revorma, remenio, reniro, ruiso, secrevo, senarar, suzerar, urvencia, viame, visisa, vosumen.

Word flat: necio, icono, criar, oasis, cacao, sucio, cisne, rumor, suizo, cerezo, casero, sirena, secano, vacuna, noveno, macizo, vacuno, casino, masivo, ruinoso, veraneo, coronar, caricia, invasor, evacuar, carisma, vicioso, caverna, manzano, armario, canario, venenosa, arruinar, insomnio, inversor, caravana, ascensor, numeroso, nerviosa, arrancar.

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