Automatic use of phonological codes during word recognition in deaf signers of Spanish Sign Language

Eva Gutierrez-Sigut (Universitat de València & University College London), **Marta Vergara-Martínez** (Universitat de València), **Ana Marcet** (Universitat de València), **Manuel Perea** (Universitat de València)
eva.gutierrez@uv.es, marta.vergara@uv.es, ana.marcet@uv.es, manuel.perea@uv.es

Abstract

The poor reading skills often found in deaf readers are typically explained on the basis of underspecified print-to-sound mapping and poorer use of spoken phonology. Whilst prior research using explicit phonological tasks has shown that deaf readers can use phonological codes when required, an open question is whether congenitally deaf readers can automatically use phonological codes when reading. We designed a masked sandwich priming experiment to examine whether deaf readers can automatic activate phonological codes during the early stages of lexical processing. 24 deaf participants had to decide whether a target stimulus was a word or not. We also recruited a group of 24 hearing controls. Each target word was preceded by a pseudohomophone or by an orthographic control prime. Results showed faster word identification times in the pseudohomophone than in the control condition (i.e., masked phonological priming). The magnitude of this phonological effect was similar in the two groups, thus supporting the view that phonological codes are automatically activated during word identification. The pattern of correlations of the phonological priming effect with reading ability suggested 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.

Keywords: Deaf readers, phonological processing, reading ability, lexical decision, masked priming, sandwich masked priming

1 Introduction

Reading is a difficult task for most deaf readers. 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 & García-Rodicio, 2006; Dutch: Wauters, van Bon, & Tellings, 2006). These poor reading skills are often explained in terms of their underspecified print-to-sound mapping and the accompanying poorer use of spoken phonology (Perfetti & Sandak, 2000). This difficulty may have a negative impact not only on their academic achievement, but also on their social and emotional well-being (McArthur & Castles, 2017).

It has been established that adult hearing readers automatically use phonological codes during the early stages of printed word recognition (see Rastle & Brysbaert, 2006, for a review). One technique has been particularly important in this area: masked priming (Forster & Davis, 1984). In a typical masked priming experiment, a very briefly presented prime precedes a target stimulus, to which participants respond (e.g., “Is the target a word or not?” [lexical decision]). A number of masked priming experiments with adult hearing readers have shown faster word identification times on a target word (e.g., BRAIN) when preceded briefly by a pseudohomophone prime (i.e., a nonword that is pronounced like the

Gutierrez-Sigut, Eva, Marta Vergara-Martínez, Ana Marcet & Manuel Perea (2018). Automatic use of phonological codes during word recognition in deaf signers of Spanish Sign Language. *FEAST* 1: 1-15. https://doi.org/10.2436/20.8050.03.1. http://www.raco.cat/index.php/FEAST

target word; e.g., brane) than when preceded by an orthographic control prime (brant) (see Rastle & Brysbaert, 2006, for review), thus demonstrating the fast and automatic activation of phonological codes. Importantly, prior research using masked priming with deaf readers failed to find evidence of phonological involvement during the early stages of word processing (Bélanger, Baum, & Mayberry 2012; Cripps, McBride, & Forster, 2005). Using a 67-ms prime exposure duration, Cripps et al. (2005) compared masked identity (sample-SAMPLE vs. victory-SAMPLE) and masked phonological priming (braik-BRAKE vs. scrone-BRAKE) in deaf and hearing readers. While both groups showed a facilitative identity priming effect, only the hearing readers showed a facilitative phonological priming effect. Likewise, Bélanger et al. (2012) compared masked orthographic (e.g., keit–KAÏT vs. kets–KAÏT; [kɛ]- [kɛ] vs. [kɛ]-[kɛ]) and masked phonological priming (e.g., kets-KAÏT vs. kaum–KAÏT; [kɛ]- [kɛ] vs. [kom]-[kɛ]) in hearing and deaf readers of different reading skill. Whilst masked orthographic priming occurred to a similar degree in both groups, masked phonological priming effect was only observed in the hearing readers. Importantly, the lack of a phonological priming effect occurred in both skilled and non-skilled deaf readers.

It is important to highlight that prior experiments using explicit phonological tasks have shown that deaf readers can use phonological codes, at least when explicitly required by the task (e.g., a rhyming task; see Charlier & Leybaert, 2000; Hanson & McGarr, 1989, for behavioral evidence; see MacSweeney, Goswami, & Neville, 2013, for ERP evidence; see Emmorey, Weisberg, McCullough, & Petrich, 2013; MacSweeney, Waters, Brammer, Woll, & Goswami, 2008, for fMRI studies), although their performance tends to be lower than that of their hearing peers (e.g., see Sterne & Goswami, 2000). However, when phonological encoding is only implicitly required by the task, the evidence on the automatic use of phonological codes by deaf readers is not consistent (Hanson, Goodel, & Perfetti, 1991; Hanson, Shankweiler, & Fischer, 1983; Kelly, 2003; Sehyr, Petrich, & Emmorey, 2017; see Perfetti & Sandak, 2000, for review). Taken together these results appear to strengthen the case for a weak (or absent) automatic phonological processing in deaf readers. Nonetheless, we must keep in mind that the magnitude of masked phonological priming effects with hearing readers is small (Rastle & Brysbaert, 2006). Therefore, the possibility remains that the standard set-up of the masked priming technique lacks sensitivity to capture a phonological effect in poorer readers (including most deaf readers).

The current experiment examined whether there is automatic phonological involvement during the early moments of lexical processing in deaf readers when the opportunity to enable priming is maximal. First, the present study was conducted in a language with a transparent orthography (Spanish) because it has been proposed that phonological processing is more salient in transparent than in than opaque orthographies (see Frost, 1998). Second, the experimental manipulation was restricted to the initial segments of the word because masked phonological priming effects are greater when there is phonological overlap at the beginning of the word (first-syllable) than in the internal letters (see Carreiras, Ferrand, Grainger, & Perea, 2005). Third, the standard masked priming paradigm was modified in two ways. We used a 100 ms stimulus onset asynchrony (SOA, this is the time elapsed between the beginning of the prime and the beginning of the target), which is longer than the 50 ms usually employed in studies of skilled adult hearing readers and previous studies with deaf readers. Keep in mind that masked phonological priming can only be obtained with hearing children when using a slightly longer prime duration (see Comesaña, Soares, Marcet, & Perea, 2016). Furthermore, we used the "sandwich" variation of the masked priming technique (Lupker & Davis, 2009) in which the target is presented very briefly between the forward mask and the prime (see Figure 1 for details). The sandwich variation produces greater priming effects than the standard masked priming procedure without altering the early bottom up effects (Lupker & Davis, 2009; see also Comesaña et al., 2016). Lupker and Davis (2009) demonstrated that this technique is more sensitive to small-sized effects than the conventional set-up of the masked priming paradigm (see also Comesaña et al., 2016, for converging evidence). Typically, the effect sizes are 2-3 times greater with the sandwich technique than with the conventional methodology (Lupker & Davis, 2009).

A further question of interest is whether the early automatic 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 phonological processing are necessarily related (see Mayberry, Del Giudice, & Lieberman, 2011, for review; see also Sehyr et al., 2017, for recent evidence) in deaf readers. In the Bélanger et al. (2012) masked priming experiment, the size of 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, McCullough, and Weisberg (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, explicit phonological tasks and performance during the task.

Finally, as language experience has been found to modulate the use of phonological information during visual word recognition (see Corina, Hafer, & Welch, 2014; Hirshorn et al., 2015; Koo, Crain, LaSasso, & Eden, 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 size of the phonological priming effects in native, early, and late signers.

To sum up, the present experiment examined the automatic activation of phonological codes during early lexical processing in deaf readers when the opportunity to enable priming was maximal. We registered the participants' responses (latency and accuracy) to words targets preceded by a pseudohomophone or by an orthographic control prime. As in previous masked priming studies, we also included an identity priming comparison (target words preceded by repeated vs. unrelated primes) as this would allow us to further examine the use of visual and orthographic information during word recognition. Furthermore, to answer the question of whether the magnitude of the phonological priming effect in deaf readers is similar to that found in hearing readers, we compared masked phonological and identity priming effects in congenitally deaf readers and matched hearing readers. Finally, we investigated whether the use of phonological information during isolated word recognition by deaf readers was related to their reading ability and phonological processing skills. If deaf readers use phonological codes automatically during lexical processing, we would expect faster response times for target words preceded by a pseudohomophone than for those preceded by an orthographic control—note that if deaf readers make less use of phonological codes than hearing readers, the size of the phonological priming effect would be smaller for the deaf readers than for the hearing readers. Likewise, if having acquired LSE early provides a phonological scaffold that supports the processing of phonological information from printed words, we expect to find greater phonological priming effects for those deaf readers that acquired LSE early. Finally, if early, automatic phonological processing contributes to reading ability, then we would expect a positive correlation between masked phonological priming and reading comprehension in all participants.

2 Methods

2.1 Participants

A total of 24 (10 female) profoundly or severely deaf individuals took part in the experiment. All participants were deaf from birth. Their age of acquisition of LSE (Lengua de Signos Española) differed: eight individuals learnt LSE from birth (native signers), 9 individuals learnt LSE at an early age (3-9 years old; early signers), and seven individuals learnt LSE after 9 years old (late signers). All participants were fluent signers of LSE (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). Participants were recruited in Valencia and Tenerife via flyers and word-of-mouth referrals.

A group of twenty-four hearing readers were selected to match the characteristics of the deaf readers in age, NVIQ, phonological processing, and sentence reading level. 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 normal (or corrected-to- normal) vision and normal audition.

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 and to perform the tasks was given to deaf participants both in written Spanish and LSE.

All participants were tested on:

a) Non-verbal IQ (Toni 2): All participants had a non-verbal IQ over 98 and none reported associated disorders or learning disabilities.

b) A reading comprehension test (comprehension subtest of the Magallanes scale of Reading and Writing TALE 2000: “Escalas Magallanes de Lectura y Escritura” TALE-2000; Toro, Cervera, & Urío, 2002). This subtest is untimed and comprised of 3 texts of increasing length and difficulty followed by comprehension questions. An average score of percentage of correct responses in the 3 texts was computed for each participant. Both groups differed significantly in reading comprehension; the hearing participants achieved higher scores in this test.

c) A sentence reading test (collective test of reading efficiency: “Test Colectivo de Eficacia Lectora” TECLE; Carrillo & Marin, 1997). This test provides a combined measure of reading speed and comprehension. The groups were balanced for sentence reading level. Note that 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.

d) A phonological processing task (syllable counting). Participants performed a syllable counting task on a series of highly consistent and highly discrepant words regarding their phonological and orthographic structure. The consistent words were: a) 5-letter/2-syllable words such as mo.lar (molar) or b) 7-letter/3-syllable words such as ca.vi.dad (cavity). The discrepant words were: a) 5-letter/3-syllable words such as e.ne.ro (January) or b) 7-letter/2-syllable words such as men.sual (monthly). We computed an index of the degree in which orthographic/visual factors (i.e., word length) influenced the participants’ response during online syllabification: the percentage of accurate responses for discrepant words was subtracted from the percentage of accurate responses for consistent words. The higher the values in this index, the more biased the processing was toward the visual characteristics of words (higher accuracy for visually consistent words). The groups of deaf and hearing participants were balanced in this index.

e) A measure of word knowledge. As a proxy to word knowledge, we used participant's percentage of correct responses in several online lexical decision experiments composed of more than 400 Spanish words and pseudowords. The two groups differed significantly on this measure.

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

	Deaf	**Hearing**		
	Mean (SD)	Mean (SD)	t value	*p*
Age	36.5 (8.9)	37.7 (7.9)	-.47	>.10
NVIQ	98.2 (19)	107 (16)	-1.8	>.05
Phonological processing (visual bias index)	34.5 (19)	25.4(18)	1.74	>.05
Sentence reading (% correct)	68.8% (27)	79.3% (18)	-1.6	>.10
Reading comprehension (raw score % correct)	**48.4% (23.7)**	**80.6% (9.7)**	**-6.3**	**<.0001**
Word Knowledge (% correct across several lexical decision tasks)	**91.1% (0.8)**	**95.7% (0.2)**	**2.8**	**<.01**

2.2 Materials and design

The set of word stimuli was composed of one hundred and sixty Spanish words, between 4 and 7 letters long, taken from a masked priming experiment with developing readers (Comesaña et al., 2016). To make the lexical decision task possible, 160 pseudoword targets were also taken from the Comesaña et al. (2016) set of stimuli. Each target item was preceded by: a) a prime that was the same as the target (coral-CORAL, identity condition); b) a pseudoword prime that was phonologically matched with the target: the first letter was replaced by another letter that represented the same phoneme (koral-CORAL, pseudohomophone condition); c) a pseudoword prime in which the first letter was replaced by another letter to create an orthographic control (toral-CORAL, orthographic control condition)—this letter was matched with the replaced letter in the pseudohomophone priming condition in shape (e.g., the letter "k", which contains an ascending visual feature could be replaced with the letter "t", also containing an ascending feature); and d) a pseudoword prime that was unrelated to the target (fisol-CORAL, unrelated condition). Four counterbalanced lists of materials were constructed in a Latin-square manner so that each target appeared once in each list, while all conditions were present in each list.

The main question of this experiment concerns phonological processing. Therefore, the main comparison is between the pseudohomophone and orthographic control conditions for word targets. For comparison, we also include the identity priming result (i.e., the comparison between the identity and unrelated conditions), as this allows us to contextualize the phonological effect in both groups. Finally, we focus on the word targets because pseudowords typically reveal negligible masked priming effects (see Forster, 1998).

2.3 Procedure

Participants were seated comfortably in a darkened room with no visual stimuli other than those from the experimental setting. The stimuli were displayed at the center of a computer screen. The sequence of events in each trial was as follows. The participant was presented with a pattern mask (a series of #'s that matched the length of the target) for 500 ms, then a lowercase target stimulus (8-pt Courier New font) was presented for 33.3 ms (see Lupker & 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 2,500 ms had passed. After the participant response, the drawing of an eye stayed on screen for 2,000 ms to allow for blinks and resting the eyes, followed by a blank screen of a random duration between 700 and 1,000 ms. Participants were asked to decide as quickly and accurately as possible if the target stimulus was a real Spanish word or not by pressing the SÍ (YES) or NO keys in the computer keyboard. Response times were measured from target onset until the participant's response. Each participant was randomly assigned to one of the four lists. The order of stimuli presentation from each list was randomized for each participant. Before the experiment began, participants were given a brief practice block composed sixteen trials, to acquaint them with the format of the experiment.

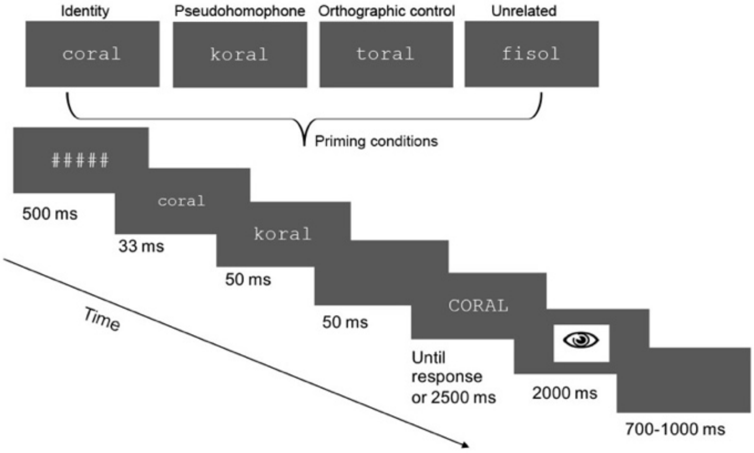

Figure 1: Depiction of events in a trial and experimental conditions

3 Results

Four target words (barril, buzo, careta, and velero) produced a high percentage of errors (more than 42% of errors in the deaf group) and were excluded from the analyses. Incorrect responses (5.9 %) and response times beyond 2.5 SDs of the mean per participant and condition (2.0 %) were excluded from the latency analyses. The mean lexical decision times and percentage of correct responses per condition are displayed in Table 2.

3.1 Masked phonological priming

We conducted Analyses of Variance (ANOVAs) separately for the latency and accuracy data. The factors were type of prime (pseudohomophone vs. control), group (deaf vs. hearing readers), and the dummy between-subjects factor list (see Pollatsek & Well, 1995). These ANOVAs were conducted over the subjects (*F*1) and items (*F*2) means per condition. To test whether the phonological effect were driven by the hearing participants, we examined the phonological effect separately in each group.

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 by-items analysis $F1(1,43) = 1.8$, $MSE = 29470$, $p = .19$, $\eta^2 = .042$; $F2(1,62) = 8.1$, $MSE = 4916$, $p = .006$, $\eta^2 = .11$. The interaction between type of prime and group was not significant (both Fs < 1). The 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 of prime and group approached significance in the by-subjects analysis, $F1(1,43) = 3.72$, $MSE = 6.63$, $p = .061$, $\eta^2 = .85$; $F2 < 1$.

Planned comparisons on the latency data showed a significant phonological masked priming effect in deaf readers, $F1(1,20) = 22.82$, $MSE = 459.6$, $p < .001$, $\eta^2 = .53$; $F2(1,62) = 8.46$, $MSE = 8010$, $p = .005$, $\eta^2 = .11$. As typically reported in the literature, hearing participants also showed faster word recognition times in the pseudohomophone than in the orthographic control condition, $F1(1,20) = 7.02$, $MSE = 841.8$, $p = .015$ $\eta^2 = .26$; $F2(1,62) = 7.91$, $MSE = 5315$, $p = .006$, $\eta^2 = .11$. Planned comparisons on the accuracy data did not show any significant effect in deaf readers (both Fs < 1). For hearing participants, results showed an effect of type of prime (responses were more accurate to targets preceded by a pseudohomophone than when preceded by an orthographic control) that was only significant in the by-subjects analysis, $F1(1,20) = 5.23$, $MSE = 4.93$, $p = .033$ $\eta^2 = .21$; $F2(1,62) = 1.9$, $MSE = 39.95$, $p = .172$, $\eta^2 = .027$).

To examine whether the size of phonological masked priming was affected by LSE AoA in deaf signers, we conducted an ANOVA with the factors type of prime, subgroup (native signer, early signer, late signer) and list. Results on the latency data showed a main effect of type of prime $F1(1,13) = 15.45$, $MSE = 555.3$, $p = .002$ $\eta^2 = .54$; $F2(1,62) = 3.59$, $MSE = 11721$, $p = .059$ $\eta^2 = .017$). The main effect of subgroup was not significant in the by-subjects analysis $F1 < 1$; $F2(1,62) = 12.6$, $MSE = 8470.12$, $p < .001$, $\eta^2 = .059$). While the size of the masked phonological priming was greater for the native signers (39 ms) and late signers (30 ms) than for early signers (19 ms), the interaction between type of prime and subgroup did not approach significance, both Fs < 1. Results on the accuracy data showed no significant effects (all ps > .1).

Table 2: Mean lexical decision times (RTs, in milliseconds) and percentage of accurate responses for the experimental conditions in deaf and hearing participants.

	RT Mean (SD)		Accuracy Mean (SD)	
	Deaf	**Hearing**	**Deaf**	**Hearing**
Pseudohomophone primes	719 (134)	761 (131)	92.5 (6.9)	95.7 (2.4)
Orthographic control primes	748 (151)	782 (147)	93.2 (4.7)	94.7 (3.8)
Difference	**29****	**21***	**0.7**	**-1.0***
Identity primes	669 (142)	739 (146)	94.2	95.0 (3.5)
Unrelated primes	750 (134)	792 (128)	(4.02)	95.1 (3.5)
Difference	**81*****	**53*****	94.4 (5.6)	**0.1**
			0.2	

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

3.2 Masked identity priming

The analyses were parallel to those described above, except that we compared the identity and the unrelated conditions (i.e., masked identity priming).

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, $F1(1,43) = 5.83$, $MSE = 780.3$, $p = .020$, $\eta^2 = .77$; $F2(1,62) = 3.6$, $MSE = 6728$, $p = .062$, $\eta^2 = .04$. While the two groups showed faster responses to the identity than the unrelated conditions (Deaf: $F1(1,20) = 97.7$, $MSE = 803.03$, $p < .001$; $F2(1,62) = 49.1$, $MSE = 9529$, $p < .001$; Hearing: $F1(1,20) = 55.6$, $MSE = 587.3$, $p < .001$; $F2(1,62) = 34.14$, $MSE = 6299$, $p < .001$), the difference was greater in deaf than in hearing participants (81 vs. 53 ms, respectively). The ANOVA on the accuracy data showed no significant effects (all Fs < 1).

We also examined whether the size of masked identity priming was affected by LSE AoA in deaf signers, hence we conducted the same analysis than for the phonological masked priming. Results on the latency data showed a main effect of type of prime $F1(1,13) = 74.82$, $MSE = 975.3$, $p < .001$ $\eta^2 = .85$; $F2(1,62) = 111.44$, $MSE = 11593.24$, $p < .001$, $\eta^2 = .35$). The main effect of subgroup was not significant in the by-subjects analysis $F1 < 1$; $F2(1,62) = 13.66$, $MSE = 8686.69$, $p < .001$, $\eta^2 = .062$). The interaction between type of prime and subgroup did not approach significance, both Fs < 1. The size of the masked phonological priming was similar for all subgroups: native signers (79 ms), late signers (98 ms) and early signers (71 ms). Results on the accuracy data showed no significant effects (all ps > .3).

3.3 Correlations of masked priming effects with reading-related measures

Correlations between performance in the reading related measures and the size of the masked phonological effects (difference in response times between the orthographic control and pseudohomophone conditions) and masked identity priming effects (difference in response times between the unrelated and identity conditions) showed that the size of the masked phonological priming effect was correlated with measures of phonological processing and reading ability in the hearing but not in the deaf participants (see Table 3). The size of the masked phonological priming effect was correlated with our estimate of word knowledge in both groups. The size of the masked identity priming effect was not correlated significantly with any of the measures in neither group.

Table 3: Correlations between the reading related measures (on the left) and between those measures and the size of the masked priming effects (on the right).

	Reading comprehension	Phonological processing	Written word knowledge	Masked phonological priming	Masked identity priming
DEAF					
Sentence reading (% correct)	**0.831*****	**-0.472***	**0.775*****	-0.104	0.141
Reading comprehension (% correct)		**-0.490***	**0.669*****	0.029	0.142
Phonological processing (visual bias index)			-0.263	-0.227	-0.250
Written word knowledge (% correct)				**-0.571****	0.207
HEARING					
Sentence reading (% correct)	0.250	**-0.701*****	**0.763*****	**-0.479***	0.396
Reading comprehension (% correct)		-0.317	0.349	-0.334	0.101
Phonological processing (visual bias index)			**-0.553****	**0.401(*)**	-0.351
Written word knowledge (% correct)				**-0.421***	-0.026

* $p < .05$, ** $p < .01$, *** $p < .001$; (*) $p = .052$

4 Discussion

The most important finding of the current experiment is the existence of a masked phonological priming effect in congenitally deaf readers: word identification times were significantly faster for those word targets preceded by a pseudohomophone prime than when preceded by an orthographic control. Importantly, the masked phonological priming effect occurred to a similar degree in deaf and hearing readers. Thus, when the chances to detect automatic phonological priming are maximized (masked sandwich priming; 50 ms prime exposure duration plus 50 ms blank; see Figure 1), deaf readers can automatically activate phonological codes early during visual word recognition. These results are in line with previous experiments, showing masked phonological priming in hearing readers (e.g., Ferrand & Grainger, 1992, 1993, 1994; Pollatsek, Perea, & Carreiras, 2005; see Rastle & Brysbaert, 2006, for review). Thus, this finding favors the view that there is automatic use of phonological information during visual word recognition (Carreiras, Amstrong, Perea, & Frost, 2014; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Frost, 1998; Grainger & Holcomb, 2009). Furthermore, this behavioral masked priming effect converges with electrophysiological evidence (co-registered from the same participants) that shows that deaf readers use phonological codes at the sub-lexical stage of visual word recognition (Gutiérrez-Sigut, Vergara-Martínez, & Perea, 2017).

Nonetheless, while both groups (deaf readers; hearing readers) showed a sizeable and significant masked phonological effect, the deaf readers were slightly less accurate than the hearing readers in both the pseudohomophone and the orthographic control conditions. Furthermore, the magnitude of the masked identity priming effect was greater with deaf than with hearing readers—deaf readers showed an advantage when processing the identity priming condition, which points to a more efficient use of visual and orthographic information from words. Taken together, these findings favor the idea of a different balance in the use of orthographic and phonological information in deaf and hearing readers (see Bélanger & Rayner, 2015). This is consistent with the view that deaf readers follow a route to lexical access more heavily based on the use of orthographic codes than hearing readers do (Bélanger & Rayner, 2015; Corina, Lawyer, Hauser, & Hirshorn 2013; Hirshorn et al., 2015).

At the theoretical level, the obtained effects are consistent with the bi-modal interactive activation model (Grainger & Holcomb, 2009), where following the initial activation of orthographic codes upon presentation of a printed word, there is the automatic activation of the sub-lexical phonological codes. Further research on the time course of visual and orthographic codes during early word processing is needed to complete our understanding of how and when visual (orthographic) and phonological codes contribute to efficient lexical access in deaf readers.

As indicated in the Introduction, the few existing behavioral experiments with adult deaf readers failed to find a significant processing advantage for pseudohomophones relative to orthographic controls with the masked priming technique (Bélanger et al., 2012; Cripps et al., 2005). The variations in methodological parameters introduced in the present experiment are likely to account for these differences. First, we used a longer SOA than these other experiments (100 ms in present study vs. 40 and 60 ms: Bélanger et al., 2012; 67 ms: Cripps et al., 2005), thus allowing for some extra time to extract the phonological codes of the prime. Indeed, prior experiments in adult hearing readers in Spanish reported significant masked phonological priming effects at a 66 ms SOA, but only a non-significant trend at a 50 ms SOA (Pollatsek et al., 2005). Therefore, the discrepancies between the current and previous experiments might reflect that deaf readers need more time to extract information from the prime. Second, the use of the sandwich methodology is likely to have resulted in a larger effect size than the traditional masked priming used in previous experiments with deaf readers (see Lupker & Davis, 2009). Thus, the present experimental set-up provides a suitable paradigm to further study phonological processing in deaf readers. What we should also note is that the differences between the present and previous studies of phonological priming in deaf readers might also be due to the transparency of the languages under scrutiny. Unlike the present experiments (Spanish), previous research employed languages with more opaque orthographies (French: Bélanger et al., 2012; English: Cripps et al., 2005). As stated in the Introduction, word recognition may rely more on the use of phonological information in transparent than in opaque orthographies (see Frost, 1998). Further cross-linguistic research is needed to explore this possibility with deaf readers.

We also examined the role of other potentially modulating factors in masked phonological priming. First, we assessed whether LSE AoA influenced the use of both visual and phonological information from printed words. Native, early and late signers did not differ significantly in their use of either type of information. Second, we examined whether the early automatic use of phonological information by deaf readers impacts their reading ability or their performance in explicit phonological tasks. Sentence processing and reading comprehension measures were strongly correlated in the group of deaf readers, thus showing good consistency. Interestingly, both measures of reading ability were also correlated with phonological processing during an explicit task (syllable counting) and with written word knowledge. A similar correlation between a syllable counting task and reading has been reported for adult deaf readers of Spanish (Domínguez, Carrillo, Pérez, & Alegría, 2014) and English (Emmorey et al., 2016). Likewise, parallel correlations between knowledge of written words and reading ability have been reported in studies with adult deaf readers (e.g., see Emmorey et al., 2016). Notably, the explicit phonological processing measure and the word knowledge measure were not correlated in deaf readers but they were correlated in hearing readers. This dissociation suggests that deaf readers might make a greater use of other types of information to build their vocabulary of written words. Furthermore, reading comprehension did not correlate with any of the other measures for the hearing readers. This might be due to a reduced variability in the scores (although not a ceiling effect), and thus on a reduced capacity to detect relationships with the other measures. This lack of variability in reading comprehension might be due to more time spent doing this task (as it was untimed and hearing participants in general took longer to complete it than the deaf participants). There is also the possibility of different general comprehension mechanisms during reading in deaf and hearing participants. Researchers have suggested that the hearing but not the deaf participants use other grammatical information (e.g., syntax) to complete this task. In this line, Mehravari, Emmorey, Prat, Klarman, and Osterhout (2017) found that the size of the P600 (an ERP component associated with syntactic processing) was related to reading comprehension in hearing but not in deaf readers (for a similar view see Domínguez et al., 2014). However, this question is beyond the scope of the current study.

Remarkably, both the deaf and hearing readers showed a correlation between the size of masked phonological priming and knowledge of written words. This finding suggests that good phonological processing might be a consequence rather than a cause of more experience with language (Kyle & Harris, 2010). However, only hearing readers showed a significant correlation between the size of masked phonological priming and any of the reading ability or explicit phonological processing variables. This result is consistent with recent evidence from Sehyr et al. (2017), who found that the use of phonological codes by deaf participants during a word recall task was not correlated with participant's reading ability. In summary, the relationships between the early automatic use of phonological information 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 for hearing readers (see Goswami & Bryant, 1990: Wagner & Torgensen, 1987, Waters, Seidenberg, & Bruck, 1984), but other factors should also be considered for deaf readers.

To conclude, we found evidence of early automatic activation of phonological codes in congenitally adult deaf readers in a masked priming experiment. The magnitude of masked phonological priming was similar to that obtained in a group of hearing readers. Thus, these findings are consistent with those accounts that assume that phonology is an automatic part of word identification, at least in transparent orthographies. Furthermore, this was so in participants who have not had access to speech sounds and therefore have an underspecified phonological representation (i.e., constructed upon articulatory feedback and visual information of speech lip patterns). Additional correlational analyses of the magnitude of this phonological effect with reading-related measures suggest that this use of sub-lexical of phonological information might be a main contributor to reading ability for hearing but not for deaf readers. Our results go in line with the view that deaf readers follow a route to lexical access that is more reliant in visual and orthographic information than hearing readers. Future research should examine in detail the implications of the present results for theoretical accounts of reading comprehension mechanisms in deaf readers.

Acknowledgments

This work has been supported by a fellowship from the Ministerio de Economía y Competitividad from Spain awarded to EG [Grant Number PSI2014-60611-JIN]. We would like to thank ASORTE, FASICAN, FESORD and FUNCASOR, Roberto Suarez, Juan Molina, Verónica Rodríguez, Belén Darias for their support for recruiting participants and facilitating data collection, Daniel Díaz for his help programming the experiments, and Yurena Martín for her help collecting data. We would also like to thank Eva Rosa for her involvement in the development of the phonological processing task.

References

Bélanger, Nathalie N., and Keith Rayner (2015). “What eye movements reveal about deaf readers.” *Current Directions in Psychological Science* 24 (3): 220–226. doi:10.1177/0963721414567527.

Bélanger, Nathalie N., Shari R. Baum, and Rachel I. Mayberry (2012). “Reading difficulties in adult deaf readers of French: Phonological codes, not guilty!” *Scientific Studies of Reading* 16 (3): 263–285. doi:10.1080/10888438.2011.568555.

Carreiras, Manuel, Blair C. Armstrong, Manuel Perea, and Ram Frost (2014). “The what, when, where, and how of visual word recognition.” *Trends in Cognitive Sciences* 18 (2): 90–98. doi:10.1016/j.tics.2013.11.005.

Carreiras, Manuel, Ludovic Ferrand, Jonathan Grainger, and Manuel Perea (2005). “Sequential effects of phonological priming in visual word recognition.” *Psychological Science* 16 (8): 585–589. doi:10.1111/j.1467-9280.2005.01579.x.

Carrillo, María S., and Javier Marín (1997). “Test de Eficiencia Lectora–TECLE.” In *Evaluación del nivel lector. Manual técnico del test de Eficacia Lectora (TECLE)*, ed. by Ariel Cuadro et al., 20-38. Uruguay: Prensa Médica Latinoamericana.

Charlier, Brigitte L., and Jacqueline Leybaert (2000). “The rhyming skills of deaf children educated with phonetically augmented speechreading.” *Quarterly Journal of Experimental Psychology A* 53 (2): 349–375. doi:10.1080/027249800390529.

Coltheart, Max, Kathleen Rastle, Conrad Perry, Robyn Langdon, and Johannes Ziegler (2001). “DRC: A Dual Route Cascaded model of visual word recognition and reading aloud.” *Psychological Review* 108 (1): 204–256. doi:10.1037/0033-295x.108.1.204.

Comesaña, Montserrat, Ana P. Soares, Ana Marcet, and Manuel Perea (2016). “On the nature of consonant/vowel differences in letter position coding: Evidence from developing and adult readers.” *British Journal of Psychology* 107 (4): 651–674. doi:10.1111/bjop.12179.

Conrad, R. (1977). “The reading ability of deaf school-leavers.” *British Journal of Educational Psychology* 47 (2): 138–148. doi:10.1111/j.2044-8279.1977.tb02339.x.

— (1979). *The Deaf Schoolchild: Language and Cognitive Function*. London and New York: Harper and Row.

Corina, David P., Sarah Hafer, and Kearnan Welch (2014). “Phonological Awareness for American Sign Language.” *Journal of Deaf Studies and Deaf Education* 19 (4): 530–545. doi:10.1093/deafed/enu023.

Corina, David P., Laurel A. Lawyer, Peter Hauser, and Elizabeth Hirshorn. 2013. “Lexical processing in deaf readers: An fMRI investigation of reading proficiency.” *PLoS ONE* 8 (1): e54696. doi:10.1371/journal.pone.0054696.

Cripps, Jody H., Kara A. McBride, & Kenneth I. Forster (2005). “Lexical processing with deaf and hearing: Phonology and orthographic masked priming.” *Arizona Working Papers in Second Language Acquisition and Teaching 12*: 31-44.

DiFrancesca, S. (1972). *Academic achievement test results of a national testing program for hearing-impaired students*. United States: Spring 1971 DC (Series D, No. 9). Washington: Gallaudet College, Office of Demographic Studies.

Domínguez, Ana-Belén, María-Soledad Carrillo, María del Mar Pérez, and Jesús Alegría

(2014). “Analysis of reading strategies in deaf adults as a function of their language and meta-phonological skills.” *Research in Developmental Disabilities* 35 (7): 1439–1456. doi:10.1016/j.ridd.2014.03.039.

Emmorey, Karen, Stephen McCullough, and Jill Weisberg (2016). “The neural underpinnings of reading skill in deaf adults.” *Brain and Language* 160: 11–20. doi:10.1016/j.bandl.2016.06.007.

Emmorey, Karen, Jill Weisberg, Stephen McCullough, and Jennifer A.F. Petrich (2013). “Mapping the reading circuitry for skilled deaf readers: An fMRI study of semantic and phonological processing.” *Brain and Language* 126 (2): 169–180. doi:10.1016/j.bandl.2013.05.001.

Ferrand, Ludovic, and Jonathan Grainger (1992). “Phonology and orthography in visual word recognition: Evidence from masked non-word priming.” *The Quarterly Journal of Experimental Psychology Section A* 45 (3): 353–372. doi:10.1080/02724989208250619.

— (1993). “The time course of orthographic and phonological code activation in the early phases of visual word recognition.” *Bulletin of the Psychonomic Society* 31 (2): 119–122. doi:10.3758/bf03334157.

— (1994). “Effects of orthography are independent of phonology in masked form priming.” *Quarterly Journal of Experimental Psychology Section A* 47 (2): 365–382. doi:10.1080/14640749408401116.

Forster, Kenneth I. (1998). “The pros and cons of masked priming.” *Journal of Psycholinguistic Research* 27 (2): 203–233. doi:10.1023/a:1023202116609.

Forster, Kenneth I., and Chris Davis (1984). “Repetition priming and frequency attenuation in lexical access.” *Journal of Experimental Psychology: Learning, Memory, and Cognition* 10 (4): 680–698. doi:10.1037/0278-7393.10.4.680.

Frost, Ram (1998). “Toward a strong phonological theory of visual word recognition: True issues and false trails.” *Psychological Bulletin* 123 (1): 71–99. doi:10.1037/0033-2909.123.1.71.

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

Gutierrez-Sigut, Eva, Marta Vergara-Martínez, and Manuel Perea (2017). “Early use of phonological codes in deaf readers: an ERP study”. *Neuropsychologia* 106: 261–279. doi:10.1016/j.neuropsychologia.2017.10.006

Hanson, Vicki L., and Nancy S. McGarr (1989). “Rhyme generation by deaf adults.” *Journal of Speech Language and Hearing Research* 32 (1): 2. doi:10.1044/jshr.3201.02.

Hanson, Vicki L., Donald Shankweiler, and F. William Fischer (1983). “Determinants of spelling ability in deaf and hearing adults: Access to linguistic structure.” *Cognition* 14 (3): 323–344. doi:10.1016/0010-0277(83)90009-4.

Hanson, Vicki L., Elizabeth W. Goodell, and Charles A. Perfetti (1991). “Tongue-twister effects in the silent reading of hearing and deaf college students.” *Journal of Memory and Language* 30 (3): 319–330. doi:10.1016/0749-596x(91)90039-m.

Hirshorn, Elizabeth A., Matthew W. G. Dye, Peter Hauser, Ted R. Supalla, and Daphne Bavelier (2015). “The contribution of phonological knowledge, memory, and language background to reading comprehension in deaf populations.” *Frontiers in Psychology* 6. doi:10.3389/fpsyg.2015.01153.

Kelly, Leonard P. (2003). “The importance of processing automaticity and temporary storage capacity to the differences in comprehension between skilled and less skilled college-age deaf readers.” *Journal of Deaf Studies and Deaf Education* 8 (3): 230–249.

doi:10.1093/deafed/eng013.

Koo, Daniel, Kelly Crain, Carol LaSasso, and Guinevere F. Eden (2008). “Phonological awareness and short-term memory in hearing and deaf individuals of different communication backgrounds.” *Annals of the New York Academy of Sciences* 1145 (1): 83–99. doi:10.1196/annals.1416.025.

Kyle, Fiona E., and Margaret Harris (2010). “Predictors of reading development in deaf children: A 3-year longitudinal study.” *Journal of Experimental Child Psychology* 107 (3): 229–243. doi:10.1016/j.jecp.2010.04.011.

Lupker, Stephen J., and Colin J. Davis (2009). “Sandwich priming: A method for overcoming the limitations of masked priming by reducing lexical competitor effects.” *Journal of Experimental Psychology: Learning, Memory, and Cognition* 35 (3): 618–639. doi:10.1037/a0015278.

MacSweeney, Mairéad, Dafydd Waters, Michael J. Brammer, Bencie Woll, and Usha Goswami (2008). “Phonological processing in deaf signers and the impact of age of first language acquisition.” *NeuroImage* 40 (3): 1369–1379. doi:10.1016/j.neuroimage.2007.12.047.

MacSweeney, Mairéad, Usha Goswami, and Helen Neville (2013). “The neurobiology of rhyme judgment by deaf and hearing adults: An ERP study*.” Journal of Cognitive Neuroscience* 25 (7): 1037–1048. doi:10.1162/jocn_a_00373.

Mayberry, Rachel I., Alex A. del Giudice, and Amy M. Lieberman. 2010. “Reading achievement in relation to phonological coding and awareness in deaf readers: A meta-analysis.” *Journal of Deaf Studies and Deaf Education* 16 (2): 164–188. doi:10.1093/deafed/enq049.

McArthur, Genevieve, and Anne Castles (2017). “Helping children with reading difficulties: Some things we have learned so far.” *Science of Learning* 2 (1). doi:10.1038/s41539-017-0008-3.

Mehravari, Alison S., Karen Emmorey, Chantel S. Prat, Lindsay Klarman, and Lee Osterhout (2017). “Brain-based individual difference measures of reading skill in deaf and hearing adults.” *Neuropsychologia* 101: 153–168. doi:10.1016/j.neuropsychologia.2017.05.004.

Perfetti, Charles A. (2000). “Reading optimally builds on spoken language: Implications for deaf readers.” *Journal of Deaf Studies and Deaf Education* 5 (1): 32–50. doi:10.1093/deafed/5.1.32.

Pollatsek, Alexander, and Arnold D. Well (1995). “On the use of counterbalanced designs in cognitive research: A suggestion for a better and more powerful analysis.” *Journal of Experimental Psychology: Learning, Memory, and Cognition* 21 (3): 785–794. doi:10.1037/0278-7393.21.3.785.

Pollatsek, Alexander, Manuel Perea, and Manuel Carreiras (2005). “Does conal prime canal more than cinal? Masked phonological priming effects in Spanish with the lexical decision task.” *Memory & Cognition* 33 (3): 557–565. doi:10.3758/bf03193071.

Rastle, Kathleen, and Marc Brysbaert (2006). “Masked phonological priming effects in English: Are they real? Do they matter?” *Cognitive Psychology* 53 (2): 97–145. doi:10.1016/j.cogpsych.2006.01.002.

Sánchez, Emilio, and Héctor García-Rodicio (2006). “Re-lectura del Estudio PISA: Qué y Cómo se Evalúa e Interpreta el Rendimiento de los Alumnos en la Lectura.” *Revista de Educación* 1: 195-226.

Sehyr, Zed Sevcikova, Jennifer Petrich, and Karen Emmorey (2016). “Fingerspelled and printed words are recoded into a speech-based code in short-term memory.” *Journal of Deaf Studies and Deaf Education* 22 (1): 72–87. doi:10.1093/deafed/enw068.

Sterne, Abram, and Usha Goswami (2000). “Phonological awareness of syllables, rhymes, and phonemes in deaf children.” *Journal of Child Psychology and Psychiatry* 41 (5): 609–625. doi:10.1017/s0021963000005680.

Toro, Josep, Montserrat Cervera, and Carlos Urío (2002). *Escalas Magallanes de Lectura y Escritura TALE-2000*. Vizcaya: RBS.

Traxler, Carol B. (2000). “The Stanford Achievement Test, 9th Edition: National norming and performance standards for deaf and hard-of-hearing students.” *Journal of Deaf Studies and Deaf Education* 5 (4): 337–348. doi:10.1093/deafed/5.4.337.

Wauters, Loes N., Wim H. J. Van Bon, and Agnes E. J. M. Tellings (2006). “Reading comprehension of Dutch deaf children.” *Reading and Writing* 19 (1): 49–76. doi:10.1007/s11145-004-5894-0.