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Early use of phonological codes in deaf readers: An ERP study

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ABSTRACT

Previous studies suggest that deaf readers use phonological information of words when it is explicitly demanded by the task itself. However, whether phonological encoding is automatic remains controversial. The present experiment examined whether adult congenitally deaf readers show evidence of automatic use of phonological information during visual word recognition. In an ERP masked priming lexical decision experiment, deaf participants responded to target words preceded by a pseudohomophone (koral – CORAL) or an orthographic control prime (toral – CORAL). Responses were faster for the pseudohomophone than for the orthographic control condition. The N250 and N400 amplitudes were reduced for the pseudohomophone when compared to the orthographic control condition. Furthermore, the magnitude of both the behavioral and the ERP pseudohomophone effects in deaf readers was similar to that of a group of well-matched hearing controls. These findings reveal that phonological encoding is available to deaf readers from the early stages of visual word recognition. Finally, the pattern of correlations of phonological priming with reading ability suggested that the amount of sub-lexical use of phonological information could be a main contributor to reading ability for hearing but not for deaf readers.

1. Introduction

Most deaf readers fail to achieve the reading levels of their hearing peers. Previous research has shown that young deaf adults achieve an average reading level of 4th grade (English: Conrad, 1977, 1979; DiFrancesca, 1972; Traxler, 2000; Spanish: Sánchez and García-Rodicio, 2006; Dutch: Wauters et al., 2006). This reading deficit may have a negative impact not only on their academic achievement, but also on their social and emotional well-being (McArthur and Castles, 2017). Typically, the poor reading skills in deaf individuals are explained in terms of their underspecified print-to-sound mapping and poorer use of spoken phonology (e.g., see Perfetti and Sandak, 2000).

Although their performance is lower than that of their hearing peers (see, for instance, Sterne and Goswami, 2000), deaf readers can make use of the phonological structure of words when the use of phonology is explicitly required (e.g. a rhyming task; see Charlier and Leybaert, 2000; Hanson and McGarr, 1989 for behavioral evidence; MacSweeney et al., 2013 for ERP evidence; MacSweeney et al., 2008; Emmorey et al., 2013 for fMRI studies). Nonetheless, the explicit use of phonological codes in rhyming tasks—or other tasks that require the activation of phonological codes—does not necessarily imply that these codes are regularly involved during visual word recognition, which is the main aim of this study. In an fMRI study, Emmorey et al. (2013) examined the neural circuits associated with word reading in skilled deaf readers during an implicit semantic (abstract vs. concrete) and an explicit phonological task (syllable counting) and found that hearing readers showed a similar pattern of activation in the two tasks. However, deaf readers showed functional segregation across tasks. To explain this dissociation, Emmorey et al. (2013) argued that the activation of phonological codes may not be automatically engaged in skilled deaf readers if the task does not require it explicitly (i.e., semantic judgement). Similarly, Corina et al. (2013) found that during an implicit reading task (detection of letters with ascenders in either English words or false font letter strings) the pattern of brain activation of less skilled deaf readers was qualitatively different to that traditionally found in hearing individuals reading alphabetic scripts. In addition to these neuroimaging findings, the behavioral studies that have investigated on-line word recognition using implicit tasks have not consistently reported an automatic use of phonological codes in deaf readers. On the one hand, several studies reported that adult deaf readers can use phonological information of words during implicit tasks (e.g. Hanson et al., 1991; Kelly, 2003; see Perfetti and Sandak, 2000, for review). For example, in a semantic acceptability judgement task, Hanson et al. (1991) found that adult deaf readers made more errors judging tongue-twister (e.g., Tom and Tim talked together) than judging control sentences. More recently, Sehyr et al. (2016) found that deaf signers

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recoded printed words to an English based phonological code during a serial recall task. On the other hand, other studies either failed to find evidence of the use of phonological codes by deaf readers (Chamberlain, 2002; Bélanger et al., 2012; Bélanger et al., 2013) or found that deaf readers use phonological codes to a lesser degree than hearing readers (e.g., Hanson et al., 1983). In the study by Hanson et al. (1983), deaf participants produced fewer phonologically accurate spelling errors than hearing participants in both a recognition and a production task—these results suggest that deaf readers are less reliant on the phonological representation of words than hearing readers.

Thus, the role of phonological encoding during visual word recognition in deaf readers seems a controverted issue in light of this heterogeneous pattern of results. Noticeably, the lack of consistency across previous findings could be partially accounted for by the use of different experimental paradigms (i.e. short term memory tasks, Stroop paradigm, lexical decision with pseudohomophones as foils, analysis of spelling errors; see Mayberry et al., 2011, for a meta-analysis).

To investigate the automatic encoding of phonology in visual word recognition, here we focus on a technique that has been demonstrated to tap onto the automatic use of phonological codes: masked priming (Forster and Davis, 1984; see also Kinoshita and Lupker, 2004). In a typical masked priming experiment, a very briefly presented prime precedes a target stimuli, to which participants respond—typically deciding whether the target is a word or a pseudoword (i.e., lexical decision). Masked priming is sensitive to early automatic processes during visual word recognition while minimizing contamination from strategic factors (Forster, 1998). This paradigm has been extensively used in studies with hearing readers (see Rastle and Brysbaert, 2006, for a review of studies using masked phonological priming). In a word recognition task (e.g., lexical decision), responses to a target word are shorter when preceded by a briefly presented pseudohomophone prime than when by an orthographic control prime (brane-BRAIN vs brant-BRAIN; e.g., Carreiras et al., 2005; Frost et al., 2003; Lukatela and Turvey, 1994; Perfetti and Bell, 1991). Masked phonological effects with adult hearing readers are fully established with a prime exposure of 67 ms (Ferrand and Grainger, 1993), but they may be already detectable with prime exposures of around 50 ms (Grainger et al., 2006).

Whilst masked priming has been established as a useful paradigm to investigate early automatic orthographic and phonological contributions to visual word recognition, only a few behavioral studies have employed this technique with deaf readers. Cripps et al. (2005) compared repetition (sample-SAMPLE vs. victory-SAMPLE) and phonological (braik-BRAKE vs. scrone-BRAKE) masked priming (67 ms prime exposure) effects in deaf and hearing readers. While both groups showed a facilitative repetition priming effect (see also Perea et al., 2016, for further evidence of masked repetition priming effects with deaf readers), only the hearing readers showed a facilitative phonological priming effect. More recently, Bélanger et al. (2012) compared masked orthographic (e.g., keit–KAÎT vs. kets–KAÎT; [kɛ]- [kɛ] vs. [kɛ]- [kɛ]) and phonological (e.g., kets-KAÎT vs. kaum–KAÎT; [kɛ]- [kɛ] vs. [kom]-[kɛ]) priming effects in hearing and deaf readers of different reading skill. An orthographic priming effect of similar magnitude was present in both groups (at a 60 ms prime exposure). However, a significant masked phonological priming effect was only observed in the hearing readers (null effects of phonological priming were found in both skilled and non-skilled deaf readers).[1] While the Cripps et al. (2005) and the Bélanger et al. (2012) results may suggest that deaf readers do not have an early, automatic access to phonological codes, one should keep in mind that masked phonological priming effects with hearing readers are small (Rastle and Brysbaert, 2006, p. 110). In addition, masked phonological priming effects are not only modulated by prime exposure durations, but also by the nature of the phonological overlap between prime and target, the specific control condition to which the phonological condition is compared with, and the participants' characteristics. For example, prior research has shown that prime exposure durations of 50 ms immediately followed by a target is not enough for normally hearing developing readers to activate phonological codes (Comesaña et al., 2016). Indeed, the significant masked phonological priming effects reported in the literature with developing readers have employed prime durations or stimulus-onset asynchronies (SOAs) longer than 65 ms (67 ms: Chetail and Mathey, 2012; 100 ms: Eddy et al., 2014; 150 ms: Goikoetxea, 2005; 70 ms: Grainger et al., 2012; Ziegler et al., 2014). Thus, given that most deaf readers fail to achieve high reading levels, it may be reasonable to assume that if deaf readers access phonological codes during reading SOAs of 50–67 ms may not be enough time for them.

The main goal of the current experiment was to investigate the phonological involvement during early lexical processing in deaf readers using a masked priming lexical decision task. Using behavioral and event-related potential (ERP) measures, we compared participants' responses to target words that were preceded by either a pseudohomophone or an orthographic control (e.g. koral – CORAL vs. toral – CORAL). For comparison with previous research, we also included an identity and an unrelated priming conditions (see Results in Appendix B). We aimed to enable maximal opportunity to find a masked phonological priming effect—if present—in deaf readers. In order to do so, we conducted the study in a transparent language (Spanish) and limited the experimental manipulation to the initial segments of the word (see Carreiras et al., 2005, for greater masked phonological priming effects on first-syllable phonological overlap than on second-syllable phonological overlap). Furthermore, the 50 ms prime was not immediately followed by the target stimulus; instead, there was 50-ms blank between the offset of the prime and the onset of the target (see Holcomb et al., 2005; Holcomb and Grainger, 2007, for an analysis of the effects of different prime and SOA durations). Finally, we employed the “sandwich” variation of the masked priming technique (Lupker and Davis, 2009) in which the target is presented very briefly between the forward mask and the prime (see Fig. 1). Prior research has consistently shown that this paradigm produces greater priming effects than the standard masked priming procedure without altering the early bottom up effects (Lupker and Davis, 2009; see also Comesaña et al., 2016; and Ktori et al., 2012 for an ERP study). The mechanism by which this methodology has been proposed to boost the size of the priming is via the reduction of lateral inhibition from whole-word level (lexical) competition from similar words that are also activated by the prime in non-sandwich paradigms (Lupker and Davis, 2009). Lupker and Davis (2009) demonstrated that this technique allows to capture masked priming effects that were not easily captured using the conventional set-up (see also Perea et al., 2014, for converging evidence). In addition, in conditions where priming is usually found with the conventional methodology, the effect sizes are 2–3 times greater with the sandwich technique (Lupker and Davis, 2009). In a recent ERP experiment using the sandwich masked priming, Ktori et al. (2012) replicated a boost on the size of the behavioral orthographic priming effect. Notably, the ERP effect sizes were larger than in previous studies, demonstrating the increased measurement sensitivity of the sandwich methodology, while keeping a similar timing of the ERP effects.

Importantly, the present experiment combined masked priming with the recording of the event-related potentials (ERPs) to study the temporal dynamics of the automatic use of phonological codes by deaf readers. As stated earlier, the evidence suggests that at least some deaf readers can use phonological information of words when it is explicitly demanded by the task itself. Hence, it has been proposed that phonological activation occurs at a post-lexical level rather than at the earliest stages of word processing (Bélanger et al., 2012, 2013; Perea et al., 2016). However, whether phonological encoding is automatically processed by deaf readers continues to be debated. The excellent time resolution of the ERP technique makes it a well-suited methodology for

[1] Belanger et al. (2013) found the same pattern of results using a similar technique, the gaze contingent boundary change paradigm (Rayner, 1975).

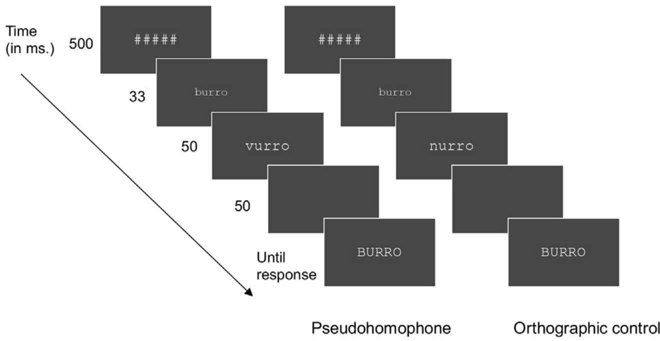


Fig. 1. Depiction of events within a trial.

addressing this issue.

Previous research using masked phonological priming has identified two components that are modulated by the degree of phonological overlap between prime and target: the N250 and the N400. The N250 is a negative going component that peaks around 250 ms after target onset with a midline and anterior scalp distribution (Grainger and Holcomb, 2009; Grainger et al., 2006). This component is thought to reflect sublexical processes at the mapping between orthographic and phonological codes (Grainger and Holcomb, 2009; Holcomb and Grainger, 2006). The N400 is a negative going component peaking around 400 ms after target onset with a widespread central scalp distribution. For words presented in isolation, the N400 has been associated with lexical-semantic processing and the modulation of its amplitude reflects processing costs during the retrieval of properties associated with a word form stored in memory (Holcomb et al., 2002; Kutas and Federmeier, 2000). In the context of masked priming experiments, N400 effects are assumed to reflect processing at the mapping of whole-word forms and their meanings (Grainger and Holcomb, 2009; Grainger et al., 2006; Holcomb and Grainger, 2006). Grainger et al. (2006) found a reduction of both N250 and N400 amplitudes for target words when preceded by pseudohomophones (brane-BRAIN) than when preceded by controls (brant-BRAIN). Note that although the N250 component was also modulated by orthographic overlap (transposed letters priming: barin-BRAIN), the orthographic effect was found on an earlier time window than the phonological effect and over posterior scalp areas. This pattern of results provided a time boundary for the beginning of the phonological processing (around 250 ms after target onset for a 50 ms SOA) as well as a depiction of its scalp distribution (anterior electrodes). Both phonological and orthographic overlap modulated the N400 similarly, supporting the view that the N400 reflects the mapping between whole-word representations and their meaning. Interestingly, similar effects have been recently found in developing readers using a SOA of 100 ms (Eddy et al., 2014), thus suggesting that the combination of masked priming and ERPs is sensitive enough to discriminate sub-lexical and whole-word processing.

The predictions of the present study are clear. Behaviorally, if deaf readers use phonological codes automatically during lexical processing, we expect faster response times for target words preceded by a pseudohomophone than for those preceded by an orthographic control prime. Furthermore, the current experiment analyzes the time course of masked phonological priming in deaf readers by examining the N250 and N400 ERP components. If deaf readers can use phonological codes early during word recognition, we expect to find a reduction of the amplitude in both ERP components for the pseudohomophone condition compared to the orthographic control condition similar to what has been observed with hearing readers. Conversely, if deaf readers are only able to use phonological codes after having accessed to the whole-word representation, we expect to find a reduction of the N400 for the pseudohomophone condition in the N400 but not in the N250 time window.

A final question of interest is whether the early use (or lack of use) of phonological codes by deaf readers is related to their reading ability. Previous research has failed to demonstrate that skilled reading and adequate phonological processing are necessarily related (see Mayberry et al., 2011 for review) in deaf readers. In the Bélanger et al. (2012) experiment, the size of masked phonological priming was not predictive of the reading level in deaf readers. Similarly, in a recent fMRI study comparing skilled and less skilled deaf readers, Emmorey et al. (2016) found that reading ability was not correlated with off-line measures of phonological awareness nor with neural activity during a phonological (syllable counting) task. In the current study, we make use of the variability of reading levels existing amongst congenitally deaf participants to analyze the relationships between their score in standardized reading tests and performance during the task as well as the size of the ERP effects.

Finally, as language experience has been found to modulate the use of phonological information during visual word recognition (see Corina et al., 2014; Hirshorn et al., 2015; Koo et al., 2008), we recruited congenitally deaf participants with different language experiences, from native signers to those who had learnt Spanish Sign Language (Lengua de Signos Española: LSE) in adolescence. We examined the relationship between LSE age of acquisition (AoA) and our behavioral and electrophysiological dependent variables.

To sum up, the present masked phonological priming experiment investigated whether profoundly congenitally deaf readers access phonological codes automatically during single visual word processing. Faster responses to target words preceded by pseudohomophones than when preceded by orthographic controls would indicate automatic use of phonological information. Furthermore, we explored the time course of these phonological effects by examining the electrophysiological correlates of target processing. If deaf readers only use phonological information relatively late during word processing, masked phonological priming effects on the N400, but not in the N250 would be expected. Alternatively, if congenitally deaf readers can use phonological codes sub-lexically during word recognition, we would expect a reduction in the amplitude of both N250 and N400 components for the pseudohomophone priming condition. Whilst our main interest was to characterize the use of phonological information by deaf readers, we also examined its relationship with reading ability. If early phonological processing contributes to reading ability, then a positive correlation would be expected between the size of the early phonological effect and a measure of reading comprehension. In order to further characterize the phonological effects (size, timing, etc.), data from deaf readers was compared to that of matched hearing controls.

2. Methods

2.1. Participants

Twenty-eight congenitally deaf participants were recruited for this study. All participants were profoundly deaf, had no history of neurological or psychiatric impairment, and had normal (or corrected-to-normal) vision. All participants were right-handed, as assessed with a Spanish abridged version of the Edinburgh Handedness Inventory (Oldfield, 1971). The data from four participants were discarded because of noisy electroencephalogram (EEG) data. Of the remaining 24 participants (10 female, 14 male), seven were native signers of Spanish sign Language (LSE), eight had learned LSE from teachers and friends before the age of 9 and nine were late signers who had learned LSE after the age of 9. All participants were skilled signers (self-ratings of 6–7 in a 1-to-7 Likert scale) and used LSE as their preferred means of communication in their daily lives. Their ages ranged from 21 to 56 years (M = 36.5, SD = 8.9). All participants reported to have attended to mainstream schools and have undergone literacy training based on a phonological (syllabic) method. Participants were recruited from Valencia and Tenerife via flyers and word-of-mouth referrals.

A group of twenty-seven hearing readers also participated in the study. These participants were recruited from the same communities as the deaf participants via flyers and word-of-mouth referrals. Their ages ranged from 20 to 53 years (M = 37.7, SD = 7.9). Hearing participants were native Spanish speakers with no history of neurological or psychiatric impairment, and normal (or corrected-to- normal) vision. All participants reported to have undergone literacy training based on a phonological (syllabic) method All participants were right handed.

All participants were tested on non-verbal IQ (Toni 2), a reading comprehension (TALE 2000), a sentence reading (TECLE) and a phonological processing task (syllable counting).

2.1.1. Non-verbal IQ

We used the Test of Nonverbal Intelligence, Second Edition (TONI-2; Brown et al., 1990) to test non-verbal IQ. This test is a language-free measure of cognitive ability via abstract and figural problem solving, which makes it suitable for individuals with speech, language or hearing impairments. It is a psychometrically sound test that has demonstrated a good concurrent, construct, and predictive validity with deaf children (Mackinson et al., 1997). TONI-2 contains 55 items in which participants must select the option that completes a series from multiple options (4 or 6). To select the correct alternative, the participant must identify the rule or rules that define the relationships between the figures. The difficulty varies according to the type and number of rules that must be taken into account to reach the solution. All participants had a non-verbal IQ over 98 and none reported associated disorders or learning disabilities.

2.1.2. Reading comprehension

We used the comprehension subtest of the Magallanes scale of Reading and Writing TALE 2000 ("Escalas Magallanes de Lectura y Escritura" TALE-2000; Toro et al., 2002). This test is untimed and is comprised of 3 texts of increasing length and difficulty followed by comprehension questions. Texts can be used to assess reading levels from 2nd grade (7 years) to 10th grade (16 years). Rather than selecting the starting text by age, all participants started on text 1 and answered as many questions as possible from each of the texts. Participants were allowed to amend their answers as many times as they considered necessary. An average score of percentage of correct responses in the 3 texts was computed for each participant. Both groups differed significantly in Reading comprehension.

2.1.3. Sentence reading test

In order to measure reading ability at the sentence level we used the collective test of reading efficiency ("Test Colectivo de Eficacia Lectora" TECLE; Carrillo and Marin, 1997) which has been used in previous studies of deaf readers in Spanish (Domínguez et al., 2014; Rodríguez-Ortiz et al., 2015). This test provides a combined measure of reading speed and comprehension. The test comprises 64 written sentences of increasing syntactic, semantic and orthographic complexity. The participant must select a word that completes the sentence from among four options: 1) the correct word, 2) a phonologically similar pseudoword, 3) an orthographically similar pseudoword and 4) a similar but incorrect word. After adding the number of correct responses during the 5-min administration period a percentage of correct responses is computed. The groups were balanced in terms of sentence reading level. Note that these two reading tests were used in order to assess the relationship between the use of phonological information and the reading strategies underlying the completion of each test. While the sentence-reading test requires the selection of one appropriate lexical item from a set of otherwise semantically unfitting items, the reading comprehension test allows to measure the ability in the use of more complex semantic and grammatical information.

2.1.4. Phonological processing

We used an explicit phonological task, i.e. syllable counting, to assess the participants' metaphonological ability. In Romance languages such as Spanish or French, the syllable counting task requires access to phonological forms (see e.g. Chetail, 2012). It has been shown that words that display consistent orthographic and phonological structures are responded to faster and more accurately than words with discrepant orthographic and phonological structures (e.g. hiatus words; Chetail and Content, 2014; Chetail et al., 2015). Furthermore, the pattern of errors found in syllable counting tasks can be influenced by word length (Chetail et al., 2015). Here we computed an index of the degree in which orthographic/visual factors (i.e. word length) influenced the participants' response during online syllabification. This index was obtained as a function of accuracy of responses to highly consistent and highly discrepant words regarding their phonological and orthographic structure.

Participants saw 70 low frequency words (5, 6 and 7 letters) that had either 2, 3 or 4 syllables. Nineteen words were highly consistent and twenty-one words were highly discrepant. The consistent words were a) 5 letters and 2 syllables words such as mo.lar (molar) or b) 7 letters and 3 syllables words such as ca.vi.dad (cavity). The discrepant words were a) 5 letters and 3 syllables words such as e.ne.ro (January) or b) 7 letters and 2 syllables words such as men.sual (monthly). In order to avoid response strategies, two types of filler stimuli were used: ten 4 syllable words (which were included only to avoid a two-choice response) and twenty 6 letter words for which syllabification remained ambiguous (ten had 2 syllables and the remaining ten had 3 syllables). Participants saw each word displayed on the center of a computer monitor until their response or 4000 ms elapsed. The percentage of accurate responses for discrepant words was subtracted from the percentage of accurate responses for consistent words. This resulted on an index where the higher values indicated that processing was more biased by the visual characteristics of words (higher accuracy for visually consistent words). The groups of deaf and hearing participants were balanced for this measure (see Table 1).

In order to evaluate the consistency of the present measures of reading and phonological processing, we looked at the Pearson correlations between them separately in each group (see Table 2). The correlation between the present measures of reading and phonological processing and age of LSE acquisition (LSE AoA) was also evaluated for the deaf participants. In the deaf group the scores of reading comprehension and sentence reading were highly correlated. Both were moderately correlated with phonological processing. Interestingly only the measure of reading comprehension showed a positive correlation with LSE AoA. The findings in the deaf group differed from those in the hearing group. While sentence reading and phonological processing were positively correlated in the hearing group, none of them showed a relationship with reading comprehension. Note that there is less variability in the scores for reading comprehension in the hearing group than in the deaf group, which can partially account for the lack of correlations. Furthermore, the possibility of amending the responses and the lack of time limit might have resulted on a different strategy in the hearing participants, who generally spent more time on this task

Table 1
Participants' characteristics and performance in the NVIQ and reading-related tests.

	Deaf mean (SD)	Hearing mean (SD)	t (46)	p
Age	36.5 (8.9)	37.7 (7.9)	−.47	> .1
NVIQ	98.2 (19)	107 (16)	−1.8	> .05
Phonological processing	34.5 (19)	25.4(18)	1.74	> .05
Sentence reading	68.8% (27) range (14–100%)	79.3% (18) range (19–99%)	−1.6	> .1
Reading comprehension	**48.4% (23.7)** range (11–82%)	**80.6% (9.7)** range (60–90%)	**−6.3**	**< .0001**

Table 2
Correlations between performance in the phonological processing, sentence reading and reading comprehension measures for both groups. For the deaf readers, correlations with LSE age of acquisition are also shown.

		Deaf			Hearing	
		Reading comprehension	Phonological processing	AoA LSE	Reading comprehension	Phonological processing
Sentence reading	r	**0.831*** **	**−.472***	.69	.25	**−.701*** **
	p	**< .001**	**.02**	.748	.24	**< .001**
Reading comprehension	r		**−.490***	**.433***		−.317
	p		**.015**	**.035**		.131
Phonological processing	r			.025		
	p			.908		

* p < .05, ** p < .01, *** p < .001

and switched more responses that the deaf.

Out of the 28 hearing participants tested, twenty-four (16 female, 8 male) were selected to match the group of deaf participants according to age, NVIQ, phonological processing and sentence reading level (see description below and Table 1 for a comparison between groups).

This study was approved by the Research Ethics Committee of the University of Valencia 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.

2.2. Materials

The target stimuli were one hundred and sixty Spanish words taken from a masked priming experiment with developing readers (i.e. 4th grade children; Comesaña et al., 2016). In the Comesaña et al. (2016) experiment, the words were selected from the LEXIN database, which offers linguistic indexes for words contained in a corpus of beginning readers (Corral et al., 2009). The mean of word frequency per million in the ESPAL database (Duchon et al., 2013) was of 48.30 (range: 0.38–727, SD = 95.9).[2] The words (and pseudowords, see below) were between four and seven letters long (Mean= 5.51, SD = 1.1). The target words were preceded by: a) a prime that was the same as the target (burro-BURRO, identity condition); b) a pseudoword prime that was phonologically matched with the target: the first letter was replaced by another letter which represented the same phoneme (vurro-BURRO, pseudohomophone condition; in Spanish, the graphemes "v" and "b" represent the phoneme /b/), c) a pseudoword prime in which the first letter was replaced by another letter to create an orthographic control (nurro-BURRO, orthographic control condition). Importantly, this letter was matched with the replaced letter in the pseudohomophone priming condition in shape (either ascending, descending, or neutral); and d) a pseudoword prime that was unrelated to the target (saeca-BURRO, unrelated condition). To make the lexical decision task possible, we employed one hundred and sixty pseudoword targets, also taken from the Comesaña et al. (2016) set of stimuli. The pseudowords were orthographically legal grapheme strings generated with Wuggy (Keuleers and Brysbaert, 2010), and contained the same prime-target manipulation. The full set of stimuli can be found in Comesaña et al. (2016) Appendix B. Four counterbalanced lists of materials were constructed in a Latin-square type so that each target appeared once in each list, while all conditions were present in each list. Note that for clarity, as the main question of this study concerns phonological processing, only the comparison between the pseudohomophone and orthographic control conditions for word targets is presented in the results section. Nonetheless, for the interested readers, the comparison between the pseudohomophone vs. identity condition, and between the unrelated vs. identity conditions (identity priming) for word targets are displayed in the Appendices A and B respectively.

2.3. Procedure

Participants were seated comfortably in a darkened room with no visual stimuli other than from the experimental setting. 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° horizontally. Stimuli were presented in white Courier New font against a dark-gray background. Stimulus display was controlled by Presentation software (Neurobehavioral Systems). The stimuli were displayed at the center of the screen.

The sequence of events in each trial was as follows (see Fig. 1): the participant viewed a pattern mask (a series of #'s that matched the length of the stimulus test) for 500 ms, then a lowercase target stimulus (8-pt Courier New font) was presented for 33.3 ms (see Lupker and Davis, 2009, for a similar procedure) followed by a lowercase prime (12-pt Courier New) for 50 ms Following a 50 ms blank screen, an uppercase target (either a word or a pseudoword presented in 12-pt Courier New), remained on the screen until the participant responded or 2500 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. To minimize participant-generated artifacts in the EEG signal during the presentation of the experimental stimuli, participants were asked to refrain from blinking and moving from the onset of each trial to the set up period after response. 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 (YES/NO). The hand used for each response was counterbalanced across participants. RTs were measured from target onset (second appearance) until the participant's response. Each participant was randomly assigned to one of the four counterbalanced lists. The order of stimuli presentation from each list was randomized for each participant. Before the experiment began, participants were given a brief practice session, sixteen trials long, to acquaint them with the format of the experiment. The stimuli used in the practice session were different from those used in the actual experiment. The whole session, including set up and behavioral tasks lasted approximately 2.5 h.

2.4. EEG recording and analysis

The electroencephalogram (EEG) was recorded from 29 Ag/AgCl active electrodes mounted in an elastic cap (EASYCAP GmbH, Herrsching, Germany) according to the 10/20 system. Eye movements and blinks were monitored with four electrodes providing bipolar recordings of the horizontal and vertical (over the left eye) electro-oculogam (EOG). Signals were sampled continuously throughout the

[2] Accuracy for words and pseudowords was over 91% in both groups. Deaf participants had a 93.6% correct responses to words and 89.9% correct to pseudowords. Hearing participants had a 95.1% correct responses to words and 91.1% correct to pseudowords. There were no differences in accuracy between the groups for either words or pseudowords (both p > .1).

experiment with a sampling rate of 250 Hz, and filtered offline with a bandpass filter of 0.01–20 Hz. Data from scalp and eye electrodes were referenced offline to the average of left and right mastoids. Initial analysis of the EEG data was performed using the ERPLAB plugin (Lopez-Calderon and Luck, 2014) for EEGLAB (Delorme and Makeig, 2004). Epochs of the EEG corresponding to 100 ms pre- to 550 ms post-target onset were analyzed. Baseline correction was performed using the average EEG activity in the 100 ms preceding the onset of the target stimuli. Following baseline correction, trials with eye movements, blinks, muscle activity or other artifacts were rejected (5.1%).

To characterize the time course and scalp distribution of the pseudohomophone effect (pseudohomophone condition vs. orthographic control condition) in deaf readers, and capture potential differences in either the time course or scalp distribution of this effect between deaf and hearing readers, we performed statistical analysis on the mean voltage values for 4 different consecutive time windows: 160–270 ms, 270–330 ms, 330–400 ms and 400–550 ms. The first and the second epochs, and the third and the fourth epochs, allowed for detailed assessment of the N250 and N400 components respectively. The selection of this epochs was based on the previous literature and the visual inspection of the ERP waves. The selection of the epochs was also informed by repeated measures *t*-tests at every 4-ms intervals between a 150 and 550 ms. To correct for multiple comparisons, we considered the experimental contrast reliable when the *t*-test samples exceeded the .05 significance level for 15 consecutive samples[3] (see e.g. Guthrie and Buchwald, 1991; Vergara-Martínez et al., 2016, for a similar approach; see Fig. 3, right panel). Visual inspection of the data showed two subsequent negative going components with timings consistent with the N250 and N400 components. The repeated measures *t*-tests suggested that the analysis of the four described time windows would depict better the phonological effect in both groups, as well as potential differences in timing or scalp distribution.

We analyzed the topographical distribution of the ERP results by including the averaged amplitude values across five electrodes of four representative scalp areas (see Fig. 2) that resulted from the factorial combination of the factors hemisphere (left vs. right) and anterior-posterior (A-P) distribution (anterior vs. posterior): anterior left (Fp1, F3, F7, FC1, FC5), anterior right (Fp2, F4, F8, FC2, FC6), posterior left (CP1, CP5, P3, P7, O1) and posterior right (CP2, CP6, P4, P8, O2). For each time window, we performed a separate repeated measures analysis of variance (ANOVA), including the factors hemisphere, A-P distribution and type of prime (pseudohomophone vs. control. (See Appendix B for the same type of analysis for identity vs. unrelated conditions)). In all analyses, List (1–4) was included as a dummy between-subjects factor in order to extract the variance that was due to the counterbalanced lists (Pollatsek and Well, 1995). Effects of hemisphere or A-P distribution factors are only reported when they interact with the experimental manipulations. Interactions between factors were followed up with simple-effects tests. We first report the statistical analyses for the phonological priming effect including the factor group (combined analyses with deaf and hearing readers). However, as the main question of the present study is whether deaf readers show evidence of early automatic use of phonological information during word recognition, we then conduct follow up analyses on each group separately. These follow up analyses are needed to ensure that any phonological masked priming effect found for both groups is not driven solely by the hearing group.

[3] As pointed by a reviewer, Groppe et al. (2011) suggested other methods for multiple comparison corrections that are particularly useful for robust effects or when there is little a priori knowledge of the timing and distribution of the ERP effect. However, these approaches come at the cost of less statistical power and might result in an increase of Type II errors (i.e. false negatives; see Luck and Gaspelin, 2017). We finally adopted a less restrictive approach because the masked phonological priming effect, while typically small in magnitude relative to the appropriate control condition, has been consistently found, thus allowing for clear a priori predictions. The time windows in the present experiment are not only consistent with those previously described in the literature, but they also allow for a detailed description of the effect in both groups of readers.

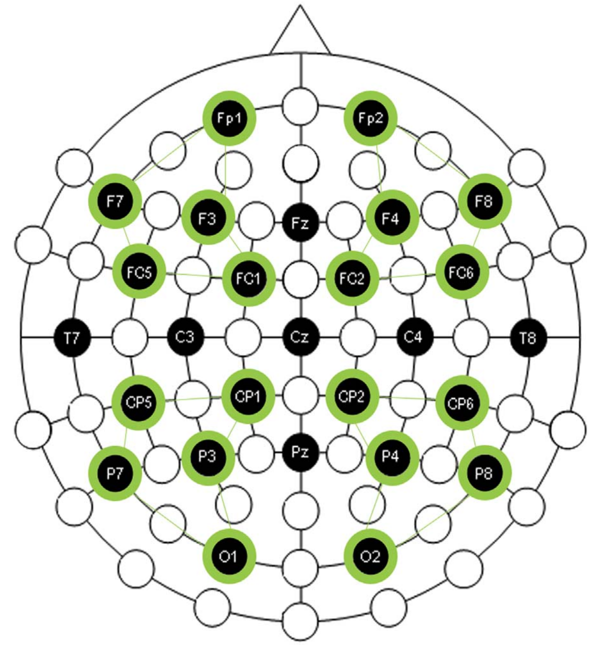


Fig. 2. Schematic representation of the electrode montage. Electrodes are grouped in four different areas (anterior-left, anterior-right, posterior-left and posterior-right) for statistical analyses.

For each group, we then explore the correlation between the priming effects (difference between the pseudohomophone and the orthographic control conditions) and the reading related variables.

3. Results

3.1. Combined analysis with deaf and hearing readers

3.1.1. Behavioral results

Four target words (barril, buzo, careta and velero) were excluded from all analyses due to the low accuracy (< 58% correct responses in the deaf group).

Incorrect responses (6%) and lexical decision times above and below the 2.5 SDs of the average per participant and condition (2%) were excluded from the latency analysis. The mean lexical decision times and percentage of correct responses per condition are displayed in Table 3. ANOVAs with the within factor type of prime (pseudohomophone vs. control), the between-subjects factor group (deaf vs. hearing readers) and the dummy between-subjects factor List (see Pollatsek and Well, 1995) were performed separately for the latency and accuracy data (subjects -F1- and items -F2- analyses were performed for both).

The latency analyses showed faster responses in the pseudohomophone condition than in the orthographic control condition, $F1(1,43) = 24.6$, $MSE = 651$, $p < .001$, $\eta^2 = .38$; $F2(1,62) = 12.84$, $MSE = 8408$, $p < .001$, $\eta^2 = .16$. The main effect of group was only significant in the item analysis $F1(1,43) = 1.8$, $MSE = 29{,}470$, $p = .19$, $\eta^2 = .042$; $F2(1,62) = 8.1$, $MSE = 4916$, $p = .006$, $\eta^2 = .11$. The interaction between type of prime and group did not approach significance (both Fs < 1).

ANOVA on the accuracy data showed no significant effect of type of prime (both Fs < 1). There was a main effect of group $F1(1,43) = 5.9$, $MSE = 19.26$, $p = .020$, $\eta^2 = .13$; $F2(1,62) = 14.18$, $MSE = 68.27$, $p < .001$, $\eta^2 = .17$. Deaf participants had slightly lower accuracy than hearing participants (92.7 vs. 95%, respectively). The interaction between type of prime and group approached significance in the subjects' analysis, $F1(1,43) = 3.72$, MSE = 6.63, p = .061, $\eta^2 = .85$; $F2 < 1$.

Table 3
Mean lexical decision times (RTs, in milliseconds) and percentage of accurate responses for the pseudohomophone and the orthographic control priming conditions in deaf and hearing participants.

	Deaf		Hearing	
	RT mean (SD)	Accuracy mean (SD)	RT mean (SD)	Accuracy mean (SD)
Pseudohomophone primes	719 (134)	92.5 (6.9)	761 (131)	95.7 (2.4)
Orthographic control primes	748 (151)	93.2 (4.7)	782 (147)	94.7 (3.8)
difference	−29**	−.7	−21*	1*

* p < .05, ** p < .01, *** p < .001

for each group separately and for the conjoined analysis can also be seen in Fig. 4 (panels c and b respectively).

3.1.2.1. 160–270 ms. The main effect of type of prime was not significant, $F(1,40) = 1.975$, $MSE = 3.15$, $p = .168$, $\eta^2 = .047$. There was an interaction of type of prime by A-P distribution, $F(1,40) = 5.38$, $MSE = .75$, $p = .026$, $\eta^2 = .12$—the difference between the pseudohomophone condition and the orthographic control condition was present in the anterior ($F(1,20) = 4.87$, p = .039) but not in the posterior electrodes ($F < 1$). The interaction between type of prime and hemisphere as well as the three-way interaction were not significant (both F < 1). There was no main effect of group ($F(1,40) = 2.43$, $MSE = 23.57$, $p = .127$, $\eta^2 = .057$) nor interactions with group involving type of prime (all p > .19).

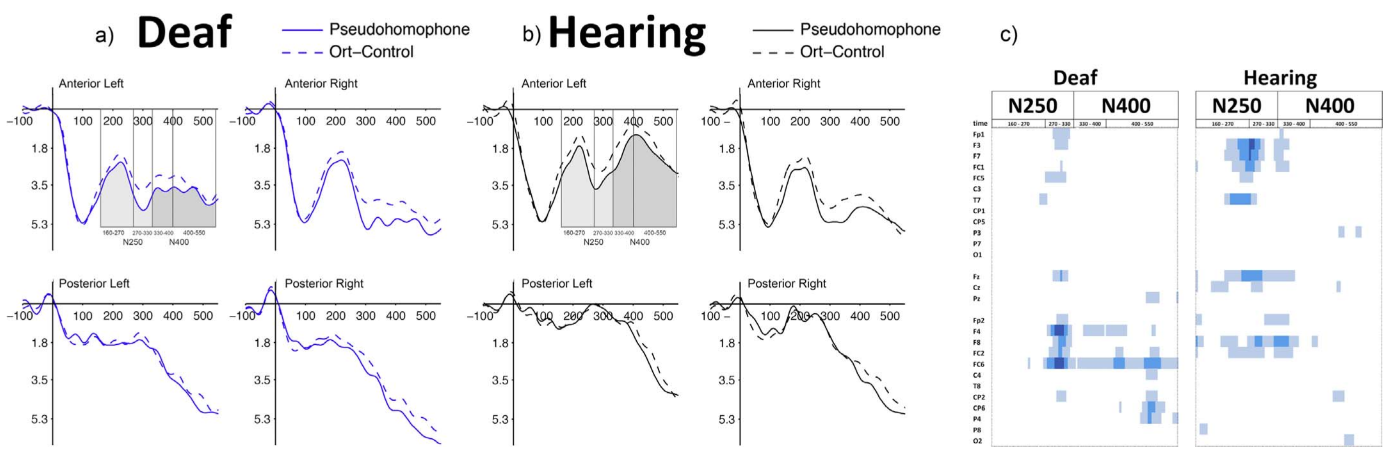


Fig. 3. Grand average ERPs to targets preceded by pseudohomophone primes (solid line) and orthographic control primes (dashed line) in the four analyzed electrode groupings in the deaf (panel a) and hearing (panel b) group. The four analyzed time windows (160–270, 270–330, 330–400 and 400–550 ms) are indicated in the anterior left electrodes. Panel c) shows the results of the univariate statistical analyses of the time course of the phonological effect. The plots convey the results of repeated-measures *t*-tests at every 4 ms interval between 150 and 550 ms at all 27 electrodes (listed in an anterior-posterior progression within the left hemisphere at the top, midline and right hemisphere at the bottom). P values are coded from lighter (lighter blue: < .05) to darker (dark blue: < .001). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.1.2. ERP results

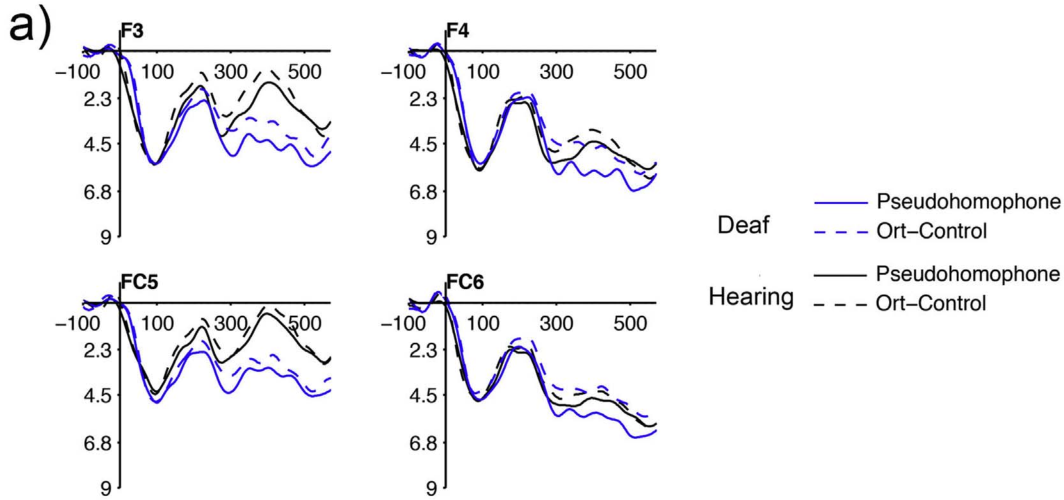
Fig. 3 shows the ERP waves of the pseudohomophone and orthographic control conditions for the deaf (left panel) and hearing readers (right panel) in the four groups of electrodes included in the analyses. In both groups, the ERPs show a positive potential peaking around 100 ms (ranging from 50 to 160 ms) followed by a negative going component peaking around 220 ms (ranging from 160 to 300 ms). Following these early potentials there is a slow negative going component ranging between 350 and 550 ms (N400). Importantly, the ERP responses in the first 170 ms show no difference between conditions. It is from around 170 ms that the orthographic control condition elicits a larger negativity than the pseudohomophone condition. This difference is more strongly observed in anterior electrodes. The observed reduction of the negativity for the pseudohomophone condition is present until the end of the epoch. Below, we report the statistical description of this comparison. In addition, Fig. 4 shows the ERP waves for the two conditions of interest across the two groups in four representative anterior electrodes. The left electrodes seem to show more positive amplitudes in both conditions for the deaf than the hearing readers. These possible differences across groups might develop over time. However, no differences in the timing of the peaks for the different components are visible in the ERPs.[4] The topographic distribution of the effect in both groups as well as a summary of the statistical results

The interaction between hemisphere, A-P distribution and group was significant, $F(1,40) = 6.23$, $MSE = 1.24$, $p = .017$, $\eta^2 = .135$. The deaf readers had more positive amplitude values than the hearing at posterior left ($F(1,40) = 4.25$, $p = .046$) and posterior right ($F(1,40) = 4.34$, $p = .044$) electrodes but not at anterior left ($F(1,40) = 1.17$, $p = .29$) or anterior right ($F < 1$). The interaction between hemisphere, A-P distribution and group approached significance, $F(1,40) = 3.30$, $MSE = 4.82$, $p = .077$, $\eta^2 = .076$. The interactions between A-P distribution and group and hemisphere and group were not significant (both p > .1).

3.1.2.2. 270–330 ms. There was a main effect of type of prime, $F(1,40) = 6.7$, MSE = 2.5, p = .013, $\eta^2 = .14$. There was an interaction of type of prime by A-P distribution, $F(1,40) = 9.71$, MSE = 1.13, p = .003, $\eta^2 = .195$—the difference between the pseudohomophone condition and the orthographic control condition was present in the anterior ($F(1,40) = 13.38$, < .001) but not in the posterior electrodes ($F < 1$). The interaction between type of prime and hemisphere as well as the three-way interaction were not significant (both $F < 1$). There was no main effect of group ($F(1,40) = 2.67$, MSE = 32.27, p = .110, $\eta^2 = .063$) nor interactions with group involving type of prime (all p > .17). The interaction between hemisphere, A-P distribution and group approached significance, $F(1,40) = 3.19$, $MSE = 1.88$, $p = .082$, $\eta^2 = .074$. The interactions between hemisphere and group and A-P distribution and group were not significant (both p > .1).

3.1.2.3. 330–400 ms. The main effect of type of prime approached

[4] Analyses of the latency of the peaks revealed no differences between both groups (all p > .18) in latency for any of the two conditions of the N250 negative peak (160–270 ms time window), positive peak at the end of the N250 (270–330 ms time window) nor the N400 (negative peak at the 330–550 ms time window).



b)

Time epochs	*Deaf*	*Hearing*	*Combined*
160-270ms	n.s	* (anterior)	* (anterior)
270-330ms	** (anterior)	** (anterior)	*** (anterior)
330-400ms	* (anterior)	* (p = .07 anterior)	** (anterior)
400-550ms	* (main effect)	n.s	(p = .064, main effect)
* p < .05, ** p < .01, *** p < .001			No effect of group nor interaction with group

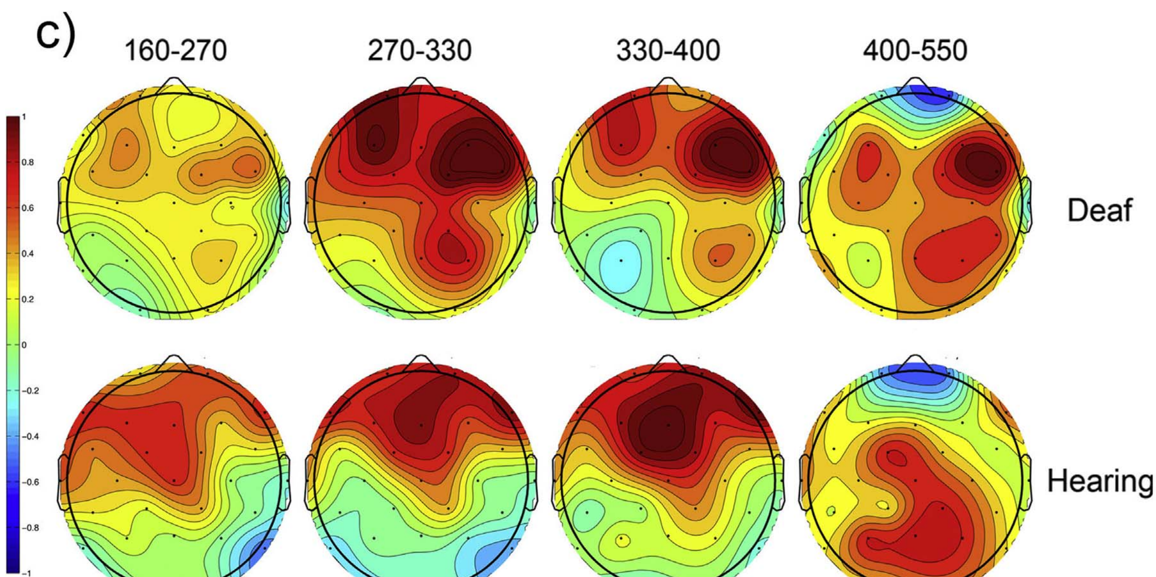


Fig. 4. Grand average ERPs overlapped for comparison purposes for both groups in four representative electrodes (panel a). Summary table of the statistical results in the four windows of interest in both groups separately as well as in the conjoined analysis for the four windows of interest (panel b). Topographic distribution of the masked phonological priming effect (calculated as the difference in voltage amplitude between the ERP responses to the pseudohomophone vs. the orthographic control conditions) for deaf (panel c, top) and hearing (panel c, bottom) readers in the four time windows of the analysis.

significance, $F(1,40) = 4.01$, $MSE = 4.17$, $p = .052$, $\eta^2 = .091$. There was an interaction of type of prime by A-P distribution, $F(1,40) = 9.08$, $MSE = 1.2$, $p = .004$, $\eta^2 = .19$—the difference between the pseudohomophone condition and the orthographic control condition was present in the anterior ($F(1,40) = 8.27$, $p = .006$) but not in the posterior electrodes ($F < 1$). The interaction between type of prime and hemisphere as well as the three-way interaction were not significant (both Fs < 1). The main effect of group approached significance ($F(1,40) = 3.89$, $MSE = 45.25$, $p = .056$, $\eta^2 = .089$), there were no significant interactions with group involving type of prime (all $p > .18$). However, the interaction of hemisphere by group was significant, $F(1,40) = 4.62$, $MSE = 4.82$, $p = .038$, $\eta^2 = .103$. The deaf readers had more positive amplitude values than the hearing at left hemisphere electrodes ($F(1,40) = 6.51$, $p = .015$) but not at right hemisphere electrodes ($F(1,40) = 1.45$, $p = .24$). The interaction between hemisphere, A-P distribution and group approached significance, $F(1,40) = 3.30$, $MSE = 4.82$, $p = .077$, $\eta^2 = .076$. The interaction between A-P distribution and group was not significant ($F < 1$).

3.1.2.4. 400–550 ms. The main effect of type of prime approached significance, $F(1,40) = 3.64$, MSE = 2.3, p = .064, $\eta^2 = .083$. The interactions between type of prime and A-P distribution, type of prime and hemisphere as well as the three-way interaction were not significant (all $F < 1$). The main effect of group approached significance ($F(1,40) = 3.31$, $MSE = 54.41$, $p = .077$, $\eta^2 = .076$) but there were no significant interactions with group involving type of prime (all $p > .38$). However, the interaction of hemisphere by group was significant, $F(1,40) = 4.98$, $MSE = 4.61$, $p = .031$, $\eta^2 = .111$. The interaction between hemisphere, A-P distribution and group was significant, $F(1,40) = 7.52$, $MSE = 4.82$, $p = .009$, $\eta^2 = .158$. The deaf readers had more positive amplitude values than the hearing at anterior left hemisphere electrodes ($F(1,40) = 4.21$, $p = .047$) but not at anterior right hemisphere electrodes ($F < 1$). This difference between deaf and hearing readers approached significance at posterior left electrodes ($F(1,40) = 8.82$, $p = .057$) and posterior right sites ($F(1,40) = 2.91$, $p = .096$). The interaction between A-P distribution and group was not significant ($F < 1$).

In summary, both groups showed a phonological masked phonological priming effect in the behavioral data and in the two ERP components analyzed. The comparison between groups showed an overall attenuation of the negativities for the deaf readers, in posterior electrodes for the N250 time window and in left electrode sites (anterior and posterior) for the N400 time window.

There were no interactions involving group and type of prime in any of the 4 time windows considered separately. In order to further explore the time course of the masked phonological priming effects in both groups, a repeated measures ANOVA was performed over the phonological masked priming effect amplitudes including the factors group, AP-distribution, hemisphere, and time window (1–4). The results of this ANOVA showed a significant main effect of AP-distribution ($F(1,3) = 5.66$, $MSE = 5.99$, $p = .022$, $\eta^2 = .124$) that was qualified by an interaction between AP-distribution and time window, $F(1.80,72.14) = 6.79$, $MSE = 148$, $p = .003$, $\eta^2 = .145$. The phonological masked priming effect was larger during window 3 (330–400 ms) than during window 4 (400–550 ms; $F(1,38) = 1.85$, $p = .041$) in anterior electrodes for both groups. In posterior electrodes however, the phonological masked priming effect was larger during window 4 than during window 3 ($F(1,38) = 2.08$, $p = .024$) for both groups. There was no main effect or interaction involving group (all $p > .19$). The remaining effects were not significant (all $F < 1$).

The effect of type of prime did not interact with group, suggesting that the magnitude of the phonological masked priming was similar for deaf and hearing readers. However, this null effect does not guarantee that deaf readers indeed show a significant priming effect in the studied time windows. There is still a possibility that the significant priming effect observed was largely driven by the hearing readers. In order to rule out this possibility follow up analyses were carried out for both groups separately. Furthermore, we explored the correlations between the priming effects and reading related variables in each of the groups.

3.2. Deaf group

3.2.1. Behavioral results

ANOVAs with the within factor type of prime (pseudohomophone vs. control) and the dummy between-subjects factor List (see Pollatsek and Well, 1995) were performed separately for the latency and accuracy data (subjects -F1- and items -F2- analyses were performed for both).

On average, word recognition times were 29 ms faster when preceded by a pseudohomophone prime than when preceded by an orthographic control, $F1(1,20) = 22.82$, $MSE = 459.6$, $p < .001$, $\eta^2 = .53$; $F2(1,62) = 8.46$, $MSE = 8010$, $p = .005$, $\eta^2 = .11$. That is, deaf readers can activate phonological codes in the early moments of word processing.

There were no differences in accuracy between the pseudohomophone and control conditions (both Fs < 1).

3.2.2. ERP results

3.2.2.1. 160–270 ms. There were no significant effects, all ps $> .34$.

3.2.2.2. 270–330 ms. There was a main effect of type of prime, $F(1,20) = 5.3$, $MSE = 3.9$, $p = .032$, $\eta^2 = .21$. The interaction between type of prime and A-P distribution approached significance, $F(1,20) = 3.2$, MSE = 1.3, $p = .088$, $\eta^2 = .14$ —the difference between the pseudohomophone condition and the orthographic control condition occurred in the anterior ($F(1,20) = 10.86$, $p = .004$) but not in the posterior electrodes ($F < 1$). The other interactions were not significant.

3.2.2.3. 330–400 ms. The main effect of type of prime was not significant, $F(1,20) = 2.45$, $MSE = 5.118$, p = .1.33, $\eta^2 = .11$. More important, there was a significant interaction of type of prime by A-P distribution, $F(1,20) = 4.8$, MSE = 1.02, p = .041, $\eta^2 = .19$ —the difference between the pseudohomophone condition and the orthographic control condition was present in the anterior ($F(1,20) = 4.87$, p = .039) but not in the posterior electrodes ($F < 1$). The other interactions were not significant.

3.2.2.4. 400–550 ms. There was a main effect of type of prime, $F(1,20) = 4.96$, MSE = 2.7, p = .038, $\eta^2 = .2$. None of the interactions was significant.

3.2.3. Correlations with reading- related variables

Correlations between the behavioral and electrophysiological priming effects (the difference between the pseudohomophone and the orthographic control priming conditions in response times, accuracy and amplitude) and performance in the reading related measures: a) phonological processing, b) sentence reading and c) reading comprehension are shown in Table 4. Correlations between LSE AoA and behavioral and ERP phonological priming effects are also included in the table.

The reading-related measures did not correlate with the magnitude of the behavioral priming (response times). There was a significant correlation between performance in the sentence reading measure and phonological priming in accuracy, r = .46, p = .024. The other two reading measures as well as LSE AoA did not correlate with accuracy (all p > .1).

The pattern of correlations with the electrophysiological measures showed that the masked phonological priming ERP effect correlated with the 3 reading related-variables only in the later N400 time window (400–550 ms). The ERP effects in the earlier windows (270–330 and the 330–400 ms), but not the late N400 window, were correlated with the size of the behavioral priming effect (response times). There were no significant correlations between the ERP and accuracy priming effects (all $p > .2$).

Table 4
Correlations between performance in the reading-related variables and the behavioral and electrophysiological (in left and right anterior electrodes for the analysis windows where there was significant priming) masked phonological priming effects in both groups of participants. Correlation with age of acquisition of LSE are also shown for the deaf readers.

		Deaf					Hearing			
		AoA LSE	Phonological processing	Sentence reading	Reading comprehension	Phon effect RTs	Phonological processing	Sentence reading	Reading comprehension	Phon effect RTs
Phon	r	−0.10	−.227	−.104	.029		**.401**	**−.479***	−.33	
Effect RTs	p	.633	.287	.628	.892		**.052**	**.018**	.11	
160–270 ms	r						−.332	**.402**	.09	−.01
Anterior Left	p						.113	**.051**	.68	.95
160–270 ms	r						**−.442***	**.582****	.23	−.24
Anterior Right	p						**.031**	**.003**	.28	.27
270–330 ms	r	**−.46***	−.21	−.15	−.196	**.453***	**−.492***	**.568****	.02	−.24
Anterior Left	p	**.02**	.325	.48	.36	**.03**	**.015**	**.004**	.92	.26
270–330 ms	r	−.29	−.291	.001	.062	.33	**−.492***	**.535****	.13	−.36
Anterior Right	p	.17	.167	.998	.772	.12	**.015**	**.007**	.55	.08
330–400 ms	r	−.34	−.359	.15	.113	**.504***	−.163	.25	−.05	−.14
Anterior Left	p	.10	.085	.48	.599	**.01**	.446	.23	.83	.51
330–400 ms	r	−.1	−.318	.09	.249	**.465***	−.29	.36	.03	−.15
Anterior Right	p	.64	.13	.66	.241	**.02**	.17	.09	.90	.48
400–550 ms	r	−.15	**−.499***	.33	**.402**	.25				
Anterior Left	p	.49	**.013**	.11	**.051**	.24				
400–550 ms	r	−.02	**−.558****	**.434***	**.545****	.103				
Anterior Right	p	.928	**.005**	**.034**	**.006**	.631				

* p < .05, ** p < .01, *** p < .001

3.3. Hearing controls

3.3.1. Behavioral results

We conducted the same statistical analyses as those for the deaf group

As typically found in the literature on hearing participants, word recognition times were on average 21 ms faster when preceded by a pseudohomophone prime than when preceded by an orthographic control $F1(1,20) = 7.02$, MSE = 841.8, p = .015 $\eta^2 = .26$; $F2(1,62) = 7.91$, $MSE = 5315$, $p = .006$, $\eta^2 = .11$.

Analysis of the accuracy data showed an effect of type of prime (responses were more accurate to targets preceded by pseudohomophones than when preceded by orthographic controls) that was only significant in the subjects' analysis $F1(1,20) = 5.23$, MSE = 4.93, p = .033 $\eta^2 = .21$; $F2(1,62) = 1.9$, $MSE = 39.95$, $p = .172$, $\eta^2 = .027$.

3.3.2. ERP results

3.3.2.1. 160–270 ms. The main effect of type of prime was not significant, $F(1,20) = 1.36$, $MSE = 2.1$, $p = .26$, $\eta^2 = .064$. There was an interaction of type of prime by A-P distribution, $F(1,20) = 4.54$, $MSE = .846$, $p = .046$, $\eta^2 = .19$—the difference between the pseudohomophone condition and the orthographic control condition was present in the anterior ($F(1,20) = 4.87$, $p = .039$) but not in the posterior electrodes ($F(1,20) < 1$). The remaining interactions were not significant.

3.3.2.2. 270–330 ms. The main effect of type of prime was not significant, $F(1,20) = 1.55$, $MSE = 1.11$, $p = .23$, $\eta^2 = .072$. There was an interaction of type of prime by A-P distribution, $F(1,20) = 7.15$, $MSE = .98$, $p = .015$, $\eta^2 = .26$ — the difference between the pseudohomophone condition and the orthographic control condition was present in the anterior ($F(1,20) = 7.8$, $p = .01$) but not in the posterior electrodes ($F < 1$). The remaining interactions were not significant.

3.3.2.3. 330–400 ms. The main effect of type of prime was not significant, $F(1,20) = 2.45$, $MSE = 5.18$, $p = .133$, $\eta^2 = .109$. There was an interaction of type of prime by A-P distribution, $F(1,20) = 4.4$, $MSE = 1.4$, $p = .050$, $\eta^2 = .18$—the difference between the pseudohomophone condition and the orthographic control condition approached significance in the anterior ($F(1,20) = 3.5$, $p = .077$) but not in the posterior electrodes ($F(1,20) < 1$). The remaining interactions were not significant.

3.3.2.4. 400–550 ms. There were no significant effects, all ps > .17.

3.3.3. Correlations with reading- related variables

Correlations between the behavioral and electrophysiological priming effects and performance in the reading-related measures are shown in Table 4. Correlations between behavioral and ERP phonological priming effects are also included in the table.

Hearing readers showed a pattern of correlations quite different to deaf readers: Two of the reading related variables (phonological processing and sentence reading) were correlated with the behavioral phonological priming effect (response times) and the ERP priming effect in the earlier time windows (160–270 and 270–330 ms) but not in the N400 time window. The behavioral and electrophysiological priming effects were not correlated. There were no significant correlations between the reading related measures or the ERP priming effects and the accuracy priming effects (all ps > .1).

4. Discussion

The main aim of the current masked priming experiment was to study whether congenitally deaf adult readers can activate phonological codes early in word processing. Both the behavioral and the ERP data provided converging evidence of the automatic use of these codes. First, we discuss the presence of masked phonological priming in deaf readers within the context of prior studies on hearing and deaf readers.

Likewise, by examining the ERP responses, we consider whether deaf readers make use of phonological codes at a sub-lexical or at a whole-word level of processing. Second, we discuss the relationships between the magnitude of the masked phonological priming effects and the reading scores. Finally, we briefly argue on the role of age of acquisition of LSE in the present findings.

4.1. Automatic phonological processing: time course of phonological encoding

We found a sizeable automatic phonological effect in adult congenitally deaf readers in an experiment were the opportunities to find masked phonological priming were optimized (i.e., masked sandwich priming). The behavioral data showed a robust advantage for target words when preceded by pseudohomophones (vurro – BURRO) than when preceded by orthographic controls (nurro – BURRO). The magnitude of this effect was similar for deaf and hearing readers (29 vs. 21 ms, respectively). Thus, the present results are consistent with the ample evidence from masked priming studies in normally hearing readers that show phonological priming (e.g. Ferrand and Grainger, 1992, 1993, 1994; Perfetti and Bell, 1991; Pollatsek et al., 2005; see Rastle and Brysbaert, 2006, for review). This result therefore supports the view that there is automatic use of phonological information during visual word recognition (Carreiras et al., 2014; Coltheart et al., 2001; Frost, 1998; Grainger and Holcomb, 2009; Rastle and Brysbaert, 2006) and that this occurs not only for hearing adult readers, but also for deaf adult readers. It is also worth to notice that deaf participant' responses tend to be faster and, unlike hearing readers, were less accurate in the pseudohomophone than the identity condition (specially in the identity priming condition, see Appendices A and B). This result suggests a different balance in the use of orthographic and phonological information between deaf and hearing readers (see, for instance, Bélanger and Rayner, 2015 for a view of a more direct route to lexical access in deaf readers).

The ERP data revealed masked phonological priming effects on two components that have been found to be sensitive to phonological processing, the N250 and the N400. The N250 component has been associated with the mapping of orthographic and phonological representations onto whole-word representations (Grainger et al., 2006; Grainger and Holcomb, 2009). Importantly, this is thought to take place at the sub-lexical level of processing. Deaf readers showed a reduction of the amplitude of the N250 for those words preceded by a pseudohomophone prime. This difference is only significant at the 270–330 ms time window. Hearing participants also showed a reduction of the N250 over anterior electrodes—this was significant in both the 160–270 and 270–330 ms time windows. Taken together, these effects are consistent with the bi-modal interactive activation model (BIAM, Grainger and Holcomb, 2009), following the initial activation of orthographic codes upon presentation of a printed word, there is the activation of the phonological codes at a sublexical level of representations (see Grainger and Holcomb, 2009, Figure 12, for a depiction of these effects in ERP experiments). Consistent with the BIAM, the present ERP data showed that both hearing participants and, more importantly, congenitally deaf participants can automatically activate phonological representations in the early stages of printed word identification. It is also worth to note that the effects on the 270–330 ms window were clearly anterior for the hearing readers but the interaction with A-P distribution was only marginally significant for the deaf readers. These separate analyses of both groups suggest differences in the onset and possibly the distribution of the N250 effect. However, a direct contrast of the two groups did not reveal significant differences in any of the two time-windows. Instead, we found a significant priming effect for both groups starting at 160 ms until 330 ms. Furthermore, there were no differences across groups in the peak latency for this component and a direct contrast of the priming effect in both groups across the four time windows did not revealed significant differences in the time course. These results provide important confirmation that congenitally deaf readers can access phonological codes sub-lexically during visual word recognition. The lack of significant differences when contrasting the two groups points to similar mechanisms underlying the early use of phonological codes. However, further research is needed to provide cumulative evidence of whether subtle differences in phonological processing between deaf and hearing readers are reflected in the exact time course of the N250. The present study provides a paradigm that could be used to further explore in a consistent manner the factors that modulate the time course and strength of early automatic phonological processing in deaf readers.

Deaf readers also showed a reduction of the amplitude of the N400 over anterior electrodes in the earlier (330–400 ms window) that extended over posterior electrodes in the later (400–550 ms) window. Hearing participants, when considered alone, only showed an effect over anterior electrodes in the earliest of the two N400 windows.[5] Again, the combined analysis of the two groups did not reveal significant differences between groups that involved the phonological masked priming effect. However, the deaf readers showed overall smaller negativities in left electrode sites than the hearing readers. In single word recognition, the N400 is thought to reflect the mapping of the whole-word representations onto meaning (Grainger and Holcomb, 2009; Holcomb and Grainger, 2006, 2007). The finding of the N250 and N400 amplitudes being modulated by the phonological overlap between prime and target, in both deaf and hearing readers, parallels previous masked phonological priming studies of hearing readers. For instance, Grainger et al. (2006) found a phonological N250 effect over anterior electrodes arising at 250 ms, followed by an N400 effect lasting from 350 to 550 ms. Note that in the current study the N250 seems to arise earlier than in the Grainger et al. (2006) experiment. However, earlier N250 effects have been found in masked priming experiments that used a longer SOA (Eddy et al., 2014 and see also Holcomb and Grainger, 2007 for effects of SOA duration in masked repetition priming).

Another noteworthy feature of the present ERPs is a less obvious separation of the N250 and the N400 components (see Fig. 4) than in prior studies (Grainger et al., 2006; Eddy et al., 2014). Similar results have been reported in an ERP masked priming study using the sandwich methodology (Ktori et al., 2012). Ktori et al. (2012) argue that this less pronounced separation between the two components might be due to a slightly earlier rise of the N400 produced by the reduction of lexical competition.

Finally, the lower negativity found for the N400 in deaf readers could be partially accounted for by the fact that deaf readers were performing the task in a language that was not their first or preferred language (all deaf participants reported to communicate mainly in LSE since this was learnt). Previous studies with hearing bilinguals have found smaller N400s for their second languages. For example, the larger N400 amplitudes for L1 compared to L2 words observed in the study by Midgley et al. (2009) was interpreted in terms of a less active lexical-semantic network for the L2 than for the L1 in bilinguals, where L1 was the preferred language (i.e., they were more frequently exposed to words in L1 than in L2).

Although consistent with previous findings from hearing readers, the present masked phonological priming effects in deaf readers differ from previous results in this population. The few existing behavioral and eye movement studies of adult deaf readers have failed to find a significant processing advantage for pseudohomophones (Cripps et al., 2005; Bélanger et al., 2012, 2013). It is possible that variations in methodological parameters such as the SOAs, subtle changes in the paradigm (sandwich priming), or the language under study, can explain

[5] Note that a more frontal distribution of the phonological N400 has been found in similar studies, e.g. Eddy et al. (2014). Furthermore, the use of the sandwich priming methodology has been associated with earlier disappearance of the N400 effects in a masked repetition priming experiment (Ktori et al., 2012).

these contrasting results. First, previous masked priming studies with deaf readers used shorter SOAs (40 and 60 ms: Bélanger et al., 2012; 67 ms: Cripps et al., 2005; 100 ms: present study). The longer SOA used here might have elicited a larger effect size that reached statistical significance (note that, although the difference did not reach statistical significance, in the Bélanger et al., 2012 study the responses to phonological overlap stimuli were slightly faster than to control stimuli). Prior studies have reported significant masked phonological priming effects at 66 ms SOA (66 ms prime immediately followed by the target), but only a non-significant trend at 50 ms SOA in adult hearing Spanish readers (Pollatsek et al., 2005). Holcomb and Grainger (2007) reported an earlier and larger N250 effect when using a 180 ms SOA than when using a 60 ms SOA in a masked repetition priming experiment. Therefore, discrepancies between the current and previous studies might reflect that deaf readers need more time to extract information from the prime. One might think that this need of extra processing time is due to deaf having an underspecified phonological representation. However, the fact that our hearing controls show a masked phonological priming effect of the same magnitude might point to reading experience as a modulating factor. Further research is needed to shed light on this point as in the present set of data measures of phonological processing and sentence reading are also correlated in the hearing participants. Second, the use of the sandwich methodology in the present study is likely to have resulted in a larger effect size than the traditional masked priming used in previous experiments with deaf readers. In the sandwich technique, the brief presentation of the target between the forward mask and the prime has been proposed to boost the size of the facilitation effects via the reduction of inhibition from lexical competition (Lupker and Davis, 2009; see also Ktori et al., 2012, for ERP evidence).

Finally, differences between the present and previous studies of phonological priming in deaf readers may be due to the transparency of the languages studied. Unlike the present study (Spanish), previous studies have been conducted in languages with an opaque orthography (French: Bélanger et al., 2012; and English: Bélanger et al., 2013 and Cripps et al., 2005). Although homophone-priming studies of hearing readers have found early phonological processing in different languages (English: Pollatsek et al., 1992, French: Ferrand and Grainger, 1992, 1993, 1994, Hebrew: Frost et al., 2003, Chinese: Pollatsek et al., 2000), it has been proposed that word recognition more heavily reliant on phonological processing is better supported by transparent than opaque orthographies (see Frost and Katz, 1992). Further research is needed to contrast the size of the phonological priming in deaf readers of different orthographies.

4.2. Relationships between phonological priming and reading-related variables

Our measures of sentence processing and reading comprehension were strongly correlated in the group of deaf readers. Interestingly, both measures of reading ability were also correlated with phonological processing during an explicit task (syllable counting). Similar correlations between a syllable counting task and reading have been reported for adult deaf readers of Spanish (Domínguez et al., 2014) and English (Emmorey et al., 2016). More interestingly, in the present study we made use of the sensitivity of the ERPs to the time course of linguistic processing to examine the relationship between these reading-related measures and the ERP components at different stages of lexical access. Deaf readers did not show a significant correlation between any of the reading-related variables and their sub-lexical use of phonological codes (N250). This result is consistent with recent evidence from Sehyr et al. (2016), who found that during a serial recall experiment, deaf readers made use of English phonological codes. The use of those codes during the experimental task however, was not correlated with their reading ability. However, the size of the N400 effect on the later analysis window was correlated with phonological processing and both reading ability measures. This pattern of correlations indicates that in adult deaf readers, better metaphonological abilities and a higher reading ability are related to late, lexical effects. The correlation between the size of the N400 on the later window and reading ability measures is also consistent with results from a recent ERP study (Mehravari et al., 2017) that found a correlation in deaf readers between the size of the N400 for semantically anomalous sentence endings and their standardized reading scores. Mehravari et al. (2017) conclude that, unlike hearing readers, deaf readers rely primarily on semantic information, using the “good-enough” approach to reading (Ferreira et al., 2002).

In contrast, for hearing readers, we found sizeable correlations between the size of the N250, but not the N400, and both phonological processing and sentence reading. The reading comprehension task did not correlate with any of the other reading measures nor the behavioral or ERP priming effects for the hearing readers. Although hearing participants did not show a ceiling effect on this task, the variability of the scores was reduced in comparison with the deaf participants, which could result on a reduced capacity to detect relationships with the other measures. One contributing factor to these more levelled reading comprehension scores in the hearing participants can be the way they approach the task (as mentioned in Section 2.1, hearing readers spent more time and changed more responses than deaf participants). When the task was timed, and hence measured efficiency as was the case of the sentence reading task, a large variability in the scores is observed in both groups. Another contributing factor to the lack of correlation between reading comprehension scores and the rest of the measures in the hearing but not in the deaf participants might be their use of other grammatical information, such as syntax, to complete this task. Mehravari et al. (2017) found that the size of the P600 (ERP component associated with syntactic processing) was related to reading comprehension in hearing but not in deaf adult participants. In summary, the relationship found here between the early automatic use of phonological information at the sub-lexical level of processing and both reading and metaphonological abilities is consistent with the accounts that assume that lexical access through sub-lexical use of phonology supports a better reading ability (see for instance, Goswami and Bryant, 1990: Wagner and Torgesen, 1987, Waters et al., 1984), although other factors, such as the use of grammatical information should also be considered.

In summary, we found no overall differences in the magnitude of the behavioral or ERP masked phonological priming between the deaf and hearing readers when both groups are contrasted directly. However, analyses of both groups separately suggest subtle differences in the onset and possibly the distribution of the N250 that should be taken into account for further research. Furthermore, differences in the correlation patterns between neural activity and reading related variables suggest dissimilar contributions of automatic phonological processing to reading abilities in both groups. Our results suggest that the amount of phonological processing performed during early stages of word recognition might be a main contributor of reading ability in hearing readers, but not in deaf readers. One possibility is that both groups engage a differently balanced use of phonological and orthographic codes previous to lexical access. Indeed, it has been proposed (Bélanger and Rayner, 2015; Corina et al., 2013; Hirshorn et al., 2015) that deaf readers might follow a different route to lexical access than hearing readers, achieving word identification through a type of processing more heavily based on the use of orthographic codes. For instance, Corina et al. (2013) found brain activations during single word reading in non-skilled deaf readers similar to that of Chinese readers of logographic scripts. Further evidence in support of this argument comes from the present results in the identity priming (see Appendix B), where the ERP effects are larger and peak earlier for deaf than for hearing participants. The fact that deaf readers show a clear advantage over hearing readers in the identity condition points to a larger contribution of visual and orthographic factors during their lexical access. Further research on the time course of visual and orthographic codes during early lexical access in deaf readers, as well as its relationship with reading ability is needed to complete our understanding of how and when visual (orthographic) and phonological codes contribute to reading comprehension in deaf readers.

4.3. Use of phonological codes and language experience (correlations with LSE AoA)

We found a significant correlation between the size of the N250 effect on the anterior left electrodes and LSE AoA. This correlation was negative, indicating a larger early phonological effect for those individuals who learnt to sign later in their lives. This is consistent with previous results on deaf readers of English showing variability in the use of phonological codes depending on language experience. Koo et al. (2008) found that native deaf signers were less accurate than oral deaf readers in a phoneme detection test. Corina et al. (2014) found that late signers performed better than native signers in an explicit phonological task in English. These results have been interpreted on the basis of less experience with spoken language phonology by native signers. Our finding of a moderate positive correlation between LSE AoA and reading comprehension (the lower the AoA, the lower the reading level) is partially consistent with this interpretation. Native signers, especially during development, are less likely to rely on spoken or written Spanish for daily communication (i.e. with family and peers; see Corina et al., 2014, for discussion). This reduced familiarity with spoken Spanish could not be enough to be sizeable at the word or sentence reading levels but might become assessable on the reading comprehension task, which requires deeper use of semantic and grammatical knowledge (see Bélanger and Rayner, 2015; Domínguez et al., 2014 for a view of reading comprehension in deaf readers heavily based on semantic and syntactic knowledge). Another possibility is that deaf native signers, being bilingual, are reading in Spanish as their second language (see Chamberland and Mayberry, 2008; Hirshorn et al., 2015) while deaf individuals who acquired LSE later are likely to have Spanish as their first language. This might result in differences at the more complex levels of language processing. Indeed, Hirshorn et al. (2015) found that reading ability was best predicted by a measure of deep phonological processing in oral deaf readers, who were not exposed to SL until college years. In contrast, native signers' reading ability was best predicted by measures of semantic and visual (orthographic) processing.

However, it is worth pointing out that, in the present study, LSE AoA was only correlated with the electrophysiological effect on N250 time window. The size of the N400 effect, which in turn was correlated to performance in phonological processing and reading, was not affected by AoA. Further research on the interplay between phonological and semantic processing in deaf people that had acquired sign language at different moments in life will shed light on how language experience shapes this late ERP component.

5. Conclusions

We found converging evidence from both behavioral and ERP responses (N250 and N400) of early automatic activation of phonological codes in adult congenitally deaf readers. Furthermore, the magnitude of these effects was similar across the deaf and the hearing readers. These results are consistent with accounts that assume that phonology is an automatic part of word identification. Importantly, this is so even in participants that have not had access to speech sounds and therefore have an underspecified phonological representation (constructed upon articulatory feedback and visual information of speech lip patterns). Finally, the pattern of correlations of these phonological effects with reading ability suggests that the amount of sub-lexical use of phonological information might be a main contributor to reading ability for hearing but not for deaf readers.

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Appendix A. Pseudohomophone vs. identity conditions: results

A.1. Combined analysis of deaf and hearing readers

A.1.1. Behavioral results

ANOVAS with the within factor type of prime (pseudohomophone vs. identity), the between-subjects factor group (deaf vs. hearing readers) and the between-subjects dummy factor List were performed separately for the latency and accuracy data (subjects –F1- and items –F2- analyses were performed for both).

The latency analyses showed a main effect of type of prime, $F1(1,40) = 57.59$, $MSE = 502.1$, $p < .000$, $\eta^2 = .59$; $F2(1,62) = 20.55$, $MSE = 8562$, $p < .001$, $\eta^2 = .232$, that was qualified by an interaction with group, $F1(1,40) = 8.36$, $MSE = 502.1$, $p = .006$, $\eta^2 = .173$; $F2(1,62) = 25.87$, $MSE = 5090$, $p = .084$, $\eta^2 = .032$. Responses to the identity condition were faster than to the pseudohomophone condition for both deaf (mean = 669 and 719 ms respectively; $F1(1,40) = 56.57$, $p < .000$; $F2(1,62) = 20.61$, $MSE = 7193$, $p < .001$, $\eta^2 = .233$) and hearing (mean 739 and 761; $F1(1,40) = 10.7$, $p = .002$; $F2(1,62) = 6.71$, $MSE = 6459$, $p = .01$, $\eta^2 = .090$) readers.

The main effect of group approached significance, $F1(1,40) = 3.16$, $MSE = 15004.23$, $p = .083$, $\eta^2 = .073$; $F2(1,62) = 80.46$, $MSE = 10340$, $p < .001$, $\eta^2 = .537$.

Analyses of the accuracy data showed a main effect of group, $F1(1,40) = 4,84$, $MSE = 21.88$, $p = .034$, $\eta^2 = .108$; $F2(1,62) = 1,8.6$ $MSE = 48.14$, $p < .001$, $\eta^2 = .212$, and an interaction between group and type of prime, $F1(1,40) = 6.44$, $MSE = 4.38$, $p = .015$, $\eta^2 = .139$; $F2(1,62) = 1.283$, $MSE = 48.14$, $p = .261$, $\eta^2 = .015$. Deaf readers were more accurate in the identity than in the pseudohomophone condition (mean = 94.2

and 92.5% correct respectively, $F1(1,40) = 7.00$, $p = .012$; $F2(1,62) = 1.62$, $MSE = 74.74$, $p = .207$ $\eta^2 = .023$). There were no differences in accuracy for hearing readers ($F1 < 1$; $F2 < 1$).

The main effect of type of prime was not significant, $F1(1,40) = 1.32$, $MSE = 4.381$, $p = .258$, $\eta^2 = .032$; $F2(1,62) = 1.31$, $MSE = 45.32$, $p = .256$, $\eta^2 = .019$.

A.1.2. ERP resultsA.1.2.1. 160–270 ms. There was a four-way interaction of type of prime by A-P distribution by hemisphere by group, $F(1,40) = 4.1$, $MSE = .402$, $p = .049$, $\eta^2 = .087$. However, analysis of the simple effects revealed that there were no differences between the pseudohomophone and the identity conditions in any of the electrode sites for any of the groups (all $p > .3$). There were no other significant effects (all $p > .2$).A.1.2.2. 270–330 ms. There was a main effect of type of prime, $F(1,40) = 6.53$, $MSE = 4.89$, $p = .014$, $\eta^2 = .13$. Targets preceded by an identity prime were more positive than those preceded by a pseudohomophone at this time window. There were no other significant effects (all $p > .2$).A.1.2.3. 330–400 ms. There was a main effect of type of prime, $F(1,40) = 17.3$, $MSE = 4.71$, $p < .001$, $\eta^2 = .287$. This main effect was modulated by an interaction of type of prime and A-P distribution, $F(1,40) = 23.995$, $MSE = 1.21$, $p < .001$, $\eta^2 = .36$. The difference between the pseudohomophone and the identity condition was present in the posterior ($F(1,40) = 31.7$, $p < .001$), but not the anterior electrodes ($F(1,40) = 2.52$, $p > .1$). The interaction of type of prime A-P distribution and group approached significance, $F(1,40) = 3.81$, $MSE = 1.21$, $p = .058$, $\eta^2 = .081$. The difference between the pseudohomophone and the identity condition in the deaf readers was present in the posterior ($F(1,40) = 25.52$, $p < .001$), but not the anterior electrodes ($F < 1$). Likewise, the difference between the pseudohomophone and the identity condition in the hearing group was present in the posterior ($F(1,40) = 8.72$, $p = .005$), but not the anterior electrodes ($F(1,40) = 1.68$, $p > .2$). There were no other significant effects (all $p > .1$)A.1.2.4. 400–550 ms. There was a main effect of type of prime, $F(1,40) = 4.21$, $MSE = 7.47$, $p = .046$, $\eta^2 = .089$. This main effect was modulated by an interaction of type of prime and A-P distribution, $F(1,40) = 18.36$, $MSE = 1.44$, $p = .001$, $\eta^2 = .23$. and interaction of type of prime A-P distribution and group, $F(1,40) = 7.23$, $MSE = 1.44$, $p = .010$, $\eta^2 = .144$. The difference between the pseudohomophone and the identity condition in the deaf readers was present in the posterior ($F(1,40) = 10.07$, $p = .003$), but not the anterior electrodes ($F < 1$). Likewise, the difference between the pseudohomophone and the identity condition in the hearing group was present in the posterior ($F(1,40) = 5.01$, $p = .031$), but not the anterior electrodes ($F(1,40) = 1.66$, $p > .2$). There were no other significant effects (all $p > .3$).

As the behavioral effects for each group separately were explored in the analysis of the interactions, we only submitted the ERP data to separate analysis for each group.

A.2. Deaf readers: ERP results

A.2.1. 160–270 ms

There was a three-way interaction of type of prime by A-P distribution by hemisphere by group, $F(1,20) = 6.79$, $MSE = .091$, $p = .017$, $\eta^2 = .253$. However, analysis of the simple effects revealed that there were no differences between the pseudohomophone and the identity conditions in any of the electrode sites (all $p > .2$). There were no other significant effects (all $p > .2$).

A.2.2. 270–330 ms

The main effect of type of prime approached significance, $F(1,20) = 4.04$, $MSE = 5.24$, $p = .058$, $\eta^2 = .17$. Targets preceded by an identity prime were more positive than those preceded by a pseudohomophone at this time window. There were no other significant effects (all $p > .2$).

A.2.3. 330–400 ms

There was a main effect of type of prime, $F(1,20) = 12.51$, $MSE = 4.56$, $p = .002$, $\eta^2 = .385$. This main effect was modulated by an interaction of type of prime and A-P distribution, $F(1,20) = 15.61$, $MSE = 1.79$, $p = .001$, $\eta^2 = .438$. The difference between the pseudohomophone and the identity condition was present in the posterior ($F(1,20) = 18.99$, $p < .001$), but not the anterior electrodes ($F(1,20) = 1.27$, $p > .2$). There were no other significant effects (all $p > .1$)

A.2.4. 400–550 ms

There was an interaction of type of prime and A-P distribution, $F(1,20) = 18.92$, $MSE = 1.49$, $p < .001$, $\eta^2 = .486$. The difference between the pseudohomophone and the identity condition in the deaf readers was present in the posterior ($F(1,20) = 10.54$, $p = .004$), but not the anterior electrodes ($F < 1$). There were no other significant effects (all $p > .2$).

A.3. Hearing readers: ERP results

A.3.1. 160–270 ms

There were no significant effects (all $p > .2$).

A.3.2. 270–330 ms

The main effect of type of prime approached significance, $F(1,20) = 3.21$, $MSE = 4.71$, $p = .088$, $\eta^2 = .138$, targets preceded by an identity

Table 5
Mean lexical decision times (RTs, in milliseconds) and percentage of accurate responses for the Identity and the unrelated priming conditions in deaf and hearing participants.

	Deaf		Hearing	
	RT mean (SD)	Accuracy mean (SD)	RT mean (SD)	Accuracy mean (SD)
Identity primes	669 (142)	94.2 (4.02)	739 (146)	95 (3.5)
Unrelated primes	750 (134)	94.4 (5.6)	792 (128)	95.1 (3.5)
difference	−81	0.2	−53	−.1

prime were more positive than those preceded by a pseudohomophone at this time window. There were no other significant effects (all $p > .2$)

A.3.3. 330–400 ms

There was a main effect of type of prime, $F(1,20) = 7.001$, $MSE = 4.83$, $p = .0162$, $\eta^2 = .259$. This main effect was modulated by an interaction of type of prime and A-P distribution, $F(1,20) = 6.69$, $MSE = .777$, $p = .018$, $\eta^2 = .251$. The difference between the pseudohomophone and the identity condition was present in the posterior ($F(1,20) = 14.02$, $p = .001$), but not the anterior electrodes ($F(1,20) = 1.91$, $p > .1$).

The interaction between type of prime and hemisphere and the three-way interaction were not significant (both $F < 1$).

A.3.4. 400–550 ms

The main effect of type of prime approached significance, $F(1,20) = 4.13$, $MSE = 8.31$, $p = .056$, $\eta^2 = .171$ There were no other significant effects (all $F < 1$).

Appendix B. Identity priming: results

B.1. Combined analysis with deaf and hearing readers

As for the masked phonological priming analyses, we performed a combined analysis. Contrasting the behavioral and electrophysiological effects in the same time windows in both groups would also allow to test whether the effects differ in magnitude across groups.

B.1.1. Behavioral results

Incorrect responses and lexical decision times above and below the average plus 2.5 SD for each participant in each condition (1.4% and 5.1% respectively) were excluded from the latency analysis. The mean lexical decision times and percentage of correct responses per condition are

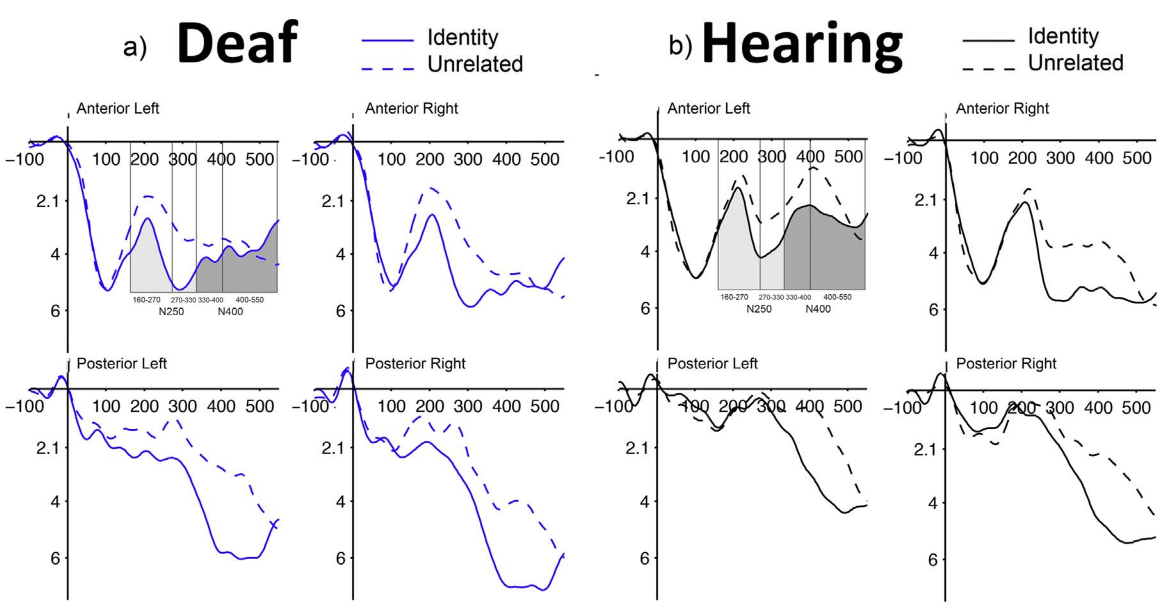
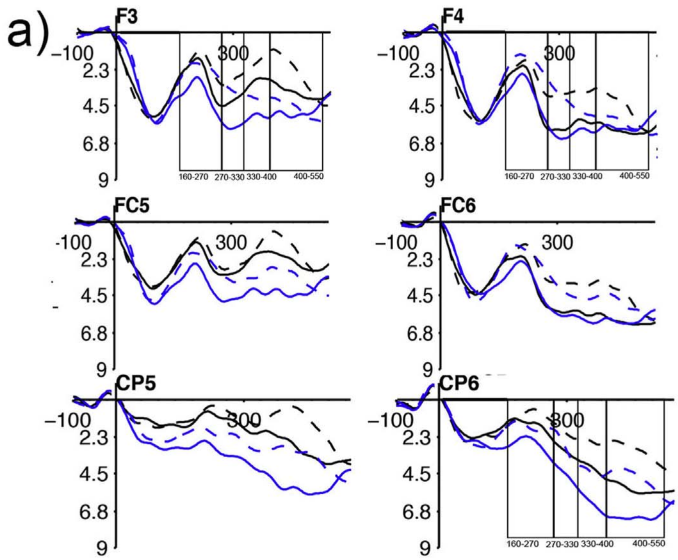


Fig. 5. Grand average ERPs to targets preceded by identity primes (solid line) and unrelated primes (dashed line) in the four analyzed electrode groupings in the deaf (panel a) and hearing (panel b) group. The four analyzed time windows (160–270, 270–330, 330–400 and 400–550 ms) are indicated in the anterior left electrodes.

a)



b)

Time epochs	*Deaf*	*Hearing*	*Combined*
160-270ms	*** (main effect)	* (anterior)	*** (main effect)
270-330ms	*** (main effect)	** (anterior)	*** (main effect)
330-400ms	*** (posterior)	*** (main effect)	*** (main effect. **Deaf posterior only**)
400-550ms	*** (posterior)	* (posterior)	***(posterior)

* p < .05, ** p < .01, *** p < .001

c)

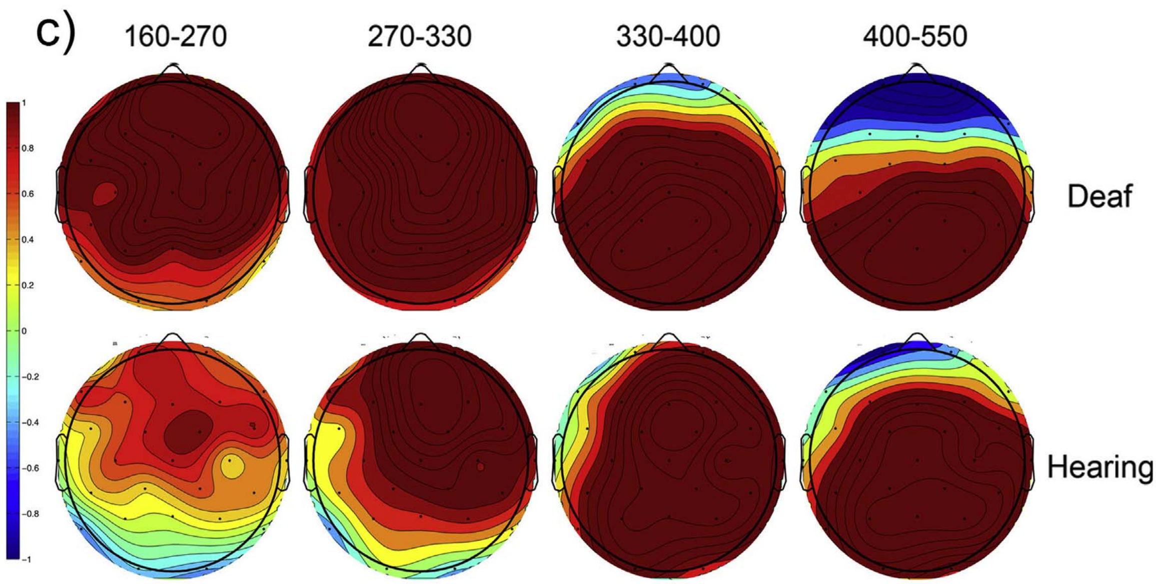


Fig. 6. Grand average ERPs overlapped for comparison purposes for both groups in four representative electrodes (panel a). Summary table of the statistical results in the four windows of interest in both groups separately as well as in the conjoined analysis for the four windows of interest (panel b). Topographic distribution of the masked phonological priming effect (calculated as the difference in voltage amplitude between the ERP responses to the identity vs. the unrelated conditions) for deaf (panel c, top) and hearing (panel c, bottom) readers in the four time windows of the analysis.

displayed in Table 5. ANOVAS with the within factor type of prime (identity vs. unrelated) the between-subjects factor group and the dummy between-subjects factor List were performed separately for the latency and accuracy data.

The latency analyses showed faster responses in the identity condition than in the unrelated condition, $F1(1,43) = 140.2$, $MSE = 780.1$, $p < .001$, $\eta^2 = .77$; $F2(1,62) = 72.4$, $MSE = 9100$, $p < .001$, $\eta^2 = .52$. The main effect of group approached significance, $F1(1,43) = 3.72$, $MSE = 29528$, $p = .061$, $\eta^2 = .080$; $F2(1,62) = 16.41$, $MSE = 6728$, $p < .001$, $\eta^2 = .19$. The interaction between type of prime and group was significant, *F1*(1,43) = 5.83, *MSE* = 780.3, p = .020, η^2 = .77; *F2*(1,62) = 3.6, *MSE* = 6728, p = .062, η^2 = .04. Examination of the simple effects showed that both groups showed faster responses to the identity than the unrelated conditions (Deaf: *F1*(1,43) = 103.57, $p < .001$; Hearing: *F1*(1,43) = 44.28, $p < .001$), the difference was larger in the deaf than in the hearing participants (81 vs. 53 ms difference). The ANOVA on the accuracy data showed no significant effects (all $F < 1$).

B.1.2. ERP results

Fig. 5 shows the ERP waves of the pseudohomophone effect for the deaf (left panel) and the hearing readers (right panel) in the four electrode groups analyzed. The ERPs show a positive potential peaking around 100 ms (ranging from 50 to 150 ms) followed by a negative going component peaking around 200 ms (ranging from 150 to 300 ms). Following these early potentials there is a slow negative going component ranging between 350 and 500 ms (N400). The ERP responses in the first 130 ms show no difference between conditions. It is from around 130 ms that the unrelated condition elicits a larger negativity than the identity condition. This difference seems to be widely distributed across all electrodes. The observed reduction of the negativity for the identity condition is present until approximately 500 ms. For comparison, below we report the statistical description for the same time windows identified for the main comparison (pseudohomophome vs. orthographic control conditions). Fig. 6 shows the overlap in both groups of the ERP waves for the two conditions of interest in four representative anterior electrodes. The topographic distribution of the effect in both groups as well as a summary of the statistical results for each group separately and for the conjoined analysis can also be seen in Fig. 6.B.1.2.1. 160–270 ms. There was a main effect of type of prime, *F*(1,40) = 15.06, *MSE* = 1.7, $p < .001$, η^2 = .27 qualified by an interaction of type of prime by A-P distribution, *F*(1,40) = 6.95, *MSE* = 1.05, p = .012, η^2 = .15—the difference between the identity and the unrelated condition was present in the anterior, *F*(1,40) = 18.6, < .001 and the posterior electrodes, *F*(1,40) = 5.57, p = .023. The interaction between type of prime and hemisphere as well as the three-way interaction were not significant (both $F < 1$).

The main effect of group was not significant prime, *F*(1,40) = 2.12, *MSE* = 24.2, p = .153, η^2 = .26. The interaction between type of prime and group approached significance, *F*(1,40) = 3.42, *MSE* = 3.522, p = .072, η^2 = .08. There were no significant interactions between type of prime, A-P distribution and group, *F*(1,40) < 1; type of prime, hemisphere and group, *F*(1,40) < 1; nor type of prime A-P distribution, hemisphere and group, *F* (1,40) = 1.41, *MSE* = .122, p = .241, η^2 = .034.B.1.2.2. 270–330 ms. There was a main effect of type of prime, *F*(1,40) = 24.27, *MSE* = 6.11, $p < .001$, η^2 = .38 that was modulated by an interaction with A-P distribution, *F*(1,40) = 14.43, *MSE* = 1.14, $p < .001$, η^2 = .265. —the difference between the identity and the unrelated condition was present in the anterior (*F*(1,40) = 31.00, $p < .001$) and posterior (*F*(1,40) = 10.51, p = .002) electrodes. The effect was stronger in anterior sites. There was also a significant interaction between type of prime and hemisphere, *F*(1,40) =4.56, *MSE* = .558, p = .039, η^2 = .102. —the difference between the identity and the unrelated condition was present in both the left (*F*(1,40) = 16.41, $p < .001$) and right (*F*(1,40) = 29.13, p = .002) electrodes. The three-way interaction was not significant, *F*(1,40) =2.28, *MSE* = .179, p = .19, η^2 = .054.

The main effect of group was not significant, *F*(1,40) = 2.13, *MSE* = 4.99, p = .153, η^2 = .05. There were no significant interactions between type of prime and group, *F*(1,40) = 1.58, *MSE* = 6.11, p = .216, η^2 = .038; type of prime, A-P distribution and group; type of prime, hemisphere and group; nor type of prime A-P distribution, hemisphere and group (all $F < 1$).B.1.2.3. 330–400 ms. There was a main effect of type of prime, *F* (1,40) = 28.24, *MSE* = 6.47, $p < .001$, η^2 = .414 that was modulated by an interaction of type of prime and A-P distribution, *F*(1,40) = 6.95, *MSE* = 1.8, p = .012, η^2 = .15. and by a three-way interaction between type of prime, A-P distribution and hemisphere, *F*(1,40) = 5.13, *MSE* = 1.5, p = .029, η^2 = .11. The difference between the identity and the unrelated condition was present in the anterior right (*F*(1,40) = 7.99, p = .007), anterior left (*F*(1,40) = 15.92, $p < .001$), posterior right (*F*(1,40) = 30.7, $p < .001$) and posterior left (*F*(1,40) = 29.56, $p < .001$) electrodes.

There was a main effect of group, F(1,40) = 5.04, *MSE* = 6.03, p = .03, η^2 = .11. There were no significant interactions between type of prime and group, *F*(1,40) < 1; type of prime, hemisphere and group, *F*(1,40) = 1.64, *MSE* = .723, p = .208, η^2 = .04.; nor type of prime, A-P distribution, hemisphere and group, ($F < 1$). The interaction between type of prime, A-P distribution and group was significant, *F*(1,40) = 5.1, *MSE* = 1.76, p = .029, η^2 = .11. For the deaf participants, the difference between the identity and the unrelated condition was present in the posterior (*F*(1,40) = 23.94, $p < .001$), but not the anterior (*F*(1,40) = 3.76, p = .060) electrodes. For the hearing participants —the difference between the identity and the unrelated condition was present in both the anterior (*F*(1,40) = 10.32, p = .003) and the posterior (*F*(1,40) = 10.1, p = .003) electrodes.B.1.2.4. 400–550 ms. There was a main effect of type of prime, *F*(1,40) = 17.8, *MSE* = 6.93, $p < .001$, η^2 = .308 that was modulated by an interaction of type of prime and A-P distribution, *F*(1,40) = 29.51, *MSE* = 2.1, $p < .001$, η^2 = .43 —the difference between the identity and the unrelated condition was present in the posterior (*F*(1,40) = 53.58, $p < .001$), but not the anterior ($F < 1$) electrodes.

The interaction between condition and hemisphere was not significant, *F*(1,40) = 1.11, *MSE* = .59, p = .299, η^2 = .027. The three-way interaction between type of prime, A-P distribution and hemisphere was not significant, $F < 1$.

The main effect of group was not significant, *F*(1,40) = 1.89, *MSE* = 67.9, p = .1773, η^2 = .045. There were no significant interactions between type of prime and group, *F*(1,40) < 1; type of prime, hemisphere and group, $F < 1$.; nor type of prime A-P distribution, hemisphere and group, $F < 1$. The interaction between t type of prime, A-P distribution and group approached significance, *F*(1,40) = 3.62, *MSE* = 2.1, p = .064, η^2 = .083.

For both groups the difference between the identity and the unrelated condition was present in the posterior (Deaf: *F*(1,40) = 32.44, $p < .001$; Hearing: *F*(1,40) = 21.83, $p < .001$), but not anterior (Deaf: $F < 1$; Hearing: *F*(1,40) = 2.19, p = .147) electrodes. This effect was larger for the deaf participants.

B.2. Deaf group

B.2.1. Behavioral results

ANOVAS with the within factor type of prime (identity vs. unrelated) and the dummy between-subjects factor List were performed separately for the latency and accuracy data.

On average, response times to target words were 81 ms faster when preceded by an identity than when preceded by an unrelated prime F1(1,20) = 97.7, *MSE* = 803.03, $p < .001$, η^2 = .83; *F2*(1,62) = 49.1, *MSE* = 9529, $p < .001$, η^2 = .42.

There were no differences in accuracy between the identity and unrelated conditions *F1* < 1; *F2* < 1.

B.2.2. ERP resultsB.2.2.1. 160–270 ms. There was a main effect of type of prime, $F(1,20) = 16.92$, $MSE = 3.5$, $p < .001$, $\eta^2 = .46$. There was no significant interaction of type of prime with A-P distribution, $F(1,20) = 2.42$, MSE = 1.27, $p = .134$, $\eta^2 = .11$ nor with hemisphere, $F(1,20) < 1$. The three-way interaction was not significant, $F(1,20) = 1.38$, $MSE = .082$, $p = .254$, $\eta^2 = .065$.B.2.2.2. 270–330 ms. There was a main effect of type of prime, $F(1,20) = 14.63$, $MSE = 8.2$, $p < .001$, $\eta^2 = .42$. There was a significant interaction of type of prime and A-P distribution, $F(1,20) = 5.33$, $MSE = 1.03$, $p = .032$, $\eta^2 = .21$. —the difference between the identity and the unrelated condition was present in both anterior ($F(1,20) = 17.4$, $p < .001$) and posterior electrodes ($F(1,20) = 8.92$, $p = .007$). This effect was stronger on the anterior than the posterior electrodes (1.94 mv vs. 1.25 mv). The interaction between type of prime and hemisphere was not significant, $F(1,20) < 1$. The three-way interaction was not significant, $F(1,20) = 1.48$, $MSE = .13$, $p = .238$, $\eta^2 = .069$.B.2.2.3. 330–400 ms. There was a main effect of type of prime, $F(1,20) = 12.41$, $MSE = 8.02$, $p = .002$, $\eta^2 = .38$. There was a significant interaction of type of prime and A-P distribution, $F(1,20) = 7.85$, $MSE = 2.77$, $p = .011$, $\eta^2 = .28$. —the difference between the identity and the unrelated condition was present in the posterior electrodes ($F(1,20) = 16.2$, $p < .001$) but the difference did not reach significance in anterior electrodes ($F(1,20) = 3.4$, $p = .080$). The interaction between type of prime and hemisphere was not significant, $F(1,20) < 1$. The three-way interaction was not significant, $F(1,20) < 1$.B.2.2.4. 400–550 ms. There was a main effect of type of prime, $F(1,20) = 7.17$, $MSE = 7.2$, $p = .015$, $\eta^2 = .26$ and a significant interaction of type of prime and A-P distribution, $F(1,20) = 24.4$, $MSE = 2.39$, $p < .001$, $\eta^2 = .55$. —the difference between the identity and the unrelated condition was present in the posterior electrodes ($F(1,20) = 29.48$, $p < .001$) but did not reach significance in anterior electrodes ($F(1,20) < 1$). The interaction between type of prime and hemisphere was not significant, $F(1,20) < 1$. The three-way interaction was not significant, $F(1,20) < 1$.

B.3. Hearing controls

B.3.1. Behavioral results

The same analysis than for the deaf group were performed. Analysis on the latency data showed that response times to target words were 53 ms faster when preceded by an identity than when preceded by an unrelated prime, $F1(1,20) = 55.6$, $MSE = 587.3$, $p < .001$, $\eta^2 = .74$; $F2(1,62) = 34.14$, $MSE = 6299$, $p < .001$, $\eta^2 = .33$, but not in accuracy, $F1 < 1$; $F2 < 1$.

B.3.2. ERP resultsB.3.2.1. 160–270 ms. The main effect of type of prime was not significant, $F(1,20) = 2.00$, $MSE = 3.52$, $p = .17$, $\eta^2 = .091$. There was a significant interaction of type of prime by A-P distribution, $F(1,20) = 5.13$, $MSE = .822$, $p = .035$, $\eta^2 = .20$. —the difference between the identity and the unrelated condition was present in the anterior ($F(1,20) = 4.56$, $p = .045$) but not in the posterior electrodes, $F(1,20) < 1$.B.3.3.2. 270–330 ms. There was a main effect of type of prime, $F(1,20) = 10.01$, $MSE = 3.992$, p = .005, $\eta^2 = .33$, modulated by a significant interaction of type of prime and A-P distribution, $F(1,20) = 9.04$, $MSE = 1.44$, $p = .007$, $\eta^2 = .31$ —the difference between the identity and the unrelated condition was present in the anterior ($F(1,20) = 13.75$, $p < .001$) but not in the posterior electrodes ($F(1,20) = 1.99$, $p = .17$). The interaction between type of prime and hemisphere approached significance, $F(1,20) = 3.85$, $MSE = .63$, $p = .064$, $\eta^2 = .16$. The three-way interaction was not significant, $F(1,20) < 1$.B.3.3.3. 330–400 ms. The unrelated condition elicited larger negativities than the identity conditions, $F(1,20) = 17.28$, $MSE = 4.93$, $p < .001$, $\eta^2 = .46$. The interaction between type of prime and A-P distribution was not significant, $F(1,20) < 1$. The interaction between type of prime and hemisphere approached significance, $F(1,20) = 4.16$, $MSE = .52$, $p = .055$, $\eta^2 = .17$. The three-way interaction approached significance, $F(1,20) = 3.65$, $MSE = .14$, $p = .071$, $\eta^2 = .15$.B.3.3.4. 400–550 ms. There was a main effect of type of prime, $F(1,20) = 11.04$, $MSE = 6.61$, $p = .003$, $\eta^2 = .36$, qualified by a significant interaction of type of prime and A-P distribution, $F(1,20) = 7.01$, $MSE = 1.81$, $p = .015$, $\eta^2 = .26$. —the difference between the identity and the unrelated condition was present in the posterior ($F(1,20) = 24.26$, $p < .001$) but not the anterior electrodes ($F(1,20) = 2.3$, $p = .15$). The interaction between type of prime and hemisphere and the three-way interaction were not significant (both Fs < 1).

References

Bélanger, N.N., Rayner, K., 2015. What eye movements reveal about deaf readers. Curr. Dir. Psychol. Sci. 24 (3), 220–226.

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

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

Brown, L., Sherbenou, R.J., Johnsen, S.K., 1990. Test of Nonverbal Intelligence: A Language-Free Measure of Cognitive Ability. Pro-ed.

Carreiras, M., Ferrand, L., Grainger, J., Perea, M., 2005. Sequential effects of phonological priming in visual word recognition. Psychol. Sci. 16 (8), 585–589.

Carreiras, M., Armstrong, B.C., Perea, M., Frost, R., 2014. The what, when, where, and how of visual word recognition. Trends Cognit. Sci. 18 (2), 90–98.

Carrillo, M.S., Marín, J., 1997. Test de Eficiencia Lectora–TECLE. Publicado en Cuadro, A., Costa, D., Trias y P. Ponce de León, D., 2009. Evaluación del nivel lector. Manual técnico del test de Eficacia Lectora (TECLE). Prensa Médica Latinoamericana: Uruguay.

Chamberlain, C., 2002. Reading Skills of Deaf Adults Who Sign: Good and Poor Readers Compared (Doctoral thesis). McGill University.

Chamberlain, C., Mayberry, R.I., 2008. American Sign Language syntactic and narrative comprehension in skilled and less skilled readers: Bilingual and bimodal evidence for the linguistic basis of reading. Appl. Psycholinguist. 29 (3), 367–388.

Charlier, B.L., Leybaert, J., 2000. The rhyming skills of deaf children educated with phonetically augmented speechreading. Q. J. Exp. Psychol.: Sect. A 53 (2), 349–375.

Chetail, F., 2012. La syllable en lecture: Rôle et implications chez l'adulte et chez l'enfant. Presses Universitaires de Rennes, Renner.

Chetail, F., Content, A., 2014. What is the difference between OASIS and OPERA? Roughly five pixels: orthographic structure biases the perceived length of letter strings. Psychol. Sci. 25 (1), 243–249.

Chetail, F., Mathey, S., 2012. Effect of syllable congruency in sixth graders in the lexical decision task with masked priming. Sci. Stud. Read. 16 (6), 537–549.

Chetail, F., Balota, D., Treiman, R., Content, A., 2015. What can megastudies tell us about the orthographic structure of English words? Q. J. Exp. Psychol. 68 (8), 1519–1540.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., Ziegler, J., 2001. DRC: a dual route cascaded model of visual word recognition and reading aloud. Psychol. Rev. 108 (1), 204.

Comesaña, M., Soares, A.P., Marcet, A., Perea, M., 2016. On the nature of consonant/vowel differences in letter position coding: evidence from developing and adult readers. Br. J. Psychol. 107, 651–674.

Conrad, R., 1977. The reading ability of deaf school-leavers. Br. J. Educ. Psychol. 47 (2), 138–148.

Conrad, R., 1979. The Deaf Schoolchild: Language and Cognitive Function. Harper and Row, London and New York.

Corina, D.P., Lawyer, L.A., Hauser, P., Hirshorn, E., 2013. Lexical processing in deaf readers: an fMRI investigation of reading proficiency. PLoS One 8 (1), e54696.

Corina, D.P., Hafer, S., Welch, K., 2014. Phonological awareness for american sign language. J. Deaf Stud. Deaf Educ. 19 (4), 530–545.

Corral, S., Ferrero, M., Goikoetxea, E., 2009. LEXIN: a lexical database from Spanish kindergarten and first-grade readers. Behav. Res. Methods 41 (4), 1009–1017.

Cripps, J.H., McBride, K.A., Forster, K.I., 2005. Lexical processing with deaf and hearing: phonology and orthographic masked priming. Ariz. Work. Pap. Second Lang. Acquis. Teach. 12, 31–44.

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J. Neurosci. Methods 134 (1), 9–21.

DiFrancesca, S., 1972. Academic Achievement Test Results of a National Testing Program for Hearing-Impaired Students—United States: Spring 1971. Gallaudet College, Office of Demographic Studies, Washington, DC (Series D, No. 9).

Domínguez, A.B., Carrillo, M.S., del Mar Perez, M., Alegría, J., 2014. Analysis of reading strategies in deaf adults as a function of their language and meta-phonological skills. Res. Dev. Disabil. 35 (7), 1439–1456.

Duchon, A., Perea, M., Sebastián-Gallés, N., Martí, A., Carreiras, M., 2013. EsPal: one-stop shopping for Spanish word properties. Behav. Res. Methods 45 (4), 1246–1258.
Eddy, M.D., Grainger, J., Holcomb, P.J., Mitra, P., Gabrieli, J.D., 2014. Masked priming and ERPs dissociate maturation of orthographic and semantic components of visual word recognition in children. Psychophysiology 51 (2), 136–141.
Emmorey, K., Weisberg, J., McCullough, S., Petrich, J.A., 2013. Mapping the reading circuitry for skilled deaf readers: an fMRI study of semantic and phonological processing. Brain Lang. 126 (2), 169–180.
Emmorey, K., McCullough, S., Weisberg, J., 2016. The neural underpinnings of reading skill in deaf adults. Brain Lang. 160, 11–20.
Ferrand, L., Grainger, J., 1992. Phonology and orthography in visual word recognition: evidence from masked non-word priming. Q. J. Exp. Psychol.: Sect. A 45 (3), 353–372.
Ferrand, L., Grainger, J., 1993. The time course of orthographic and phonological code activation in the early phases of visual word recognition. Bull. Psychon. Soc. 31 (2), 119–122.
Ferrand, L., Grainger, J., 1994. Effects of orthography are independent of phonology in masked form priming. Q. J. Exp. Psychol. 47 (2), 365–382.
Ferreira, F., Bailey, K.G.D., Ferraro, V., 2002. Good-enough representations in language comprehension. Curr. Dir. Psychol. Sci. 11, 11–15.
Forster, K.I., 1998. The pros and cons of masked priming. J. Psycholinguist. Res. 27 (2), 203–233.
Forster, K.I., Davis, C., 1984. Repetition priming and frequency attenuation in lexical access. J. Exp. Psychol.: Learn. Mem. Cognit. 10 (4), 680.
Frost, R., 1998. Toward a strong phonological theory of visual word recognition: true issues and false trails. Psychol. Bull. 123 (1), 71.
Frost, R., Ahissar, M., Gotesman, R., Tayeb, S., 2003. Are phonological effects fragile? The effect of luminance and exposure duration on form priming and phonological priming. J. Mem. Lang. 48 (2), 346–378.
Frost, R., Katz, M., 1992. Orthography, phonology, morphology and meaning, Eds. 94 Elsevier.
Goikoetxea, E., 2005. Levels of phonological awareness in preliterate and literate Spanish-speaking children. Read. Writ. 18 (1), 51–79.
Goswami, U., Bryant, P., 1990. Phonological Skills and Learning to Read. Lawrence Erlbaum, London, pp. 1.
Grainger, J., Holcomb, P.J., 2009. Watching the word go by: on the time-course of component processes in visual word recognition. Lang. Linguist. Compass 3 (1), 128–156.
Grainger, J., Kiyonaga, K., Holcomb, P.J., 2006. The time course of orthographic and phonological code activation. Psychol. Sci. 17 (12), 1021–1026.
Grainger, J., Lété, B., Bertand, D., Dufau, S., Ziegler, J.C., 2012. Evidence for multiple routes in learning to read. Cognition 123, 280–292.
Groppe, D.M., Urbach, T.P., Kutas, M., 2011. Mass univariate analysis of event-related brain potentials/fields I: A critical tutorial review. Psychophysiology 48 (12), 1711–1725.
Guthrie, D., Buchwald, J.S., 1991. Significance testing of difference potentials. Psychophysiology 28 (2), 240–244.
Hanson, V.L., McGarr, N.S., 1989. Rhyme generation by deaf adults. J. Speech Lang. Hear. Res. 32 (1), 2–11.
Hanson, V.L., Shankweiler, D., Fischer, F.W., 1983. Determinants of spelling ability in deaf and hearing adults: access to linguistic structure. Cognition 14 (3), 323–344.
Hanson, V.L., Goodell, E.W., Perfetti, C.A., 1991. Tongue-twister effects in the silent reading of hearing and deaf college students. J. Mem. Lang. 30 (3), 319–330.
Hirshorn, E.A., Dye, M.W., Hauser, P., Supalla, T.R., Bavelier, D., 2015. The contribution of phonological knowledge, memory, and language background to reading comprehension in deaf populations. Front. Psychol. 6.
Holcomb, P.J., Grainger, J., 2006. On the time course of visual word recognition: an event-related potential investigation using masked repetition priming. J. Cognit. Neurosci. 18 (10), 1631–1643.
Holcomb, P.J., Grainger, J., 2007. Exploring the temporal dynamics of visual word recognition in the masked repetition priming paradigm using event-related potentials. Brain Res. 1180, 39–58.
Holcomb, P.J., Grainger, J., O'rourke, T., 2002. An electrophysiological study of the effects of orthographic neighborhood size on printed word perception. J. Cognit. Neurosci. 14 (6), 938–950.
Holcomb, P.J., Reder, L., Misra, M., Grainger, J., 2005. The effects of prime visibility on ERP measures of masked priming. Cognit. Brain Res. 24 (1), 155–172.
Kelly, L., 2003. The importance of processing automaticity and temporary storage capacity to the differences in compre-hension between skilled and less skilled college-age deaf readers. J. Deaf Stud. Deaf Educ. 8, 230–249.
Keuleers, E., Brysbaert, M., 2010. Wuggy: a multilingual pseudoword generator. Behav. Res. Methods 42, 627–633.
Kinoshita, S., Lupker, S.J. (Eds.), 2004. Masked Priming: The State of the Art. Psychology Press.
Koo, D., Crain, K., LaSasso, C., Eden, G.F., 2008. Phonological awareness and short-term memory in hearing and deaf individuals of different communication backgrounds. Ann. N. Y. Acad. Sci. 1145 (1), 83–99.
Ktori, M., Grainger, J., Dufau, S., Holcomb, P.J., 2012. The "electrophysiological sandwich": a method for amplifying ERP priming effects. Psychophysiology 49 (8), 1114–1124.
Kutas, M., Federmeier, K.D., 2000. Electrophysiology reveals semantic memory use in language comprehension. Trends Cognit. Sci. 4 (12), 463–470.
Lopez-Calderon, J., Luck, S.J., 2014. ERPLAB: an open-source toolbox for the analysis of event-related potentials. Front. Hum. Neurosci. 8, 213.
Luck, S.J., Gaspelin, N., 2017. How to get statistically significant effects in any ERP experiment (and why you shouldn't). Psychophysiology 54 (1), 146–157.
Lukatela, G., Turvey, M.T., 1994. Visual lexical access is initially phonological: 2. Evidence from phonological priming by homophones and pseudohomophones. J. Exp. Psychol.: Gen. 123 (4), 331.
Lupker, S.J., Davis, C.J., 2009. Sandwich priming: a method for overcoming the limitations of masked priming by reducing lexical competitor effects. J. Exp. Psychol.: Learn. Mem. Cognit. 35 (3), 618.
Mackinson, J.A., Leigh, I.W., Blennerhassett, L., Anthony, S., 1997. Validity of the TONI-2 with deaf and hard of hearing children. Am. Ann. Deaf 142 (4), 294–299.
MacSweeney, M., Waters, D., Brammer, M.J., Woll, B., Goswami, U., 2008. Phonological processing in deaf signers and the impact of age of first language acquisition. Neuroimage 40 (3), 1369–1379.
MacSweeney, M., Goswami, U., Neville, H., 2013. The neurobiology of rhyme judgment by deaf and hearing adults: an ERP study. J. Cognit. Neurosci. 25 (7), 1037–1048.
Mayberry, R.I., Del Giudice, A.A., Lieberman, A.M., 2011. Reading achievement in relation to phonological coding and awareness in deaf readers: a meta-analysis. J. Deaf Stud. Deaf Educ. 16 (2), 164–188.
McArthur, G., Castles, A., 2017. Helping children with reading difficulties: some things we have learned so far. npj Sci. Learn. 2 (1), 7.
Mehravari, A.S., Emmorey, K., Prat, C.S., Klarman, L., Osterhout, L., 2017. Brain-based individual difference measures of reading skill in deaf and hearing adults. Neuropsychologia.
Midgley, K.J., Holcomb, P.J., Grainger, J., 2009. Language effects in second language learners and proficient bilinguals investigated with event-related potentials. J. Neurolinguist. 22, 281–300. http://dx.doi.org/10.1016/j.jneuroling.2008.08.001.
Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9 (1), 97–113.
Perea, M., Mallouh, Abu, Carreiras, M., 2014. Are root letters compulsory for lexical access in Semitic languages? The case of masked form-priming in Arabic. Cognition 132, 491–500. http://dx.doi.org/10.1016/j.cognition.2014.05.008.
Perea, M., Marcet, A., Vergara-Martínez, M., 2016. Phonological-lexical feedback during early abstract encoding: the case of deaf readers. PLoS One 11 (1), e0146265.
Perfetti, C.A., Bell, L., 1991. Phonemic activation during the first 40 ms of word identification: evidence from backward masking and priming. J. Mem. Lang. 30 (4), 473–485.
Perfetti, C.A., Sandak, R., 2000. Reading optimally builds on spoken language: implications for deaf readers. J. Deaf Stud. Deaf Educ. 5 (1), 32–50.
Pollatsek, A., Well, A.D., 1995. On the use of counterbalanced designs in cognitive research: a suggestion for a better and more powerful analysis. J. Exp. Psychol.: Learn. Mem. Cognit. 21 (3), 785.
Pollatsek, A., Lesch, M., Morris, R.K., Rayner, K., 1992. Phonological codes are used in integrating information across saccades in word identification and reading. J. Exp. Psychol.: Hum. Percept. Perform. 18 (1), 148–162.
Pollatsek, A., Tan, L.H., Rayner, K., 2000. The role of phonological codes in integrating information across saccadic eye movements in Chinese character identification. J. Exp. Psychol.: Hum. Percept. Perform. 26 (2), 607.
Pollatsek, A., Perea, M., Carreiras, M., 2005. Does conal prime canal more than cinal? Masked phonological priming effects in Spanish with the lexical decision task. Mem. Cognit. 33 (3), 557–565.
Rastle, K., Brysbaert, M., 2006. Masked phonological priming effects in English: are they real? Do they matter? Cognit. Psychol. 53 (2), 97–145.
Rayner, K., 1975. The perceptual span and peripheral cues in reading. Cognit. Psychol. 7, 65–81. http://dx.doi.org/10.1016/0010-0285(75)90005-5.
Rodríguez-Ortiz, I.R., Saldaña, D., Moreno-Perez, F.J., 2015. How speechreading contributes to reading in a transparent ortography: the case of Spanish deaf people. J. Res. Read.
Sánchez, E., García-Rodicio, H., 2006. Re-lectura del estudio PISA: qué y cómo se evalúa e interpreta el rendimiento de los alumnos en la lectura. Rev. Educ. 195–226.
Sehyr, Z.S., Petrich, J., Emmorey, K., 2016. Fingerspelled and printed words are recoded into a speech-based code in short-term memory. J. Deaf Stud. Deaf Educ. 1–16.
Sterne, A., Goswami, U., 2000. Phonological awareness of syllables, rhymes, and phonemes in deaf children. J. Child Psychol. Psychiatry 41 (5), 609–625.
Toro, J., Cervera, M., Urío, C., 2002. Escalas Magallanes de Lectura y Escritura. TALE-2000.
Traxler, C.B., 2000. The stanford achievement test: national norming and performance standards for deaf and hard-of-hearing students. J. Deaf Stud. Deaf Educ. 5 (4), 337–348.
Vergara-Martínez, M., Comesaña, M., Perea, M., 2016. The ERP signature of the contextual diversity effect in visual word recognition. Cognit. Affect. Behav. Neurosci. 17, 461–474.
Wagner, R.K., Torgesen, J.K., 1987. The nature of phonological processing and its causal role in the acquisition of reading skills. Psychol. Bull. 101 (2), 192.
Waters, G.S., Seidenberg, M.S., Bruck, M., 1984. Children's and adults' use of spelling-sound information in three reading tasks. Mem. Cognit. 12 (3), 293–305.
Wauters, L.N., Van Bon, W.H., Tellings, A.E., 2006. Reading comprehension of Dutch deaf children. Read. Writ. 19 (1), 49–76.
Ziegler, J.C., Bertrand, D., Lété, B., Grainger, J., 2014. Orthographic and phonological contributions to reading development: tracking developmental trajectories using masked priming. Dev. Psychol. 50, 1026–1036. http://dx.doi.org/10.1037/a0035187.