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Electrophysiological evidence for phonological priming in Spanish Sign Language lexical access

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ABSTRACT

Interactive activation models of lexical access assume that the presentation of a given word activates not only its lexical representation but also those corresponding to words similar in form. Current theories are based on data from oral and written languages, and therefore signed languages represent a special challenge for existing theories of word recognition and lexical access since they allow us to question what the genuine fundamentals of human language are and what might be modality-specific adaptation. The aim of the present study is to determine the electrophysiological correlates and time course of phonological processing of Spanish Sign Language (LSE). Ten deaf native LSE signers and ten deaf non-native but highly proficient LSE signers participated in the experiment. We used the ERP methodology and form-based priming in the context of a delayed lexical decision task, manipulating phonological overlap (i.e. related prime-target pairs shared either handshape or location parameters). Results showed that both parameters under study modulated brain responses to the stimuli in different time windows. Phonological priming of location resulted in a higher amplitude of the N400 component (300–500 ms window) for signs but not for non-signs. This effect may be explained in terms of initial competition among candidates. Moreover, the fact that a higher amplitude N400 for related pairs was found for signs but not for non-signs points to an effect at the lexical level. Handshape overlap produced a later effect (600–800 ms window). In this window, a more negative-going wave for the related condition than for the unrelated condition was found for non-signs in the native signers group. The findings are discussed in relation to current models of lexical access and word recognition. Finally, differences between native and non-native signers point to a less efficient use of phonological information among the non-native signers.

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1. Introduction

Signed languages represent a special challenge for existing theories of word recognition and lexical access, which so far have been based exclusively on the study of spoken languages. By studying the similarities and differences between signed and spoken languages, we can gain an understanding of what the genuine fundamentals of human language are and what might be modality-specific adaptations (Emmorey, 2007; Sandler & Lillo-Martin, 2001; Senghas & Coppola, 2001). Looking at the phonological and articulatory means that are used to form words/signs, one can find several dissimilarities between signed and spoken languages that might result in modality-specific mechanisms for achieving lexical access and word recognition. For instance, as spoken words are composed of phonemes, signs are composed of formational parameters that have a phonological structure. However, in contrast with spoken words, signs are characterized by the apparent simultaneous expression/perception of features and the overt visibility of articulators.

In recent decades, the processes involved in spoken word recognition and lexical access have been extensively studied in psycholinguistics. Models of spoken word recognition have addressed how an acoustic stimulus is mapped onto a mental lexical representation stored in memory. This process usually takes place without conscious effort and is almost error-free. In general, spoken word recognition is considered a three-stage process triggered by the acoustic information of the speech signal. The initial contact and

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Table 1
Overview of the main findings on signed language recognition in which handshape (HS) and location (LOC) were manipulated.

Authors	Language	Experimental manipulation	Findings	
			HS	LOC
Orfanidou et al. (2009)	BSL	Sign-spotting: combinations of two non-sense signs	More false alarm responses to non-sense signs	Fewest false alarm responses to non-sense signs
Corina and Emmorey (1993)	ASL	Sign lexical decision (*phonological priming*)	No priming effect	*Inhibitory* priming effect
Corina and Hildebrandt (2002)	ASL	Sign lexical decision (*phonological priming*)	–	*Inhibitory* priming trend at 100 ms ISI
Carreiras et al. (2008)	LSE	Sign lexical decision Neighbourhood density and familiarity	*Facilitation* high density neighbourhoods and low familiarity signs	*Inhibition* of high density neighbourhoods for low familiarity signs
		Sign lexical decision (*phonological priming*)	*Facilitation* priming only for non-signs	*Inhibitory* priming effect in signs
Dye and Shih (2006)	BSL	Sign lexical decision (*phonological priming*)	–	Facilitation priming for location + movement overlap

decoding of sensory information is followed by lexical selection, which includes the activation of multiple candidates and competition amongst them (Luce & Pisoni, 1998; McClelland & Elman, 1986; Norris, 1994). Finally, the correct or adequate lexical entry is selected and accessed (phonological, semantic, syntactic and pragmatic information becomes available) and the word is recognized (Frauenfelder & Tyler, 1987). Evidence indicates that in the course of spoken word identification, phonologically related words compete for recognition (Allopenna, Magnuson, & Tanenhaus, 1998; Dahan, Magnuson, Tanenhaus, & Hogan, 2001; Marslen-Wilson & Tyler, 1980; Marslen-Wilson & Zwitserlood, 1989; McClelland & Elman, 1986; Norris, McQueen, & Cutler, 2000; Vitevitch & Luce, 1999). For instance, phonological overlap of word-initial sounds produces an inhibitory effect suggesting that words sharing the same initial sounds compete for recognition (Marslen-Wilson & Zwitserlood, 1989); words with many neighbors (words that share all except one phoneme) are more difficult to recognize than words with few neighbors (Luce & Pisoni, 1998). Several models of spoken word recognition can account for this phonological competition. The Cohort model (Marslen-Wilson & Tyler, 1980) suggests that the initial sounds of a word activate a set or cohort of competitor words sharing these initial sounds, which is then successively reduced as the word unfolds and more constraining information arrives; when only one candidate remains, the word is recognized. The Neighborhood Activation Model (NAM; Luce & Pisoni, 1998) suggests that the auditory input activates various acoustic–phonetic patterns and, as the word unfolds, the correct candidate receives a greater amount of activation; recognition occurs when a candidate reaches a recognition threshold and surpasses the activation level of the other candidates. The TRACE model (McClelland & Elman, 1986) proposes that competition occurs via lateral inhibition between lexical candidates, allowing both bottom-up and top-down connections.

However, these theories have all been based on studies of spoken languages and relatively few studies have investigated how lexical access takes place in signers. This paper studies the role of two major phonological parameters (location and handshape) in the recognition of signs from Spanish Sign Language, "Lengua de Signos Española" (LSE), by investigating their electrophysiological correlates. We used the form-priming technique together with a delayed lexical decision task on target signs that shared either location or handshape with the primes. During task performance, event-related potentials (ERPs) time-locked to the presentation of target signs were registered. ERPs offer the possibility to measure the processing of sign language both non-invasively and with a temporal precision in the order of milliseconds (cf. Picton, Lins, & Scherg, 1995; Rugg & Coles, 1995).

LSE, like other signed languages, is a naturally occurring human language and has formal linguistic properties like those found in spoken languages. For example, signs (as words) can be decomposed into minimal meaningless units and different signed languages vary in the inventory and composition of the phonemic units they employ. In signed languages, handshape, location and movement are the major building blocks of signs (Stokoe, 1960; Stokoe, Casterline, & Croneberg, 1965). Stokoe's original proposal led to the early assumption that these parameters had equal status in the phonological system. This assumption was based on both the fact that each of these parameters enclose segmental information with contrastive properties that create minimal pairs (see Rodríguez, 1992, for examples of minimal pairs in LSE) as well as in the postulation that simultaneity is intrinsic to the sign. However, current phonological theories propose differential contributions of these parameters (for detailed descriptions of these theories see for example: Brentari, 1990; Brentari, 1998; Brentari, 2002; Chinchor, 1978; Corina, 1990; Corina & Hildebrandt, 2002; Corina & Sandler, 1993; Perlmutter, 1992; Sandler, 1989; Wilbur, 1993).

Although linguistic structure may be similar for both oral and visual–gestural languages, the special characteristics of signed language articulators as transparent and completely visible can have important consequences for processing. Psycholinguistic studies of signed languages provide some support for the idea that sublexical structure may influence processing in a signed language, but findings to date are mixed. While data from production studies suggest the necessity of a phonological encoding level (Baus, Gutierrez-Sigut, Quer, & Carreiras, 2008; Carreiras, 2010; Corina & Knapp, 2006; Thompson, Emmorey, & Gollan, 2005), results from comprehension studies are rather ambiguous. Table 1 shows an overview of the main findings on sign language recognition in which handshape and location were manipulated. Orfanidou, Adam, McQueen, and Morgan (2009) studied misperceptions in a sign-spotting task (in which participants are instructed to spot signs embedded in nonsense contexts and report the sign) in British Sign Language (BSL). They presented participants with combinations of two nonsense signs or one nonsense sign and a real BSL sign and analyzed the false alarm responses to the nonsense signs. Results show that location and handshape play different roles during sign recognition. Location showed the smallest number of errors and consequently can be considered the least mutable parameter during on-line recognition. Handshape elicited more errors than location. Corina and Emmorey (1993) investigated form-based priming in American Sign Language (ASL) using a lexical decision task. Results showed inhibitory priming when targets shared location with the primes, but no effects were found when pairs shared handshape. More recently, Corina and Hildebrandt (2002) investigated movement and location priming in ASL. Results showed an inhibitory but non-significant trend for both parameters with 100 ms ISI. Carreiras, Gutiérrez-Sigut, Baquero, and Corina (2008) investigated the role of location and handshape in lexical access in LSE. Results showed that the two phonological parameters affected

Table 2
Overview of the most relevant spoken word recognition ERP studies on the N400 component as reflecting phonological overlap.

Authors	Language and task	Experimental manipulation	Findings onset	Final
Van Petten et al. (1999)	English auditory sentence processing	Last word was semantically expected (dollars) or unexpected: cohort (dolphins) or rhyme (scholars) related vs. unrelated	Cohort overlap reduced N400 amplitude than unrelated words. Earlier latency than rhyme	Rhyme overlap and unrelated no differences in N400
Praamstra et al. (1994)	Dutch auditory lexical decision task (phonological *priming*)	Phonological overlap prime-target: alliteration or rhyme related vs. unrelated	Related alliteration (shared the consonantal onset and vowel) reduced N400 than related. Earlier latency than rhyme	Rhyme related reduced N400 than unrelated
Dumay et al. (2001)	English auditory lexical decision task (phonological *priming*)	Phonological overlap prime-target: final syllable, coda or rhyme	–	N400 was smallest for syllable overlap, intermediate for rhyme overlap and largest for coda overlap
Praamstra and Stegeman (1993)	Dutch auditory lexical decision task	Phonological overlap prime-target: rhyme related vs. unrelated	–	Rhyme related reduced N400 amplitude than unrelated
Desroches et al. (2008)	English picture-word matching task	Phonological overlap picture–word: cohort or rhyme unmatched vs. matched	Shared first sounds increased N400 amplitude than matched condition	Rhyme unmatched reduced N400 amplitude than matched condition

sign recognition in different ways. On the one hand, when signs contained a dense-neighborhood handshape, that is, many other signs shared the respective handshape, neighborhood density facilitated responses to low-familiarity signs whereas it had no effect on responses to high-familiarity. On the other hand, when signs had a dense-neighborhood location, inhibition was found for low-familiarity signs. In a form-priming experiment, results showed a facilitatory effect of handshape overlap in non-signs as well as an inhibitory effect of location overlap for signs. These data support the idea of a recognition process in which location triggers competition amongst lexical candidates, as evidenced by the inhibitory effects in both experiments. Whether handshape has an influence on the activation of the initial candidates prior to competition or whether it plays a role in a later stage of recognition remains an open question. The effect found for the non-signs in the handshape manipulation may be due to a prelexical locus of handshape influence, but further investigation must be carried out to test this hypothesis. Dye and Shih (2006) reported data from native users of BSL that showed evidence of facilitatory phonological priming for signs that shared location and movement. Importantly, these effects were not observed when primes were non-signs, suggesting that these effects are likely to be lexical rather than pre-lexical. Moreover, the use of a very short ISI (50 ms) seems to suggest that this may not be the result of a late integrative stage of processing.

Priming studies of lexical access with signs can help to clarify whether formal parameters of signed languages have the same role and are used to the same degree during recognition as in spoken languages. In addition, the use of a more sensitive measure with a high temporal resolution, such as ERPs, can help to identify the time course of the effects for the different parameters and whether the prelexical decodification of the visual signal in terms of phonological parameters is necessary during sign comprehension. One ERP component sensitive to manipulations of linguistic stimuli is the N400. This appears as a negative-going shift in the ERP that peaks in amplitude around 400 ms after stimulus onset and usually has its maximum amplitude over centro-parietal regions of the scalp. It has been widely demonstrated that the N400 component is sensitive to semantic relatedness, either within a sentence context or in a prime-target pair (Bentin, Kutas, & Hillyard, 1993; Bentin, McCarthy, & Wood, 1985; Holcomb & Neville, 1990, 1991; Kutas & Hillyard, 1980a; Kutas & Hillyard, 1980b; Kutas & Hillyard, 1984; Van Petten & Kutas, 1990; Van Petten & Kutas, 1991). In addition, several studies have also shown that "prelexical" cues related to acoustic and phonological features, and lexical-level factors such as word frequency, morphological structure, and phonology modulate the N400 component during auditory word recognition (Holcomb & Neville, 1991; Kutas & Hillyard, 1984; Munte, Say, Clahsen, Schiltz, & Kutas, 1999; Praamstra, Meyer, & Levelt, 1994; Radeau, Besson, Fonteneau, & Castro, 1998; van den Brink, Brown, & Hagoort, 2001; Van Petten, Coulson, Rubin, Plante, & Parks, 1999; Van Petten & Kutas, 1990). Regarding phonology, modulation of the N400 has been reported in response to words and pseudowords that share either the onset (Connolly & Phillips, 1994; Praamstra et al., 1994) or the rhyme (Dumay et al., 2001; Praamstra & Stegeman, 1993; Rugg, 1984a; Rugg, 1984b) with the preceding word. As a consequence, there exists some agreement that the N400 is modulated by both semantic and phonological factors (Praamstra & Stegeman, 1993).

Investigating spoken word recognition, Van Petten et al. (1999) showed that sentence-final words sharing the onset with the most expected word in a sentence elicited a smaller N400 than those with a different onset. Furthermore, the N400 had an earlier onset when sentence-final words shared the onset with the expected word than when they shared the rhyme. Praamstra et al. (1994) found a reduced N400 (between 250 and 450 ms after target onset) for spoken word-word pairs and word-non-word pairs with alliteration (shared consonantal onset and vowel). When pairs shared the rhyme, this also led to a reduced N400, but clearly later; the effect for rhyme was between 450 and 700 ms after target onset. These results indicate that the N400 can reflect the relative time at which phonological overlap occurs. Dumay et al. (2001) found that, for bisyllabic stimuli, the amplitude of the N400 was smallest for whole-syllable overlap, intermediate for rhyme overlap and largest for coda overlap. These phonological priming effects had a posterior maximum and they were larger for words than for pseudowords. Praamstra and Stegeman (1993, Experiment 3) found a smaller N400 amplitude for rhyming words than for non-rhyming words in a lexical decision task, with no effect for non-words. The authors hypothesized that participants generated a set of candidates that likely matched with the first word and developed an enhanced negativity when the word they heard did not belong to that set. Desroches, Newman, and Joanisse (2008) used a picture–word matching task to investigate the role of phonological similarity in the time course of spoken word recognition. Results showed an increased N400 amplitude when the target word shared the first sounds of the word for the previously seen picture as compared to target words that named the picture. When the picture name and following auditory word shared the rhyme, a higher amplitude phonological mismatch negativity (PMN, Connolly & Phillips, 1994), as well as a reduction of the N400 amplitude was found. The

authors propose that the representation of the word activated by the prime picture suppresses the activation of other lexical units via lateral inhibition leading to larger negativities for the partially matching words. This interpretation is consistent with word recognition models implementing lateral inhibition in the lexicon, which propose that candidate words compatible with partial information of an incoming signal are activated and then actively compete for recognition (e.g., Elman & McClelland, 1988; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981; McQueen, Norris, & Cutler, 1994; Norris, 1994). Table 2 shows an overview of the ERP experiments in spoken word recognition that find a modulation of the N400 component elicited by phonological overlap. Following similar studies in oral languages, Neville et al. (1997) found an N400 effect elicited by open-class signs in the middle of a sentence as well as by incongruent sentence endings. However, to the best of our knowledge, ERP experiments examining phonological processing of signs have not been reported.

Finally, evidence from several sign language experiments indicates that there are subtle but measurable differences in processing due to the age at which the respective signed language is acquired[1] (Corina & Hildebrandt, 2002; Dye & Shih, 2006; Emmorey, Corina, Bellugi, & Reilly, 1995; Macsweeney, Waters, Brammer, Woll, & Goswami, 2008; MacSweeney, Brammer, Waters, & Goswami, 2009; Mayberry & Eichen, 1991; Newman, Bavelier, Corina, Jezzard, & Neville, 2002; Newport, 1990). Late learners showed slower response times to phonologically related prime-target pairs in a lexical decision task as compared to native signers (Mayberry & Witcher, 2005). In probe recognition tasks, late learners were slowed by the presence of phonologically related signs, whereas early learners were not (Emmorey et al., 1995). Non-native signers made phonological errors in signed sentence shadowing and repetition tasks, in contrast to native signers who produced semantic substitutions (Mayberry, Lock, & Kazmi, 2002; Mayberry & Eichen, 1991; Mayberry & Fischer, 1989). These data suggest that late learners accomplish a less efficient processing of the form-based properties of signs (Mayberry & Eichen, 1991). Additionally, Corina and Hildebrandt (2002) found differences between late learners and native signers regarding which phonological parameters were considered most salient in a similarity judgment task; while native signers reported only movement as the most salient, late signers considered both movement and handshape as most salient. Carreiras et al. (2008) found that native signers were less affected by handshape similarity than late signers, who were slower and less accurate when signs had a dense-neighborhood handshape. Orfanidou et al. (2009) show qualitative differences in the processing of phonological structures of non-signs as a function of age of acquisition; while native and early signers evidenced more misperceptions in movement, late signers evidenced more misperceptions in handshape. Here we include LSE age of acquisition (AoA) as a factor in order to investigate whether it has an effect on ERP waves during location and handshape processing. Hence, if there is a systematic difference in the efficiency with which native and late signers process form-based properties of signs, this should be reflected in their brain waves.

In sum, in the present experiment we investigated the electrophysiological correlates of phonological overlap for signs and non-signs while participants performed a delayed lexical decision task. Participants decided whether the target was a real sign or not, viewing critical prime-target pairs that share either location or handshape, or completely unrelated prime-target pairs. For location priming, under the assumption that it influences the initial process of competition amongst candidates, we predict that overlap will elicit a modulation of the N400 component. If the sign form activated by the prime suppresses the location-related lexical units, including the related target, via lateral inhibition, we expect to find a larger N400 amplitude for the related pairs than for the unrelated ones because the phonology of the former is suppressed but not the phonology of the latter. Conversely, if the participants generate a set of candidates that likely match the prime and develop a larger negativity when the target does not belong to this list, we would find a reduced N400 for the related pairs when compared with the unrelated ones. For handshape priming we would expect an early difference in the waveforms if handshape has an influence on the activation of initial candidates. If, on the other hand, handshape plays a role at a later stage, the effect of handshape overlap would be found later in time. An additional question of interest was whether native and late learners' differences are reflected in the brain waves during location and handshape processing.

2. Methods

2.1. Participants

A total of 20 congenitally deaf persons from Madrid took part in the experiment. All 20 participants had normal or corrected to normal vision and had no history of neurological or psychiatric impairment. Their ages ranged from 20 to 40 years. All participants were right-handed, as assessed by an abridged version of the Edinburgh Handedness Inventory (Oldfield, 1971). Ten participants were native LSE signers and ten were non-native signers. Native deaf signers were born into deaf, signing households and thus had acquired LSE as their first language from their deaf parents. Non-native (late) deaf signers were born into households with hearing parents, were trained first in oral language and acquired LSE between 14 and 19 years of age. All participants reported using LSE as their primary and preferred language for at least the last 10 years. In addition, all of them were highly competent signers who either taught sign language or were taking the necessary courses to become LSE teachers. Two participants of the native signer group were not included in the analysis because they showed too many EEG artifacts.[2]

2.2. Materials

In order to obtain a large number of stimuli, the location, handshape and movement of signs from the "Diccionario de la LSE" (Pinedo, 2000) were evaluated with the aid of a deaf informant. Compound signs, signs with handshape change, bimanual signs that provide different information on the dominant and non-dominant hand, fingerspelled signs as well as classifier constructions were discarded, and only citation forms were evaluated. Signs and non-signs were recorded at a natural signing rate and cut on the first hold of the sign (first stable frame that had the initial location and handshape already formed). Signs finished at the last hold of the sign. Although the duration of each video clip was different, average duration of the signs was constant across experimental conditions. Table 3 shows the average duration (in frames) as well as the range of frames and standard deviation of the video clips used in the various conditions.

For location priming, forty pairs of signs sharing only initial location of the sign were selected and forty signs without semantic or phonological relationship to the target sign were selected as unrelated primes. In addition, forty pronounceable non-signs that kept the same location as the target sign were constructed. These target non-signs were combined with the same primes as the target signs. Fig. 1 shows an example of the materials used for the location overlap condition.

For handshape priming, thirty-eight pairs of signs that shared only handshape were selected as related primes and thirty-eight signs without a phonological relationship were selected as unrelated primes. Thirty-eight non-signs were constructed. As in the case of location, non-signs were combined with the same primes

[1] Usually deaf signers who acquired SL as a first language from deaf parents are considered native signers; whereas those who learned sign language later in life, usually through interaction with signing peers, are considered late (non-native) signers; the majority of deaf signers (90–95%) are non-native users.

[2] As a control measure, a group of 14 hearing non-signers matched in age with the deaf participants was also run on the same experiment. Their task was to watch the stimuli and try to make a lexical decision task based on their intuitions about the target signs. Average accuracy rate of these participants was 52.12% (SD 6.43), which indicates that there were no significant differences amongst signs' and non-signs' visual properties that may lead to a better discrimination of the non-signs. In addition, no significant effects or interactions related to the experimental manipulation were found (all $p > .1$), indicating that the phonological overlap effects reported for deaf participants are not due to visual characteristics of the stimuli, but to the experimental variables. As a comparison of deaf and hearing non-signers was not the main purpose of this study, thus no further analysis of this group will be presented here.

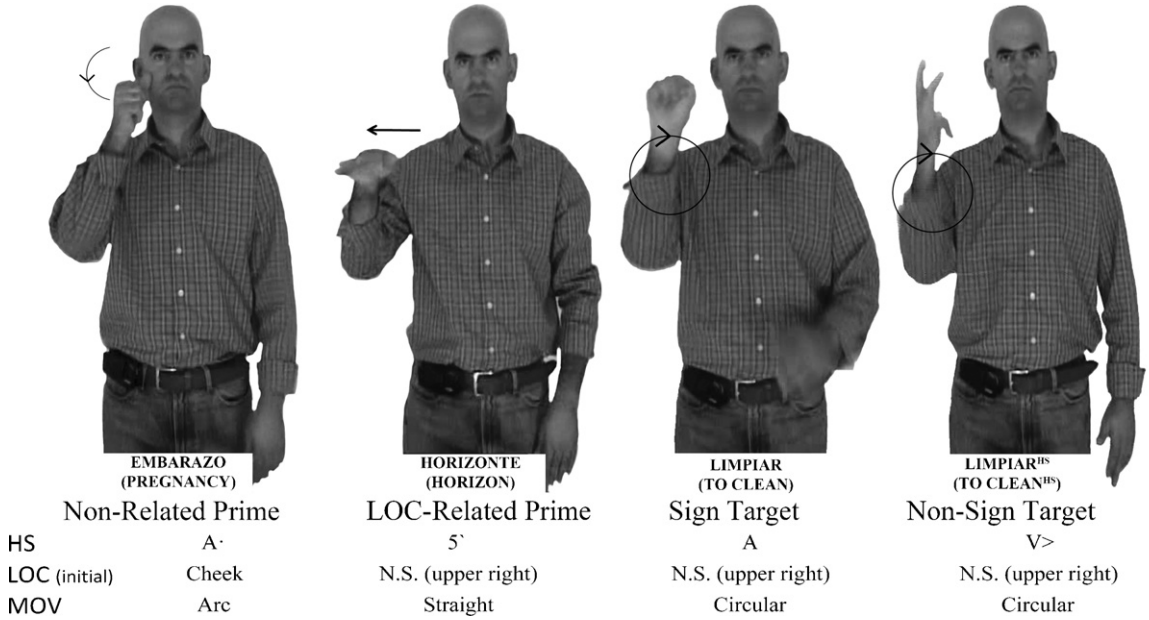

Fig. 1. Still shots taken from one experimental item. Note that the actual stimuli were dynamic, not static. The target sign illustrated here, LIMPIAR (TO CLEAN) and non-sign LIMPIAR^{HS} (TO CLEAN^{HS}), could be preceded by the location-related prime HORIZONTE (HORIZON) or the unrelated prime EMBARAZO (PREGNANCY).

Table 3
Average number of frames, range of number of frames and standard deviation of the experimental videos on each condition. Videos were displayed at 25 fps rate.

		Average number of frames	Range	SD
LOCATION	Related primes	14.4	7–25	4.9
	Unrelated primes	13.2	6–23	4.5
	Target signs	14.2	7–25	4.7
	Target non-signs	13.2	7–24	4.3
HANDSHAPE	Related primes	14.7	7–25	4.6
	Unrelated primes	14.4	8–24	4.2
	Target signs	15.5	9–24	3.7
	Target non-signs	13.4	8–19	2.9

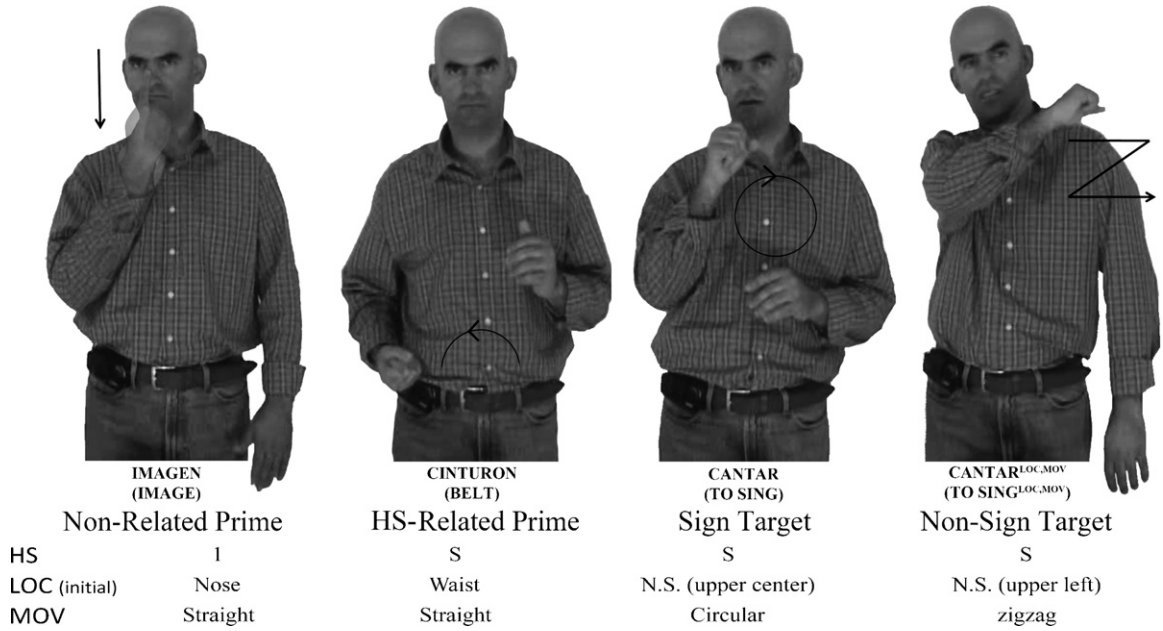

Fig. 2. Still shots taken from one experimental item. Note that the actual stimuli were dynamic, not static. The target sign illustrated here, CANTAR (TO SING) and non-sign CANTAR^{LOC,MOV} (TO SING^{LOC,MOV}), could be preceded by the handshape-related prime CINTURON (BELT) or the unrelated prime IMAGEN (IMAGE).

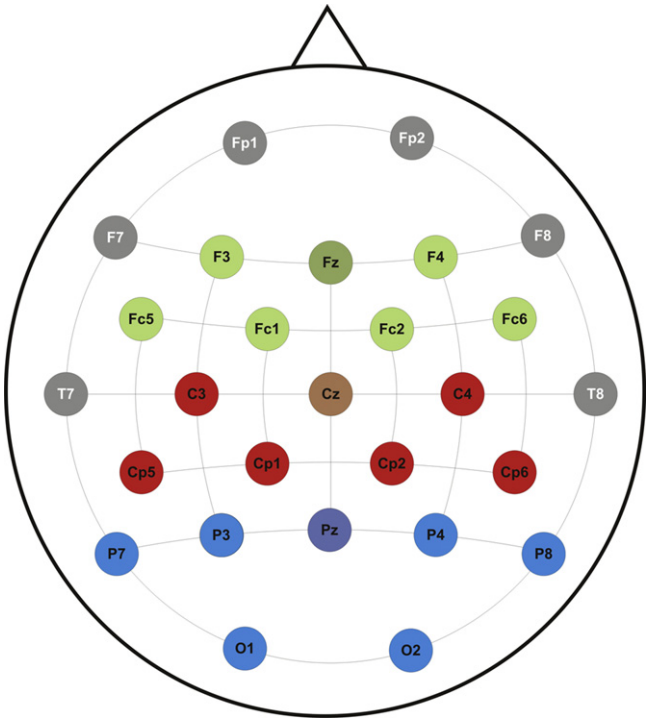

Fig. 3. Electrode groupings for the analysis.

as the target signs. Fig. 2 shows an example of the materials for this condition; a complete list of all experimental items and their phonological characteristics is given in Appendix B. In addition, the signs used in the experiment can be checked in www.bcbl.eu/lse-erp.

2.3. Procedure

All stimuli were presented on a monitor positioned at eye level in front of the participant. The signs were displayed at the center of the screen. Participants performed a lexical decision task: they were instructed to press one of two keys (L and S) on a keyboard to indicate whether the signs were a real sign of LSE or not. The sequence of events in each trial is described as follows:

First, a fixation mark (***) appeared in the center of the screen for 520 ms. It was followed by a blank screen of variable duration (40–820 ms.) and then the prime. The ISI was 120 ms of black screen, after which the target sign was presented. Then a blank screen followed with a variable duration (40–820 ms). At the end of the trial, a response cue (**¿?**) was presented. Participants were asked to avoid eye-movements and blinks during the interval between the appearance of the fixation mark and the response. They were instructed not to respond before the response cue appeared. The stimuli were presented in 3 blocks of approximately 14 min each, with two short breaks.

2.4. EEG recording and analyses

Scalp voltages were collected from 27 Ag/AgCl electrodes mounted in an elastic cap (Easycap) and referenced to the linked mastoids. Eye movements and blinks were monitored with four electrodes providing bipolar recordings of the horizontal and vertical electrooculogram (EOG). Fig. 3 shows the schematic distribution of the recording sites. Data were re-referenced offline to the average of left and right mastoids. Signals were sampled continuously throughout the experiment with a sampling rate of 250 Hz. A 0.01–100 Hz bandpass filter was applied during recording.

EEG was filtered before analysis with a bandpass filter of 0.01–20 Hz. Epochs of the EEG corresponding to 100 ms before to 800 ms after target onset were analyzed. Baseline correction was performed using the average EEG activity in the 100 ms preceding the onset of the target stimuli. Trials with artifacts were rejected, which resulted in the exclusion of approximately 19% of the trials. Six regions of interest were computed out of the 27 electrodes. These regions were (see electrode labels in Fig. 3): left-anterior (F3, FC1, FC5), left-central (C3, CP1, CP5), left-posterior (P3, P7, O1), right-anterior (F4, FC2, FC6), right-central (C4, CP2, CP6), right-posterior (P4, P8, O2), midline anterior (Fz), midline-central (CZ), and midline-posterior (PZ).

Following visual inspection of the grand average waves, two temporal windows were selected: 300–500 ms and 600–800 ms. For each window, repeated-measures ANOVAs included *Hemisphere* (left/right), *Electrode Region* (anterior, central and posterior), *Type of Prime* (related/unrelated) and *group* (native/late signers) as factors. Different ANOVAs were conducted for midline electrodes. The dependent measure was mean amplitude at each electrode region. Due to the differences in the response they require, acceptation of the signs and rejection in the case of the non-signs, these ANOVAs were performed separately for sign and non-sign targets. Where appropriate, degrees of freedom were adjusted using the Greenhouse and Geisser (1959) correction. In addition, post hoc Sidak-corrected contrasts were performed after interactions. Effects for the factors *hemisphere, Electrode Region* and *Group* are only reported when they interact with the experimental manipulations. All participants showed accuracy superior to 80%. Further analyses of reaction times were not conducted, as the response in the lexical decision task was delayed and participants were instructed to favor accuracy over speed.

3. Results

3.1. Location

ERP grand averages time-locked to the onset of the target signs are represented in Fig. 4 for one representative recording site showing the grand average waveforms corresponding to related and unrelated conditions in both groups of participants. Scalp maps of the difference wave of related and unrelated targets are also presented in Fig. 4.

Visual inspection of Fig. 4 reveals clear differences in the responses to the related and unrelated signs. Between 300 and 500 ms, the ERP displays a larger negativity for the related condition than for the unrelated condition for both groups, although effects appear to be stronger – showing larger amplitude differences – for the native signers than for the late signers. For the non-signs, however, this effect is absent.

Following visual inspection of the grand average waveforms, ANOVAs were performed separately for signs and non-signs. Lateral and midline electrodes were analyzed separately. The analysis for lateral electrodes included *Hemisphere* (left/right), *Electrode Region* (anterior, central and posterior), *Type of Prime* (related/non-related) and *Group* (native/late signers) as factors. The analysis for midline electrodes included the factors *Electrode Region* (anterior, central and posterior), *Type of Prime* (related/non-related) and *Group* (native/late signers).

3.1.1. Signs

3.1.1.1. 300–500 ms time window. Lateral Electrode Groups. A main effect of Type of Prime [$F(1,16) = 7.68$, $p < .05$, MSE = 279,637] was found, showing a higher amplitude of the location overlap condition than the unrelated one. No other main effects or interactions proved significant: Type of Prime by Group [$F(1,16) = 1.15$, $p > .1$, MSE = 279,637], type of prime by Electrode Region [$F(2,32) = 1.46$, $p > .1$, MSE = 45,508, $\varepsilon = 0.58$], type of prime by Electrode Region by Group [$F(2,32) < 1$], Type of Prime by Hemisphere [$F(1,16) < 1$], Type of Prime by Hemisphere by Group [$F(1,16) < 1$], Type of Prime by Electrode Region by Hemisphere [$F(2,32) < 1$], Type of Prime by Electrode Region by Hemisphere by Group [$F(2,32) < 1$].

Although no interaction with Group was found at any of the regions, visual inspection of Fig. 4 suggests that differences in the magnitude of the effect may be found between native and late signers. Planned post hoc comparisons (with Sidak correction) revealed simple effects for Type of Prime only for native signers in the right anterior [$F(1,16) = 4.8$, $p < .05$], left central [$F(1,16) = 7.6$, $p < .05$], right central [$F(1,16) = 6.5$, $p < .05$] and left posterior [$F(1,16) = 4.8$, $p < .05$] regions; in the right posterior region the simple effect was marginally significant [$F(1,16) = 4.1$, $p = .061$] as well as in left anterior region [$F(1,16) = 3.2$, $p = .095$]. Late signers showed a marginally significant simple effect in the right central [$F(1,16) = 3.6$, $p = .078$] region; however, Type of Prime was not significant in the left anterior [$F(1,16) < 1$] right anterior [$F(1,16) = 2.1$, $p > .1$], left central [$F(1,16) = 1.6$, $p > .1$], left posterior [$F(1,16) < 1$] and right posterior regions [$F(1,16) < 1$].

Midline electrodes. A main effect of Type of Prime [$F(1,16) = 7.004$, $p < .05$, MSE = 196,092] was found, showing a higher amplitude of

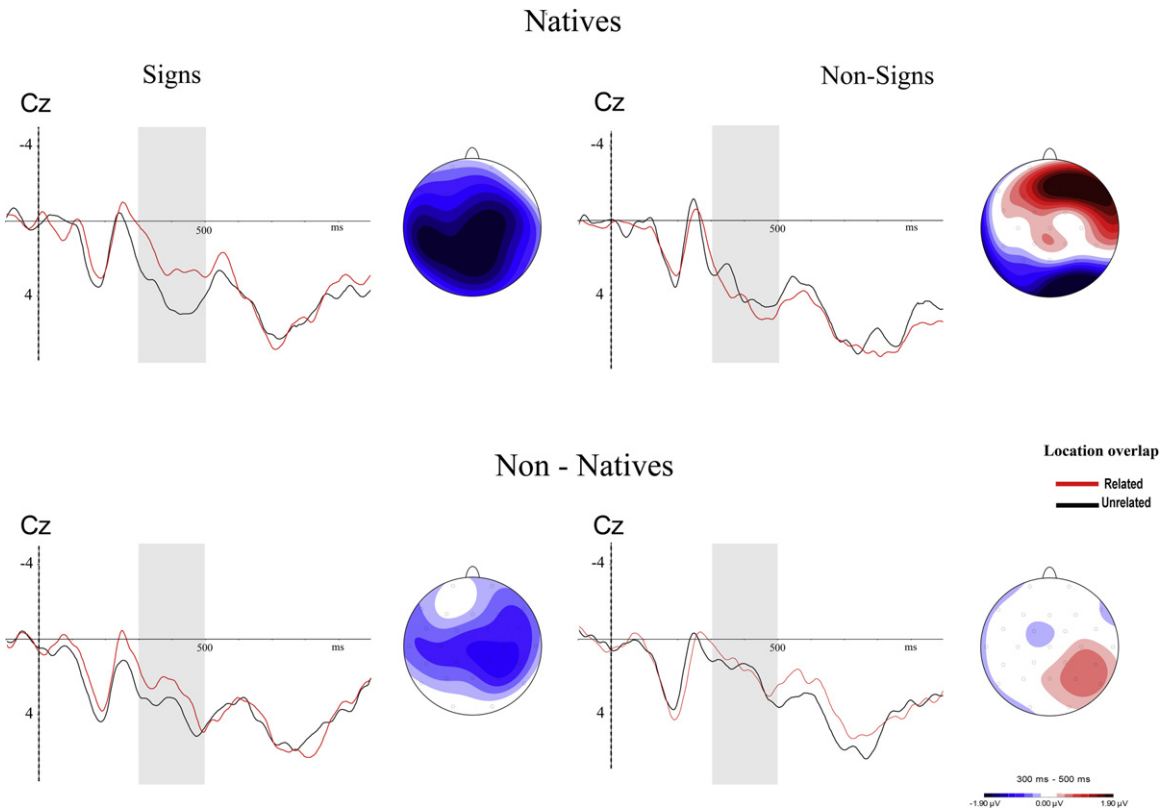

Fig. 4. Grand-average waveforms at one selected electrode site and topographic maps showing EEG response over the time window (300–500 ms). Black line corresponds with unrelated prime-target pairs, red line with location overlap pairs. Units on the vertical axis are microvolts; those on the horizontal axis are milliseconds. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the related condition than the unrelated one; Type of Prime by Group [$F(1,16) = 1.58$, $p > .1$, MSE = 196,092], Type of Prime by Electrode Region [$F(2, 32) = 1.4$, $p > .1$, MSE = 40,046, $\varepsilon = 0.81$], Type of Prime by Electrode Region by Group [$F(2, 32) < 1$].

As in the case of lateral electrode groups, post hoc comparisons (with Sidak correction) revealed significant simple effects for Type of Prime only for native signers in the central [$F(1,16) = 5.1$, $p < .05$] and posterior [$F(1,16) = 7.6$, $p < .05$] regions; in the anterior region the simple effect was marginally significant [$F(1,16) = 3.4$, $p = .086$]. For late signers the Type of Prime simple effect was not significant in the anterior [$F(1,16) < 1$], central [$F(1,16) = 1.6$, $p > .1$] nor posterior [$F(1,16) < 1$] region.

3.1.1.2. 600–800 ms time window. Lateral electrode groups. There were no significant results (all $p > .1$).

Midline electrodes. There were no significant results (all $p > .1$).

3.1.2. Non-signs

3.1.2.1. 300–500 ms time window. Lateral electrode groups. There were no significant effects of Type of Prime [$F(1,16) < 1$], Type of Prime by Group [$F(1,16) < 1$], Type of Prime by Electrode Region [$F(2,32) = 2.01$, $p > .1$, MSE = 119,502, $\varepsilon = 0.665$], Type of Prime by Electrode Region by Group [$F(2,32) = 2.4$, $p = .092$, MSE = 119,502, $\varepsilon = 0.665$], Type of Prime by Hemisphere [$F(1,16) < 1$], Type of Prime by Hemisphere by Group [$F(1,16) < 1$], or Type of Prime by Electrode Region by Hemisphere [$F(2,32) < 1$]. The four-way interaction of Type of Prime by Electrode Region by Hemisphere by Group was significant in this omnibus analysis [$F(2,32) = 4.7$, $p < .05$ MSE = 3367, $\varepsilon = 0.930$].

Midline electrodes. There were no significant effects of Type of Prime [$F(1,16) < 1$], Type of Prime by Group [$F(1,16) < 1$], Type of Prime by Electrode Region [$F(2,32) = 2.2$, $p > .1$, MSE = 55,124, $\varepsilon = .614$] or Type of Prime by Electrode Region by Group [$F(2,32) = 3.9$, $p > .05$, MSE = 55,124, $\varepsilon = .614$].

3.1.2.2. 600–800 ms time window. Lateral electrode groups. There were no significant results (all $p > .1$).

Midline electrodes. There were no significant results (all $p > .1$).

3.2. Handshape

ERP grand averages time-locked to the onset of the target signs are represented in Fig. 5 for one representative recording site, showing the grand average waveforms corresponding to related and unrelated conditions in both groups of participants. Scalp maps of the difference wave for related and unrelated targets are also presented in Fig. 5. Visual inspection of these figures suggests differences in the responses to the related and unrelated signs for the native signers between 300 and 500 ms, where the ERP features a larger negativity for the related condition than for the unrelated condition. No differences emerge in this window for the responses to the related and unrelated conditions for non-signs in the native group or for either signs or non-signs in the late signers group. However, in the 600–800 ms window (showing a positive deflection, peaking around 750 ms) visual inspection indicates differences in the responses to the related and non-related stimuli in the native signers group; these differences seem to be larger for non-signs than for signs. In this temporal window, waves display a more negative-going wave for the related condition than for the unrelated condition.

Following visual inspection of the grand average waveforms, ANOVAs were performed separately for signs and non-signs. The analysis for the lateral electrode groups included *Hemisphere* (left/right), *Electrode Region* (anterior, central and posterior), *Type*

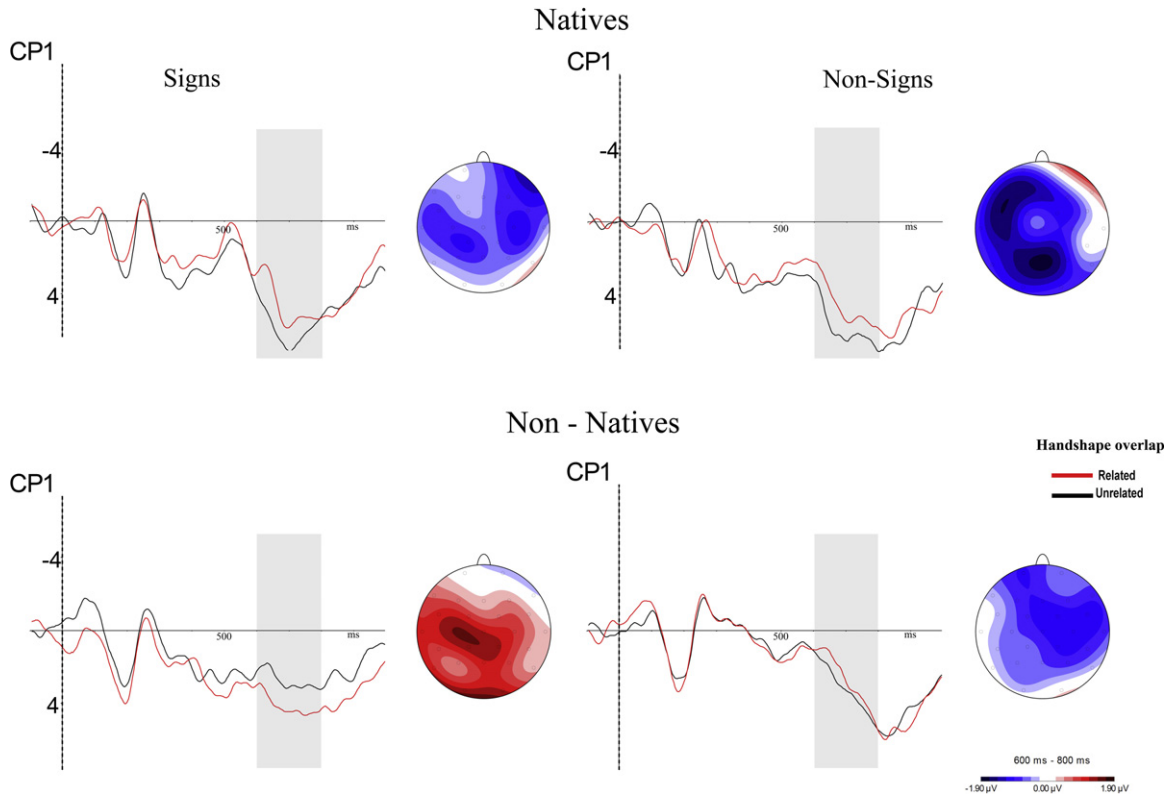

Fig. 5. Grand-average waveforms at one selected electrode site and topographic maps showing EEG response over the time window (600–800 ms). Black line corresponds with unrelated prime-target pairs; red line with handshape overlap pairs. Units on the vertical axis are microvolts; those on the horizontal axis are milliseconds. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of Prime (related/non-related) and *Group* (native/late signers) as factors. The midline electrodes analysis included *Electrode Region* (anterior, central and posterior), *Type of Prime* (related/non-related) and *Group* (native/late signers).

3.2.1. Signs

3.2.1.1. 300–500 ms time window. Lateral electrode groups. There were no significant results (all $p > .1$).

Midline electrodes. There were no significant results (all $p > .1$).

3.2.1.2. 600–800 ms time window. Lateral electrode groups. There were no significant results (all $p > .1$).

Midline electrodes. There were no significant results (all $p > .1$).

3.2.2. Non-signs

3.2.2.1. 300–500 ms time window. Lateral electrode groups. There were no significant results (all $p > .1$).

Midline electrodes. There were no significant results (all $p > .1$).

3.2.2.2. 600–800 ms time window. Lateral electrode groups. A main effect of Type of Prime [$F(1,16) = 5.6$, $p < .05$, MSE = 275,011] was found. The three-way interaction of Type of Prime by Hemisphere by Group was significant [$F(1,16) = 5.2$, $p < .05$, MSE = 14,549]. Analysis of simple effects of this interaction revealed that native signers showed a more negative-going wave for the related than for the unrelated non-signs in the left Hemisphere electrode sites [$F(1,16) = 4.81$, $p < .05$], but not in the right regions [$F(1,16) = 2.4$, $p > .1$], while no difference was found for late signers either in left [$F(1,16) = 1.1$, $p > .1$] or right Hemisphere electrodes [$F(1,16) = 2.9$, $p > .1$]. No other main effects or interactions proved significant: Type of Prime by Group [$F(1,16) < 1$], Type of Prime by Electrode Region [$F(2,32) < 1$], Type of Prime by Electrode Region by Group [$F(2,32) = 1.02$, $p > .1$, MSE = 12,195, $\varepsilon = 0.82$], Type of Prime by Hemisphere [$F(1,16) < 1$], Type of Prime by Electrode Region by Hemisphere [$F(2, 32) = <1$], Type of Prime by Electrode Region by Hemisphere by Group [$F(2,32) = 2.96$, $p > .1$, MSE = 3761, $\varepsilon = 0.97$].

Midline electrodes. A main effect of Type of Prime [$F(1,16) = 6.12$, $p < .05$, MSE = 202,182] was found, indicating that amplitude for the related condition is larger than for the unrelated condition for both groups of participants over the midline electrodes. No other main effects or interactions proved significant: Type of Prime by Group [$F(1,16) < 1$], Type of Prime by Electrode Region [$F(2,32) < 1$], Type of Prime by Electrode Region by Group [$F(2,32) = 1.4$, $p > .1$, MSE = 40,869, $\varepsilon = 0.84$].

4. Discussion

The aim of this study was to investigate the role of various sublexical factors on lexical access in LSE, using a form-priming paradigm. We used the event-related potentials technique to explore the influence and time course of location and handshape on sign recognition. In addition, both native deaf signers and late deaf signers participated in the experiment to investigate whether the age of exposure to sign language affects on-line processing of phonological characteristics of signs. Our results reveal that both location and handshape modulate brain waves. Location overlap elicited a higher amplitude N400 (300–500 ms window) than the unrelated condition, indicating that phonologically-driven lexical competition occurs on-line during LSE sign recognition. Handshape overlap, however, showed a later effect, eliciting a more negative-going wave in the 600–800 ms window for the related non-signs. These results suggest that the two parameters under study play different roles in the process of lexical access. In addition, the effects found for phonological overlap, especially for handshape, were stronger in the native signers than in the late

signers group, suggesting that late signers may accomplish a less efficient processing of form-based properties of signs.

Location overlap modulated the N400 component in signs, showing a larger negativity in the 300–500 ms window for those targets that share location with the prime than those targets unrelated with the prime. This is not the typical N400 effect in terms of direction of the effect and contrasts with studies that found a reduction of the N400 when onset overlap was present (Praamstra et al., 1994; Van Petten et al., 1999). However, a larger negativity in the N400 window for phonologically related pairs would be consistent with a lateral inhibition proposed by interactive activation models during the competition between signs related phonologically. Results of the present experiment are also consistent in the timing and the direction of the effect, although not in the topography, with auditory words exhibiting a larger frontally distributed negativity for onset overlapping targets when compared with unrelated targets (Diaz & Swaab, 2007). In general, location seems to have a privileged status in sign language processing. Studies of sign language acquisition have shown that location is more accurately produced than handshape or movement in children's early signs (Cheek, Cormier, Repp, & Meier, 2001; Clibbens & Harris, 1993; Karnopp, 2002; Marentette & Mayberry, 2000; Morgan, Barrett-Jones, & Stonehan, 2007; Siedlecki & Bonvillian, 1997; Takkinen, 2003; von Tetzchner, 1994). Location may be the most visually salient parameter at the beginning of the sign as demonstrated by studies using the gating task that found that location is the first phonological parameter of signs to be accessed (Grosjean, 1980; Emmorey & Corina, 1990). Of the major phonological parameters of signs, location is also the most resistant to errors in persons with neurological damage (Corina, 1998). One of the factors contributing to this special status of location might be that there are relatively few possible realizations of location in comparison to handshape (130 phonetically different handshapes in contrast with 26 locations have been identified in LSE; Gutiérrez & Carreiras, 2009). In other words, the repertoire of distinct locations is relatively small, which might make it easy to discriminate the location realized in a specific instant. Location is proposed to be equivalent to syllable onset, and is less influenced by sequentiality (Brentari, 2002) than, for example, movement, which requires a certain amount of time from the initiation of the movement to be perceived. Previous behavioral studies manipulating the location parameter found inhibitory effects (Carreiras et al., 2008; Corina & Emmorey, 1993). Accordingly, the ERP effect of location in the present study might reflect competition amongst phonologically similar lexical candidates in a similar way to what has been postulated in models of spoken and visual word recognition (e.g. Elman & McClelland, 1988; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981; McQueen et al., 1994; Norris, 1994). Generally speaking, in these models, the increasing activation of a specific lexical entry also leads to an increasing inhibition of competing words. This mechanism of lateral inhibition would result in a situation where forms that are closely related to the target are relatively more inhibited than unrelated entries. When a sign is presented, this input activates corresponding phonological information (its location, handshape and movement), which in turn activates lexical information. It is the case that signs that are phonologically similar to the target are inhibited, causing competition effects. Therefore, in any particular trial when a prime is presented, it activates the lexical level and lateral inhibition acts to suppress activation of similar lexical units. When a target that has the same location as the prime is presented, activation that flows from the phonological level to the lexical level reinforces the activation of the prime and consequently inhibits competitors (including the target sign). For the unrelated condition, the target sign does not strengthen the activation of the prime, either at the phonological or the lexical level, resulting in less inhibition than in the form-related condition. Thus, in the location overlap condition, correct recognition of the target requires more effort because it involves both activating the target and deactivating the prime. This process of rejecting the earlier stimulus (the prime) and accepting the competitor (the target) is what might be reflected by the larger N400. When the target is a non-sign, with no representation in the lexicon, there can be no lexical-level inhibition by the presentation of the prime; therefore, there is no difference between related and unrelated non-sign targets.

Handshape overlap showed a late (600–800 ms) effect of priming for non-signs that was more extended for the native signers than for the late signers. It should be noted that, although it did not reach significance, a similar trend could be appreciated for signs only in native signers. In this temporal window, targets with handshape overlap elicited an more negative-going wave when compared with unrelated prime-target items. Previous behavioral studies on handshape priming, in contrast to the robust inhibitory effects of location in the same studies, have either failed to find a significant effect (Corina & Emmorey, 1993) or found a facilitatory effect prevailing in non-signs (Carreiras et al., 2008). The latter authors hypothesized that this facilitatory effect of handshape overlap could be explained in terms of the early activation of candidates prior to competition; although, they do also point out that the results suggest the influence of some lexical-level inhibition process. However, studies using reaction-time measures capture only the endpoint of processing, and as a result they might not be sensitive enough to discriminate between the pre-lexical, lexical and post-lexical stages of processing. In the present experiment, we used the ERP technique that, due to its high temporal precision, allows measurement of the electrophysiological correlates of processing as the sign unfolds. Our results do not demonstrate the influence of handshape in the initial activation of candidates. On the contrary, they seem to be in accord with a process that occurs later. In any given trial, phonological parameters of the prime activate a set of candidates and, when the target is presented, location is accessed first (cf. Grosjean, 1980; Emmorey & Corina, 1990). As the location of prime and target signs is different, the activation of the prime is not strengthened and, as discussed above, the inhibition process reflected by N400 amplitude is weak. Then handshape exerts its influence and competition triggered by the overlap is reflected in the late window. Although there is not a straightforward correspondence, handshape is often considered equivalent to the rhyme in oral languages (Klima & Bellugi, 1979; Sandler & Lillo-Martin, 2001). In view of this, a later effect of handshape than of location overlap can be considered consistent with the later N400 onset found for rhyme overlap in oral languages (Praamstra et al., 1994; Van Petten et al., 1999). Results are also consistent with eye tracking studies that found that fixations of pictures of rhyme competitors tended to occur later than fixations of cohort competitors, indicating that rhyme overlap exerts its influence at a later point in word processing (Allopenna et al., 1998). Although handshape is more clearly specified than location and may be used to constrain the set of candidates, the time point of its impact may be more variable, thus adding noise to the measurement of its impact – especially in the case of ERPs, which use time-locked averaging. This variability might be due to the fact that orientation of the hand (Battison, 1978) was not controlled for in this experiment.[3] Changes

[3] Although changes in orientation between prime and target were not controlled, the orientation change did not interfere with the perception of any of the selected fingers (crucial fingers for determining what the handshape is; this is, fingers to which the phonemic feature applies) of this handshape. Consequently, handshapes could be equally well perceived in all the signs and non-signs. Besides, orientation changed in 44.7 % of the related trials but also in 39.5% of the unrelated trials. Consequently any possible influence of orientation would be equally distributed amongst the two conditions. In addition, for each set of stimuli the non-sign was created varying either movement or location from the target sign. As a result, target non-signs

in orientation between the prime and the target, even when they share the basic handshape, can make signs physically different, and, in consequence, add variability to the time point of impact. Future studies systematically varying both handshape and orientation may help to constrain the specific time point of influence of these two parameters. Moreover, in sign realization, there is considerable tolerance for handshape variations (Lucas, Bayley, & Valli, 2001), especially in new sign languages (Aronoff, Meir, Padden, & Sandler, 2008; Israel & Sandler, 2009). Israel and Sandler (2009), for example, found several accepted handshape variations, one using the index and middle fingers and the other including also the thumb, for the sign WOMAN in Al-Sayyid Bedouin sign language. The large number of acceptable allophonic variants of one particular handshape may introduce more variability or make handshape recognition slower. Further research should be carried out to elucidate whether factors specific to visual–gestural languages may lead to differences in lexical access when comparing this to spoken (auditory–vocal) languages. This might be the case for the greater perceptual salience of one parameter over another or the extended tolerance to allophonic variations (as in the case of handshape). Such specific factors might contribute to the contrasting findings for the different parameters and to the stronger effects found for non-signs.

Regarding AoA, brain wave modulations due to phonological overlap seem to be stronger for the native signers than for the late signers, suggesting that processing of form-based properties – handshape and to some extent location – is less efficient in late signers. As in the present experiment, subtle differences in the results of native and late signers have been shown in previous behavioral studies (Carreiras et al., 2008; Corina & Hildebrandt, 2002; Dye & Shih, 2006; Emmorey et al., 1995; Mayberry & Eichen, 1991; Newman et al., 2002; Newport, 1990). These differences seem to suggest that although decodification of phonological forms in late signers is accurate, it requires more effort and is less automatic. It has also been suggested that there may be qualitative differences in the way in which native and late signers process the different phonological parameters (Corina & Hildebrant, 2002; Dye & Shih, 2006; Orfanidou et al., 2009). Late signers subjectively considered handshape more salient than native signers did (Corina & Hildebrandt, 2002) and produced more handshape errors than native signers (Orfanidou et al., 2009). The present study points to a quantitative difference in the way in which native and late signers process location, as demonstrated by the fact that the main effect of overlap appears for both groups, and only a post hoc analysis of the N400 effect shows differences between groups. The case of handshape, however, may be different, as visual inspection of the brain waves suggests that the late signers may show an opposite trend for signs than for non-signs. As the trend observed for late signers did not reach significance, at this point we are not able to decide whether the difference between native and late signers in handshape processing reflects a merely quantitative difference, for example, less efficiency in decoding the phonological forms, or to a qualitatively different process. Further studies are needed to systematically investigate this question.

In summary, the present study provides compelling evidence that two sublexical parameters of signs – location and handshape – influence sign recognition. While early inhibitory effects were observed for location, later effects were observed for handshape. In addition, these effects were different for native and non-native signers. Taken together, these findings suggest that (a) the processing of signs is sensitive to sublexical units, computed through a process of competition, such as happens in spoken word recognition and (b) these sublexical computation changes seem to be modulated by the age of acquisition of the sign language by deaf people.

tend to have the same orientation (>85%) as the target signs they were compared with. Hence, if the effects were due exclusively to the changes in orientation the same results should be found for signs and non-signs. However, the fact that orientation changes occasionally between prime and target may be adding variability to the time point of handshape overlap influence.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.neuropsychologia.2012.02.018.

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