Title

Language Modality Shapes the Dynamics of Word and Sign Recognition

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Competing interests

The authors declare no competing interests.

Abstract

Spoken words and signs both consist of structured sub-lexical units. While phonemes unfold in time in the case of the spoken signal, visual sub-lexical units such as location and handshape are produced simultaneously in signs. In the current study we investigate the role of sub-lexical units in lexical access in spoken Spanish and in Spanish Sign Language (LSE) in hearing early bimodal bilinguals and in hearing second language (L2) learners of LSE, both native speakers of Spanish, using the visual world paradigm. Experiment 1 investigated phonological competition in spoken Spanish from words sharing onset or rhyme. Experiment 2 investigated competition in LSE from signs sharing handshape or location. For Spanish, the results confirm previous findings for word recognition: onset competition comes first and is more salient than rhyme competition. For sign recognition, native bimodal bilinguals (native speakers of spoken and signed languages) showed earlier competition from location than handshape, and overall stronger competition from handshape compared to location. Hearing bimodal bilinguals who learned LSE as a second language also experienced competition from both signed parameters. However, they showed later effects for location competitors and weaker effects for handshape competitors than native signers. Our results demonstrate that the temporal dynamics of spoken words and signs impact the time course of lexical co-activation. Furthermore, age of acquisition of the signed language modulates sub-lexical processing of signs, and may reflect enhanced abilities of native signers to use early phonological cues in transition movements to constrain sign recognition.

Keywords

language modality; sign language; lexical access; sub-lexical processing; visual world paradigm

1. Introduction

Language is a remarkable cognitive ability that can be expressed at least through visuo-spatial (sign languages) or audio-oral (spoken languages) modalities. Both spoken and signed languages are acquired naturally and share many properties that can be characterized at similar levels of linguistic analysis, such as phonology, morphology, syntax and semantics (Sandler & Lillo-Martin, 2006). However, they also present important differences and provide a critical test bed to investigate language universals and modality specific processes. Critically, the organization of each type of language is conditioned by modality and this impacts how the language is processed: speech requires the perception of sequential phonological units while the sub-lexical parameters that make up signs appear largely simultaneously. Here we investigate how language modality influences the temporal dynamics of lexical co-activation during recognition of auditory words and visual signs.

1.1 Sub-lexical processing in spoken and signed languages

Spoken words and signs are made up of smaller discrete sub-lexical units. In the case of spoken languages, consonants and vowels are strung together one after the other to form words. Most current models of sign language phonology agree on three sub-lexical units for signs: handshape, location and movement (e.g., Brentari, 1998; Sandler, 1989; Stokoe, 1960; van der Kooij, 2002). Handshape refers to the form that the hand or hands adopt while articulating a sign. Location concerns the body region(s) or the space around the signer where the hands are placed to perform a sign. Movement is the path the hands follow and/or changes in the handshape during the execution of a sign. The realization of these parameters varies across sign languages: in the same way that spoken languages have a specific phonological repertoire, each sign language has a specific set of handshapes, locations and movements bound by linguistic and perceptual constraints.

In spoken languages phonemes unfold sequentially, as the vocal articulators produce just one phoneme at a time. In contrast, in signed languages the visual nature of the articulators makes it possible to produce multiple sub-lexical units simultaneously. Phonological simultaneity is especially noticeable at the beginning of the articulation of a sign, when handshape and location are formed. The presence of movement in the phonological structure of signs means that there is sequential change

(Liddell & Johnson, 1989; Sandler, 1986; Perlmutter, 1992). Nevertheless, sequentiality is more pervasive in spoken languages and simultaneity in sign languages.

1.2 The temporal dynamics of sign and spoken word recognition

The current study investigates the impact of these modality-specific aspects of sub-lexical organization on the temporal dynamics of lexical processing. For this purpose we use the visual world paradigm, which has been instrumental in the study of the time course of spoken word recognition (e.g., Dahan, Magnuson, & Tanenhaus, 2001; Huettig & Altmann, 2005; Magnuson, Dixon, Tanenhaus, & Aslin, 2007; Yee & Sedivy, 2006). The technique has high temporal sensitivity, making it possible to examine when and how the unfolding speech input modulates language processing. Usually, participants are presented with a series of pictures on the screen (frequently four, one in each quadrant of the screen) while receiving auditory input. Some pictures are unrelated while others hold a semantic, phonological or visual relation with the auditory input. The proportion of looks and the time course of the looks to the different distractors reveal the nature of the lexical co-activation.

Previous experiments using the visual world paradigm with spoken language stimuli have shown that looks were first directed towards phonological neighbours with the same onset as the target, and subsequently to rhyme competitors (Allopenna, Magnuson, & Tanenhaus, 1998; see Magnuson, Tanenhaus, Aslin, & Dahan, 2003, for comparable results with an artificial language). This is in line with other studies that found stronger effects for shared onsets than rhymes (e.g., Connine, Blasko, & Titone, 1993; Marslen-Wilson & Zwitserlood, 1989), and with the temporal structure of spoken words.

Only a few previous studies have investigated the time course of the processing of sub-lexical units of signs. For example, a gating study in ASL (American Sign Language) showed that the location of the sign was identified first, followed by handshape and, finally, movement (Emmorey & Corina, 1990). This suggests that sign recognition proceeds incrementally as the parameters are processed over time. In contrast, Morford and Carlson (2011) found no differences between the identification of handshape and location in deaf native signers in a gating task, and reported earlier identification of handshape than location in hearing non-native signers. Alternatively, therefore, phonological processing may be conditioned by other factors. A recent eye-tracking study in BSL (British Sign Language) using the visual world paradigm suggested that lexical access in signed language is driven by perceptual saliency since the combination of movement and location together yielded a strong effect, whereas the temporally salient combination of handshape and location did not (Thompson, Vinson, Fox, & Vigliocco, 2013; see also Lieberman, Borovsky, Hatrak, & Mayberry, 2014). Thompson and colleagues define visual saliency in terms of ease of perception: location and movement are more salient because these parameters can be most easily seen under visually noisy circumstances.

These previous eye-tracking studies used phonological competitors that shared more than one parameter with the target. These results therefore do not provide insight into the processing of individual parameters; the similarities in signs from the combination of two or more parameters might yield competition effects that go beyond the mere summation of effects from individual overlapping parameters. Furthermore, the results do not shed light on the time course of recognition of individual parameters. In addition to assessing the broader impact of modality-specific aspects of sub-lexical organization on the dynamics of spoken word and sign recognition, another aim of the current study therefore is to compare the time course of co-activation of signs sharing location and signs sharing handshape during sign recognition.

1.2.1 The role of different sign parameters in sign recognition

Previous studies on the role of sub-lexical information in lexical access in sign language have yielded mixed results, especially for the parameters of handshape and location. For example, a phonological priming study with deaf ASL signers found inhibitory effects for location overlap, but facilitation for movement overlap, and no effect for handshape overlap (Corina & Emmorey, 1993). Inhibitory priming from location overlap has also been reported for deaf LSE signers (*lengua de signos española*-Spanish Sign Language), although handshape overlap yielded facilitation in this study (Carreiras, Gutiérrez-Sigut, Baquero, & Corina, 2008). Orfanidou, Adam, McQueen, and Morgan (2009) found that handshape was more often misperceived than location in a sign spotting experiment with deaf BSL signers, suggesting that handshape may be less reliable than location in constraining lexical access. In addition, a form-based priming experiment measuring ERPs (event-related potentials) revealed that handshape overlap produced later effects than location overlap (Gutiérrez, Müller, Baus, & Carreiras, 2012). Together, these results suggest that handshape and location may play different roles in sign recognition, and may be associated with different temporal dynamics in sign perception.

This possibility was explicitly tested by Caselli and Cohen-Goldberg (2014), using computational simulations in a lexical network based on activation principles from Chen and Mirman (2012). In this network, weak phonological neighbors facilitate target processing, while strong neighbors inhibit target processing. Whether a lexical item is weak or strong depends on sub-lexical properties that influence activation levels of phonological neighbors. Caselli and Cohen-Goldberg (2014) simulated three different possible explanations for opposing effects of handshape and location on sign recognition, in particular inhibitory effects for location competitors and facilitatory effects for handshape competitors: 1) the timing with which the two sub-lexical units are perceived; 2) differences in their resting activation in the lexical network; and 3) differences in neighborhood density. They found that earlier perception of location than handshape, and higher resting activation of location than handshape could both account for inhibitory effects of location competitors and facilitatory effects of handshape competitors; conversely, variation in lexical neighborhood density could not.

1.2.2 Age of Acquisition effects in sign recognition

Another critical factor that may modulate the recognition of lexical items is the age of acquisition (AoA) of the language in question. From work on spoken languages, we know that L2 learners show overall increased and longer activation of competitors than native listeners as a result of inaccurate phonetic processing (e.g., Broersma & Cutler, 2008; 2011; Weber & Cutler, 2004). For a review and discussion of AoA effects on sign language processing, see Carreiras (2010). Most of the available studies on AoA effects in sign language processing have investigated deaf late first language signers who were raised orally and acquired a sign language as adolescents or (young) adults. A common finding across these studies is that late signers show difficulties in processing sub-lexical information compared to early or native signers. For example, while early signers showed facilitation from phonological overlap in a primed lexical decision task with minimal pairs, late signers showed an inhibitory effect (Mayberry & Witcher, 2005) or no effect (Dye & Shih, 2006). Deaf late first language learners were also slower than deaf native signers in isolating signs in a gating task (Emmorey & Corina, 1990; Morford & Carlson, 2011), and showed later semantic and phonological competition compared to native signers in a study using the visual world paradigm (Lieberman, Borovsky, Hatrak, & Mayberry, 2015).

The unique and heterogeneous language acquisition experience of deaf late first language signers means that AoA effects in this group may not be the same for hearing L2 signers. For example, while some late deaf signers have been exposed to spoken language in the first years of life, others have little or no exposure to any language before acquiring a signed language. In contrast, hearing L2 signers are typically already fluent in a spoken language before acquiring the signed language. Studies contrasting sign processing by deaf first language signers and hearing L2 signers have yielded mixed results. Morford and Carlson (2011) compared the performance of deaf native signers, deaf late learners and hearing L2 signers on a gating task and found that both deaf late learners and hearing L2 signers identified signs more slowly than deaf native signers did. In addition, the two non-native groups were more likely to produce responses with the correct handshape than the correct location, while deaf native signers were more likely to identify both parameters correctly. One possible explanation is that deaf late first language signers and hearing L2 signers both have less well-defined phonological categorical boundaries for handshape compared to deaf native signers (Morford, Grieve-Smith MacFarlane, Staley, & Waters, 2008). Compared to deaf native signers, the two groups of late signers discriminated more handshape contrasts and showed less categorical perception. Best, Mathur, Miranda, and Lillo-Martin (2010) also found more pronounced categorization performance for dynamic handshape contrasts in deaf native signers than deaf late learners. However, in this study the hearing L2 signers did not differ significantly from the native signers.

In the current study we will further investigate the role of location and handshape information and the impact of age of acquisition on lexical access, by comparing the time course of co-activation of handshape and location competitors during sign recognition in hearing native signers and late L2 learners of a sign language.

1.3 The current study

In this study we use the visual world paradigm to investigate the processing dynamics of sub-lexical parameters in speech (onset and rhyme) and in sign language (handshape and location) in hearing native speakers of spoken Spanish who are also native speakers or late second language learners of Spanish sign language. Specifically, participants' eye movements to pictures on the screen were monitored while listening to spoken words or watching signs. In critical trials, the images on the screen included images of words that shared onset or rhyme with the target word (Experiment 1), or signs that shared location or handshape with the target sign. To examine differences in the time course of fixations on the two competitors in each language modality (i.e., onset vs. rhyme, and location vs. handshape), we performed a time series analysis (Growth Curve Analysis; Mirman, 2014). The high temporal resolution of time series analysis presents an important advantage over approaches that average fixation proportions across windows of interest and do not retain detailed information about the time course. Growth Curve Analysis characterizes a time series in terms of the average height of the curve (intercept term), steepness of the slope (linear term) and the shape of the curve (quadratic and higher-order terms). Our predictions are consequently described both in terms of differences in the overall proportion of looks to competitors (intercept term) and differences in the rate of activation of competitors (linear and quadratic term).

In spoken Spanish (Experiment 1), we hypothesize that both groups will look more to onset and rhyme competitors compared to unrelated distractors since Spanish is the dominant language for both groups of participants (native bimodal bilingual and L2 learners of LSE). This would be supported by significant differences in intercept for onset and rhyme competitors compared to unrelated distractors. Furthermore, we expect that the sequential unfolding of phonemes across time would result in more and earlier activation of shared onsets than rhymes. More specifically, while the onset competitor is a potential target until sufficient phonological information of the word has been processed, rhyme competitors are unlikely candidates as targets since the phonological onsets of the target and the rhyme competitors are different. This prediction would be supported by significant differences between onset and rhyme competitors on the intercept term (reflecting more looks to the onset competitors) and on the linear, and possibly also the quadratic, time terms (reflecting a different time course for looking behaviour for each type of competitor).

In LSE (Experiment 2), we expect native signers to look more at handshape and location competitors compared to unrelated distractors. This should be reflected by differences in the intercept (and possibly also temporal terms) for each competitor relative to the unrelated distractors. With respect to the relative strength of each parameter, the mixed results of previous studies regarding facilitation and inhibition do not generate clear predictions about which effect is stronger. For the relative time course of handshape and location competitor effects, the existing literature suggests earlier and/or more sustained activation of location competitors (Emmorey & Corina, 1990; Gutiérrez et al, 2012). Thus, we primarily expected differences in the linear and quadratic terms (reflecting differences in the onset and duration of the effects, respectively). Regarding L2 learners of LSE, we envisage two possible outcomes. On the one hand, they may perform similarly to native signers, in which case the patterns in their results should be similar to those just described. On the other hand, they may perform more like deaf late learners, who experience difficulty in processing phonology (Emmorey, Corina, & Bellugi, 1995; Mayberry & Eichen, 1991; Mayberry & Witcher, 2005) and revealed no early activation of phonology in a previous visual world paradigm study (Lieberman et al., 2015). In that case, we expect fewer and/or later fixations to one or both competitors for L2 learners of LSE, reflecting greater processing costs, compared to native signers. Since L2 signers struggle with handshape (Morford et al., 2008; Ortega & Morgan, 2015), it is reasonable to expect that processing of this parameter is especially affected. This would be supported by significant group differences on the intercept (fewer fixations) and/or linear term (later fixations) for either competitor, but especially handshape.

2. Methods

2.1 Experiment 1: spoken words

2.1.1 Participants

A group of 56 native speakers of Spanish (28 hearing native signers and another of 28 hearing L2 learners of LSE) were included in the study. Both groups were highly proficient in LSE and Spanish. All participants used LSE on a daily basis for their work: most of them were working as sign language interpreters at the time they did the task. In contrast to the native signers, who had acquired LSE from birth, the L2 learners of LSE had all been exposed to the language as adults (mean age of exposure:

21.1; range 16-28). Participants were tested in different cities across the country where participants were recruited (Bilbao, Burgos, Madrid, Palencia, Pamplona, San Sebastián and Valladolid). Participants' characteristics are shown in Table 1.

Table 1
Participant Characteristics (standard deviations in brackets)

Group	Number of participants	Gender	Mean Age	Mean years of LSE usage for professional purposes	Mean self-rated LSE competence (from 1 to 7)
Native bimodal bilinguals	28	21 women 7 men	42 (6.31)	18.6 (7.99)	6.5 (0.63)
L2 learners of LSE	28	21 women 7 men	38 (6.59)	12.5 (6.23)	6.3 (0.58)

2.1.2 Materials

The experimental task consisted of 45 trials with four images in the corners of the screen and an auditory stimulus presented over headphones. In critical trials (*n*=30), the spoken target was phonologically related to the corresponding word for two of the images: one word shared the onset with the target word, and the other competitor word rhymed with the target word. The remaining two pictures were unrelated distractors. (See Appendix A for an overview of all stimuli in critical trials.) In critical trials the target picture was absent, a common practice in Visual World Paradigm experiments (see Huettig and Altmann 2005, 2007), to increase the chances of observing competitor activation. In filler trials (*n*=15), the target image was present, and the remaining three images were unrelated distractors.

All targets, competitors and distractors were nouns in Spanish. Phonological characteristics of the Spanish words were carefully controlled such that there was only phonological overlap in the onset or rhyme of targets and competitors. In each trial, the LSE translations of the words had no phonological similarity. Two critical trials were excluded from the analysis because of visual competition between the target word and the distractor pictures, resulting in 28 analysed critical trials. Semantic relations between targets and onset competitors (M = 0.08, SD = 0.1), targets and rhyme competitors (M = 0.11, SD = 0.1), and targets and distractors (M = 0.07, SD = 0.06) were controlled using scores (between 0 and 1) from the semantic analysis tool DISCO[1] (extracting DIstributionally related words using CO-occurrences, Kolb, 2008, 2009) on a large, 232 million (word) token corpus of Spanish texts. A one-way ANOVA showed that there were no significant differences in DISCO values across targets paired with each competitor and each distractor ($F(2,54) = 2.3$, $p = .1$). We controlled for log frequency and number of phonemes, letters and syllables in competitors with EsPal, the Spanish Lexical Database (Duchon, Perea, Sebastián-Gallés, Martí, & Carreiras, 2013), using the Written and Web Tokens database (2012-11-06) and Castilian Spanish phonology. The properties of the word lists are shown in Table 2.

Table 2
Characteristics of Competitor Words (means; standard deviations in brackets)

	Onset competitor	Rhyme competitor	p-value of t-test
Log frequency	0.90 (0.68)	1.03 (0.52)	0.42
Number of phonemes	5.82 (1.74)	5.60 (1.39)	0.61
Number of letters	6 (1.82)	5.82 (1.44)	0.68
Number of syllables	2.60 (0.68)	2.57 (0.57)	0.83

[1] Only DISCO values for second-order semantic similarity are reported, as first-order values also did not significantly differ. First and second order refers to different matrices in size concerning the amount of words taken into consideration to compute the semantic similarity values. Second-order values show a reasonable correlation with human-based values (Kolb, 2008).

A male native Spanish speaker recorded the words using Goldwave audio software in a recording booth. The audio files were edited, de-noised and normalized using Praat (Boersma & Weenink, 2014). Average duration of the audio files was 620 ms (*SD* = 117).

The picture stimuli consisted of 180 black and white images (300x300 pixels). Of these, 171 standardized pictures were obtained from the International Picture Naming Project (Bates et al., 2003). Nine images in the same style were included from other sources. Name agreement for these pictures by 12 native Spanish speakers who did not participate in the experiment was 95.4%. Visual complexity values of competitor and distractor images in critical trials were obtained with Image Processing Toolbox for MATLAB (Thompson & Shure, 1995). The image contour complexity score was obtained using the "edge" function and the "canny" method that detects strong and weak edges. A one-way ANOVA showed that there were no significant differences in visual complexity between competitor and distractor images ($F(3,87) = 0.14$, $p = .93$).

2.1.3 Procedure

SR Research Experiment Builder software (v1.10.1630) was used to present the stimuli. Eye movements were recorded at a sampling rate of 1000Hz with the SR Research Eyelink 1000 system using a desk-mounted chin and forehead rest. Only the right eye was recorded. All participants sat in front of a screen (1044x768 pixels) at 60 cm from their eyes. Participants were instructed to push the appropriate key on a Cedrus RB-844 button box (with four large buttons in a two-by-two layout) when the corresponding picture matched the target word. When the target word did not have a corresponding image, participants were instructed to wait for the next trial to start. After reading the task instructions on the screen, a 10-point calibration procedure was performed. Before the experimental task, participants completed a practice block of six trials with feedback on accuracy. Drift correction was performed at the start of each trial. Subsequently, the four images appeared on the screen for 500 ms before the target word was presented over headphones. The images remained on the screen for another 2,500 ms after target word offset or until the participant pushed any of the buttons, followed by 100 ms of blank screen (Figure 1). We used two lists with different presentation sequences that were counterbalanced across participants. Competitors, distractors and target images appeared a similar number of times in each location on the screen.

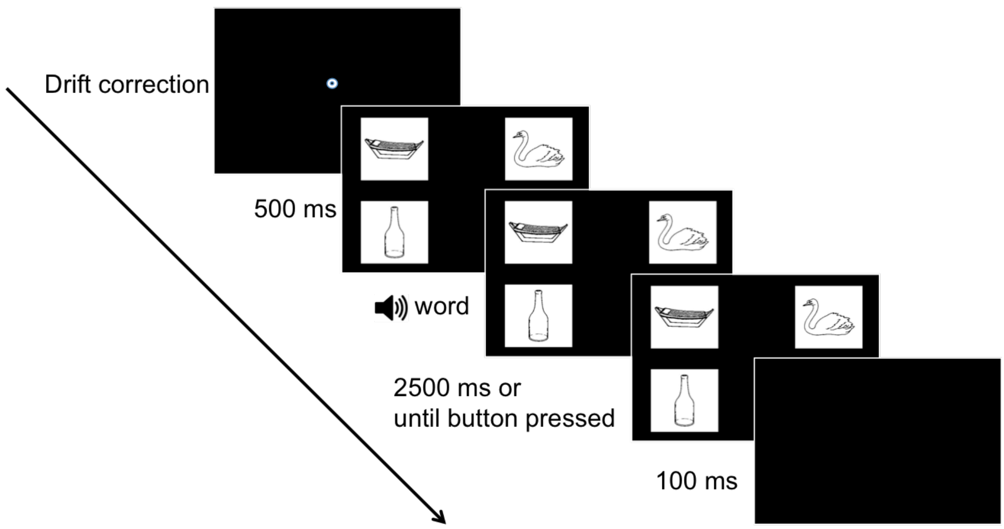


Figure 1. Trial sequence for Experiment 1: spoken words.

Trials with incorrect responses were excluded from analysis. After completing the experimental task, participants filled in a questionnaire concerning their language profile.

2.2 Experiment 2: signs

2.2.1 Participants

Same as Experiment 1.

2.2.2 Materials

The experimental task with LSE signs consisted of 45 trials with four images in the corners of the screen and a centrally presented video of an LSE target sign. In critical trials (*n*=30) the target sign in the video was phonologically related to two of the signs corresponding to the pictures: one sign had the same place of articulation as the target sign (location competitor), and the other sign had the same handshape as the target sign (handshape competitor). The other two pictures were unrelated to the target sign. In critical trials there was no image corresponding to the target sign (see Appendix A for an overview of all stimuli in critical trials). In filler trials (*n*=15) the target image was present and the other three images were unrelated distractors.

All targets, competitors and distractors were nouns in LSE. Phonological characteristics of the signs were carefully controlled such that there was only overlap in handshape or location between target signs and competitors. Target and competitor signs in critical trials were further matched for handedness (one- or two-handed signs). In each trial, the Spanish translations of the signs had no phonological similarity. Target signs in two trials were later found to have phonological overlap with one of the distractor pictures and were therefore excluded from analysis, resulting in 28 analysed critical trials. Since semantic similarity or frequency values are not yet available for LSE, we used the translation equivalents in Spanish for the signs and images to obtain approximate values from DISCO (Kolb, 2008, 2009) and EsPal (Duchon et al., 2013) respectively. Semantic relations between sign targets and location (M = 0.08, SD = 0.1), targets and handshape competitors (M = 0.06, SD = 0.07), and targets and distractors (M = 0.04, SD = 0.04) were controlled through automatic text-based values of second-order semantic similarity using DISCO. A one-way ANOVA showed that there were no significant differences in semantic similarity across targets paired with each competitor and with each distractor ($F(2,54) = 1.49$, $p = .23$). Mean log frequency of the Spanish translation equivalents of the handshape and location competitor signs was 1.07 and 1.12 respectively (t (27) = -.29 $p = .77$).

Iconicity has been shown to facilitate sign learning and lexical retrieval in some tasks (e.g., Campbell, Martin, & White, 1992; Baus, Carreiras, & Emmorey, 2013; Thompson, Vinson, & Vigliocco, 2009, 2010; Vinson, Thompson, Skinner, & Vigliocco, 2015). Although target pictures were absent in critical trials, iconicity and the use of picture stimuli in the current study may have increased the saliency of some competitor signs. To make sure that handshape and location competitors did not differ widely in degree of iconicity, we asked participants to rate the iconicity of the competitor signs on a scale from 1 to 7 after doing the experiment. The average rating for location competitors was 2.8 ($SD = 1$) and 2.5 ($SD = 0.7$) for handshape competitors ($t(54) = .83$, $p = .21$). We further calculated the correlation between the iconicity score for each competitor item and the average proportion of fixations to that item in the time window of the duration of the sign. No correlations were found for handshape competitors ($r = -0.19$, $p = .32$) or location competitors ($r = -0.21$, $p = .27$). Analysis by group (native bimodal bilinguals and L2 learners of LSE) also failed to reveal evidence for an effect of iconicity (all ps > .2).

A female deaf native signer was recorded signing the stimuli in a standing position against a white background with a Canon Legria HF G10 Camera. In the stimulus videos the signer's hands started in resting position (by her sides) followed by a transition movement to the location of the sign during which the hands formed the target handshape. The stimulus videos ended with the signer's hands back in the resting position. The sign onset was defined as the frame in which the handshape was visibly articulated at the sign's location on the body; the end of the sign was defined as the last frame before the onset of the transition movement to the resting position. Mean sign duration was 740 ms (SD = 152); the average onset for handshape was 409 ms and for location 487 ms after video onset. Due to geographic variation of LSE, the signs were selected from the Standardized LSE Dictionary (*Diccionario Normativo de la LSE,* 2011; also available online: http://www.fundacioncnse.org/tesorolse/index.html). The videos were cropped and scaled to 320x296 pixels and presented in the center of screen (25 fps). Average duration of the videos was 2,000 ms (*SD* = 253).

The picture stimuli consisted of 180 black and white images (300x300 pixels). Of these, 167 were taken from the International Picture Naming Project (Bates et al., 2003) and 13 images in the same style were included from other sources. Based on the participants' responses in the post-experiment task (see Procedure section below), name agreement in LSE for the competitor images was 91.7% (range 52-100%). Only five items had agreement below 75%. Name agreement for some items is relatively low because responses that were phonologically distinct variants of the target sign were also counted as "incorrect"; the proportion of responses that involved an incorrect lexical item was very low (0.9%). Compared to spoken languages, LSE, like other sign languages, shows a high degree of dialectal variation due to several sociolinguistic factors. Visual complexity values of competitor and distractor images in critical trials were obtained with Image Processing Toolbox for MATLAB (Thompson & Shure, 1995). A one-way ANOVA showed that there were no significant differences in visual complexity between competitor and distractor images ($F(3,87) = 0.75$, $p = .52$).

2.2.3 Procedure

The procedure was the same as that used for experiment 1 with two differences: instructions were shown in LSE; and a video with an LSE target sign was presented in the centre of the screen during each trial instead of a Spanish auditory target word. Figure 2 illustrates the trial sequence.

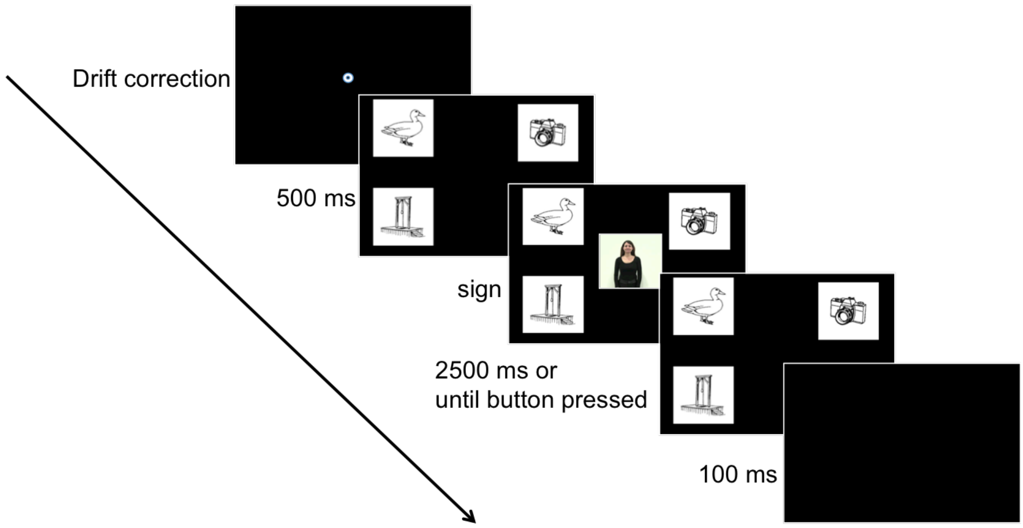


Figure 2. Trial sequence for Experiment 2: signs.

After the experiment, participants produced the sign they would normally articulate for the images used as competitor stimuli in the experiment. If they did not produce the expected sign (resulting in the absence of phonological overlap between the target and competitor sign), that trial was eliminated for that participant from the analysis. They also gave the Spanish translation of the LSE target signs in the experiment to make sure they knew the signs. Trials with incorrect translations were also excluded from analysis. In total, 21.3% of the trials were eliminated from the analysis in the case of native bimodal bilinguals (range: 2-14 trials per participant), and 17.6% of the trials for the L2 learners of LSE (range: 1-11 trials per participant).

3. Results

For the analysis of both experiments, we used R v3.3.2 (R Core Team, 2016) with the VWPre package v1.0.1 (Porretta, Kyröläinen, van Rij, & Järvikivi, 2017) for pre-processing and the lme4 package v1.1-15 (Bates, Mächler, Bolker, & Walker, 2015) for statistical analysis. Fixations to the four interest areas, corresponding to each picture presented, were grouped in 20 ms bins (20 samples) and averaged across trials. Furthermore, we averaged the proportion of looks to the two unrelated distractors to create a single unrelated baseline for the analyses.

As explained earlier we used Growth Curve Analysis to estimate parameters of fixation curves that reflected the average height of the curve (intercept term), steepness of the slope (linear term) and the shape of the curve (quadratic and higher-order terms). Unless indicated otherwise, treatment coding was used to code the contrasts for fixed effects in the growth curve models. In treatment coding, one level of the contrast is treated as the reference level and parameters are estimated for the other level of the contrast relative to this reference level. In order to choose the polynomial order for each growth curve model we used a combination of a statistical and a theoretical approach (Mirman, 2014), including only orthogonal time terms that significantly improved model fit and that were included in our predictions. Orthogonal polynomials were used to reduce collinearity between the time terms. To capture interindividual variation in the rate of lexical activation, the models also included random effects of Participants and Participant-by-Competitor. Since visual world paradigm studies typically involve a single trial per item per participant and data from a single visual world paradigm trial consist of a sequence of categorical fixations rather than a smooth fixation probability curve, it is not possible to use growth curve analysis on participant-by-item data (Mirman, Dixon, & Magnuson, 2008). For the model parameter estimates, normal approximation (z-distribution) was used to calculate p-values. Full model results for all analyses are reported in Appendix B.

3.1 Experiment 1: spoken words

In Experiment 1, in critical trials (target absent) participants heard Spanish words while pictures of onset and rhyme competitors were shown on the screen together with two unrelated pictures.

For the statistical analysis, we defined the time windows for the competitors based on the temporal properties of the auditory stimuli for all target words in critical trials and allowing for approximately 200 ms needed to programme and launch an eye movement (Matin, Shao, & Boff, 1993) (see Figure 3). Thus, for the analysis of onset competitors, a time window (200-420 ms) was selected from 200 ms after the start of the word until 200 ms after the mean duration of the onset. For rhyme competitors, a time window (440-820 ms) was selected from 200 ms after the mean point at which the rhyme starts until 200 ms after mean word offset. Individual trials with more than 25% track loss in the time window of interest were excluded from the analysis for the onset window (n=10, 0.6% of the data) and for the rhyme window (n=4, 0.3% of the data).

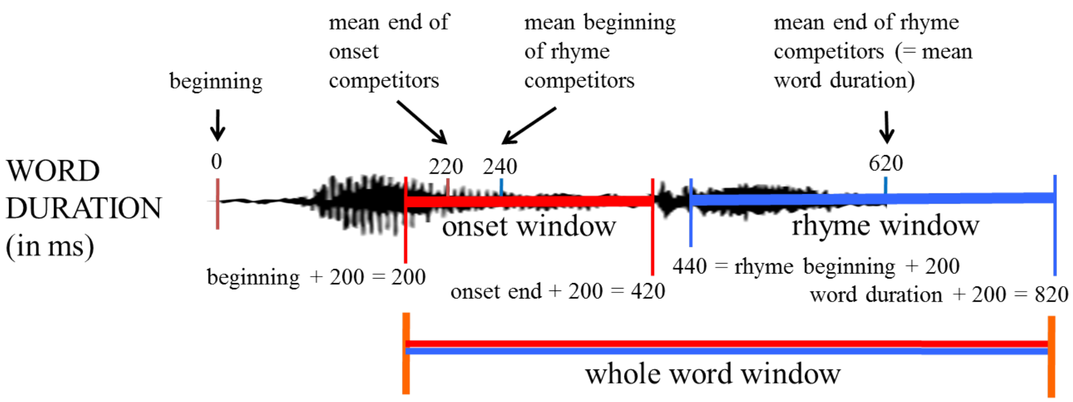


Figure 3. Illustration of word duration and the selected time windows for the analyses of onset and rhyme competitor effects.

Figure 4 shows the proportion of looks to onset and rhyme competitors and unrelated distractors across all participants for 1000 ms after the onset of the target word.

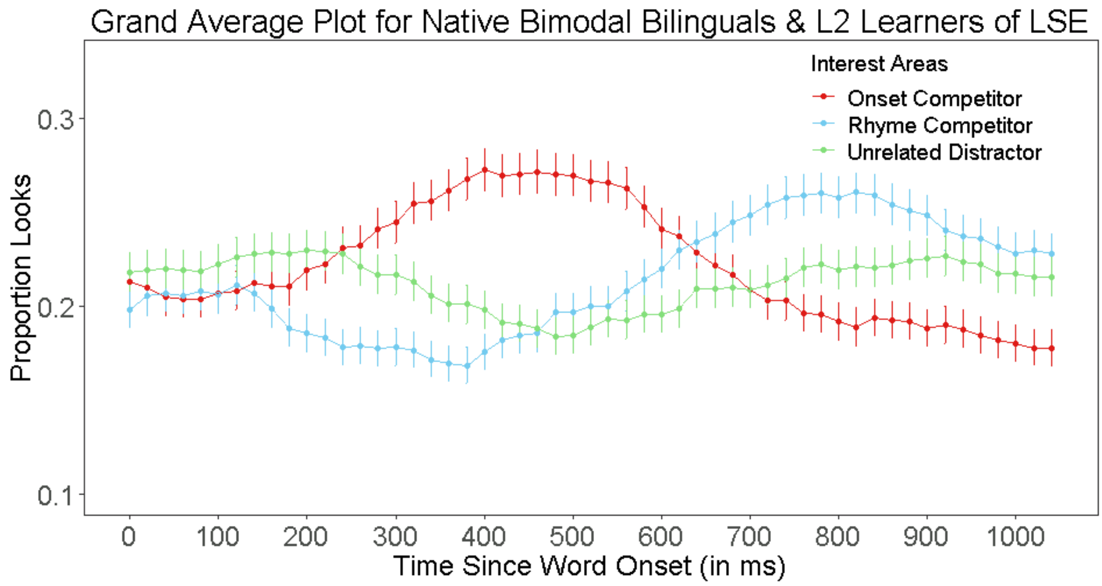


Figure 4. Proportion of looks to onset and rhyme competitors and unrelated distractors since word onset for native bimodal bilinguals and L2 learners of LSE (all native speakers of Spanish) in Experiment 1: spoken words.

Onset competitors. Growth curve analysis was used to analyze the gaze data from 200 ms to 420 ms after word onset. The overall time course of fixations was modeled with a linear orthogonal polynomial and fixed effects of Competitor type (Onset vs. Unrelated). The Unrelated distractor was treated as the reference level and parameters were estimated for the Onset competitor. There was a significant effect of Competitor type on the intercept term (*Estimate* = 0.035, *SE* = 0.011, *p* = 0.001), indicating a higher overall proportion of looks to onset competitors than unrelated distractors. There was also a significant effect of Competitor type on the linear term (*Estimate* = 0.102, *SE* = 0.023, $p < 0.001$), indicating a steeper slope for looks to the onset competitor than for unrelated distractors (see the left panel in Figure 5).

Rhyme competitors. A similar growth curve model was created to analyze the gaze data from 440 ms to 820 ms after word onset, comparing looks to rhyme competitors and unrelated distractors (reference level). The analysis showed a significant effect of Competitor type on the intercept term (*Estimate* = 0.025, *SE* = 0.007, $p < 0.001$, reflecting a higher overall proportion of looks to the rhyme competitors than to unrelated distractors. A significant effect of Competitor type on the linear term was also found (*Estimate* = 0.064, *SE* = 0.034, $p = 0.029$), indicating a steeper slope of looks to the Rhyme competitor relative to unrelated distractors (see the right panel in Figure 5).

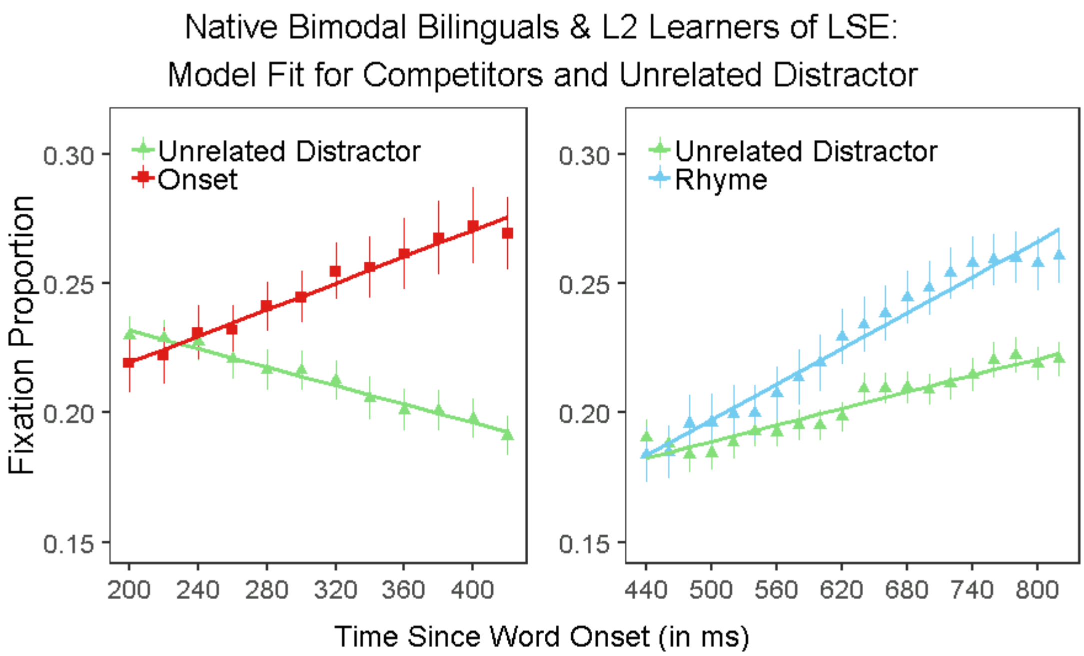


Figure 5. Model fit for onset (left) and rhyme (right) competitors and unrelated distractors across native bimodal bilinguals and L2 learners of LSE (all native speakers of Spanish) in Experiment 1: spoken words. Error bars show standard errors.

Comparison of onset and rhyme competitors. To examine differences in the time course of onset and rhyme competitor effects, we performed growth curve analysis across a whole-word length window, that is, mean duration of the target words (620 ms) plus 200 ms to account for the planning of eye movements (i.e., 200-820 ms). The overall time course of fixations was modeled with a second-order (quadratic) orthogonal polynomial and fixed effects of Competitor type (Onset vs. Rhyme) on all time terms. The Onset competitor was treated as the reference level and parameters were estimated for the Rhyme competitor. This analysis yielded a significant effect of Competitor type on the intercept (*Estimate* = -0.030, *SE* = 0.007, $p < 0.001$), indicating a greater proportion of looks to the Onset competitor compared to the Rhyme competitor. Additionally, there were significant effects of Competitor type on the linear term (*Estimate* = 0.255, *SE* = 0.042, $p < 0.001$) and on the quadratic term (*Estimate* = 0.169, *SE* = 0.034, $p < 0.001$); these differences in the time terms indicate that the time course of the two competitors differed. Specifically, the more positive linear term and the change in polarity of the quadratic term for the Rhyme competitors with respect to the Onset competitors indicate that the Rhyme effect was later than the Onset effect, as can be seen in Figure 6. Together, these results indicate earlier and stronger effects from onset than rhyme competitors.

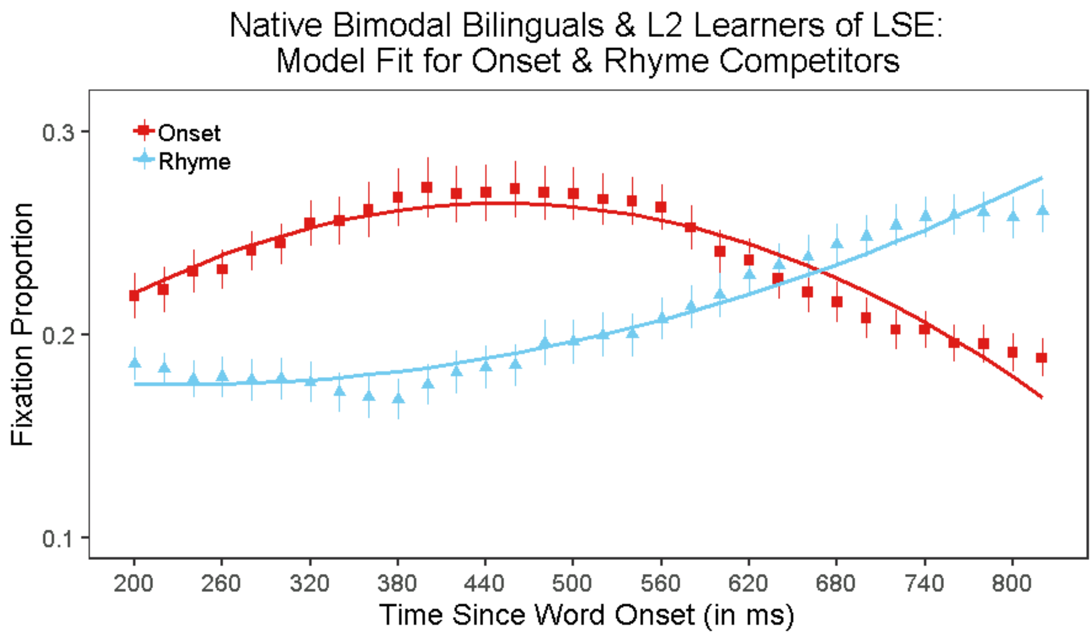


Figure 6. Model fit for onset and rhyme competitors in native bimodal bilinguals and L2 learners of LSE (all native speakers of Spanish) in Experiment 1: spoken words. Error bars show standard errors.

3.2 Experiment 2: signs

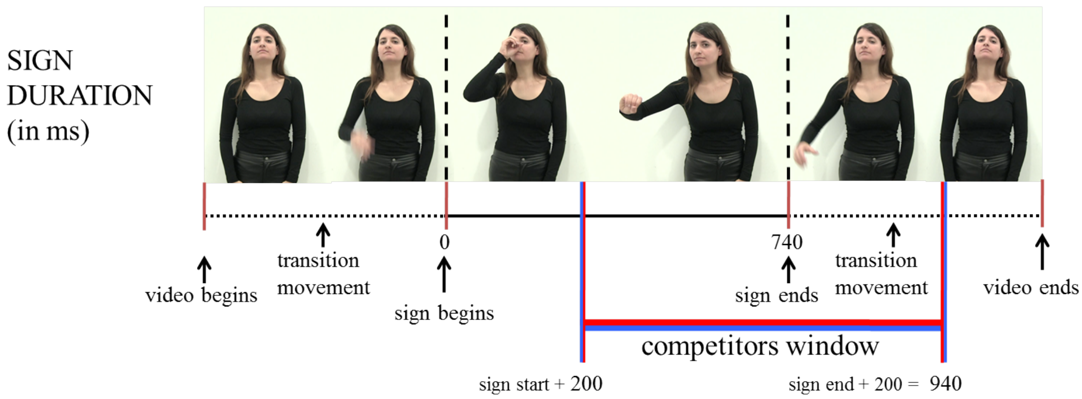
In experiment 2, in critical trials participants saw videos of LSE signs in the centre of the screen together with pictures of handshape and location competitors and two unrelated distractor pictures (looks to the unrelated pictures were averaged together to create a single unrelated baseline for the analysis).

Average response time for filler trials (target present) was 1862 ms (*SD* = 214) for the native bimodal bilinguals, and 1941 ms (*SD* = 212) for L2 learners of LSE.[2] The mean time to shift their gaze away from the stimulus video to the interest areas in

[2] A t-test showed no significant difference in the response time between native bimodal bilinguals and L2 learners of LSE; $t(54) = 1.38$, $p = .174$

critical trials was 1157 ms (*SD* = 150) for native bimodal bilinguals, and 1185 ms (*SD* = 99) for L2 learners of LSE.[3]

For the analysis of sign competitors we selected a time window motivated by the properties of the sign stimuli (see Figure 7). In contrast to onset and rhyme competitors in experiment 1, the sub-lexical parameters of signs are present simultaneously when the sign is articulated. Therefore, we selected the same time window for the analyses of handshape and location competitors. The onset point for the window of analysis was adjusted to the sign onset of each individual target sign (defined as the moment when both handshape and location were visibly articulated). Mean sign duration was 740 ms (*SD* = 152), resulting in a 200-940 ms window for analysis after accounting for the ~200 ms required to programme an eye movement (see Figure 8). Individual trials with more than 25% track loss in the time window of interest were excluded from the analysis (n=1, 0.06% of the data).



[3] A Welch t-test showed no significant difference in the time that native bimodal bilinguals and L2 learners of LSE took to shift their gaze from the video to the interest areas, $t(46.7) = 0.84$, $p = .405$

Figure 7. Illustration of video and sign duration (in ms) and the selected time windows for the analysis of location and handshape competitor effects for the LSE stimulus ELEFANTE (elephant).

3.2.1 Group comparison

To compare the time course of sign recognition between native bimodal bilinguals and L2 learners of LSE, we obtained two difference curves by subtracting the proportion of looks to the unrelated distractors from the proportion of looks to the location and handshape competitors, respectively, in the sign-length time window (200-940 ms). We performed growth curve analysis including group (native bimodal bilinguals vs. L2 learners of LSE) as a between-subjects factor. The overall time course of fixations was modeled with a second-order (quadratic) orthogonal polynomial and fixed effects of Competitor type and Group on all time terms. In order to estimate main effects of Group and Competitor type in the model, we used sum coding for these contrasts instead of treatment coding with a reference level, which estimates simple effects (Mirman, 2014). This analysis yielded a main effect of Competitor type on the linear term (*Estimate* = 0.043, *SE* = 0.015, $p = 0.006$). The interaction between Competitor type and Group was significant on the linear term (*Estimate* = 0.055, *SE* = 0.015, $p < 0.001$). Therefore, we performed follow-up growth curve analyses for each group and competitor separately.

3.2.2 Native bimodal bilinguals

Figure 8 shows the proportion of looks to location and handshape competitors and unrelated distractors for native bimodal bilinguals from sign onset and for the selected time window for analysis.

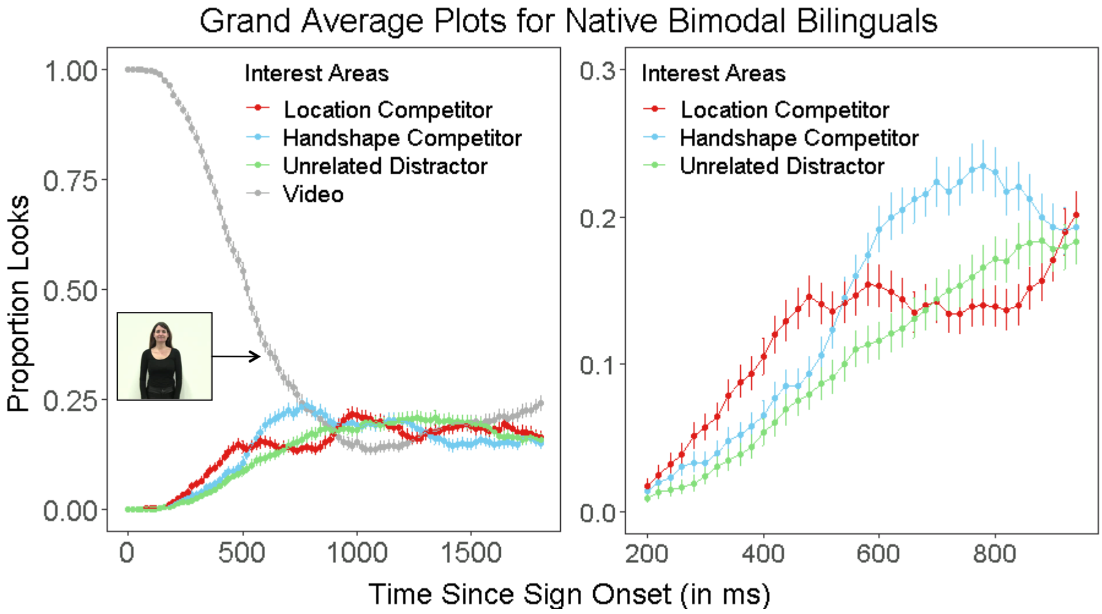


Figure 8. Proportion of looks to location and handshape competitors and unrelated distractors for native bimodal bilinguals from sign onset (0-1800 ms) including looks to the stimulus video (left) and for the window of interest (200-940 ms) (right) in Experiment 2: signs.

Growth curve analysis was used to analyze the gaze data from 200 ms to 940 ms after sign onset. The overall time course of fixations from 200-940 ms was modeled with a second-order (quadratic) orthogonal polynomial and fixed effects of Competitor type (Location vs. Unrelated Distractor, Handshape vs. Unrelated Distractor) on all time terms. The Unrelated Distractor was treated as the reference level and parameters were estimated for the Location and the Handshape competitors.

Location competitors. There was a significant effect of Competitor type on the intercept term (*Estimate* = 0.019, *SE* = 0.006, $p = 0.002$), indicating a higher overall proportion of looks to location competitors than to unrelated distractors. There was also a significant effect of Competitor type on the linear term (*Estimate* = -0.115, *SE* = 0.045, $p = 0.01$) reflecting a less positive slope for the location competitors relative to unrelated distractors, likely driven by the relative decrease of looks to location competitors in the second half of the window. See Figure 9 for model fit.

Handshape competitors. The analysis showed a significant effect of Competitor type on the intercept (*Estimate* = 0.036, *SE* = 0.006, $p < 0.001$), reflecting a higher overall proportion of looks to handshape competitors than to unrelated distractors. There was also a significant effect of Competitor type on the quadratic term (*Estimate* = -0.100, *SE* = 0.039, $p = 0.01$); as the estimate for the quadratic term for the distractors was negative, this negative effect means that the (absolute) magnitude of the quadratic term for handshape competitors was greater, indicating a sharper peak for looks to handshape competitors compared to distractors. See Figure 9 for model fit.

Comparison of location and handshape competitors. In order to directly compare location and handshape competitor effects, the two competitor fixation curves were modeled with a second-order (quadratic) orthogonal polynomial and fixed effects of Competitor type (Location vs. Handshape). Looks to the handshape competitor were treated as the reference level and parameters were estimated for the location competitor. There was a significant effect of Competitor type on the intercept (*Estimate* = -0.0164, *SE* = 0.007, $p = 0.03$), indicating a higher proportion of looks towards handshape competitors compared to location competitors (see Figure 9). The analysis also showed a significant effect of Competitor type on the linear term (*Estimate* = -0.197, *SE* = 0.047, $p < 0.001$), indicating a more positive slope for looks to handshape competitors compared to location competitors. These results suggest that compared to location, handshape competitor effects were stronger and occurred later.

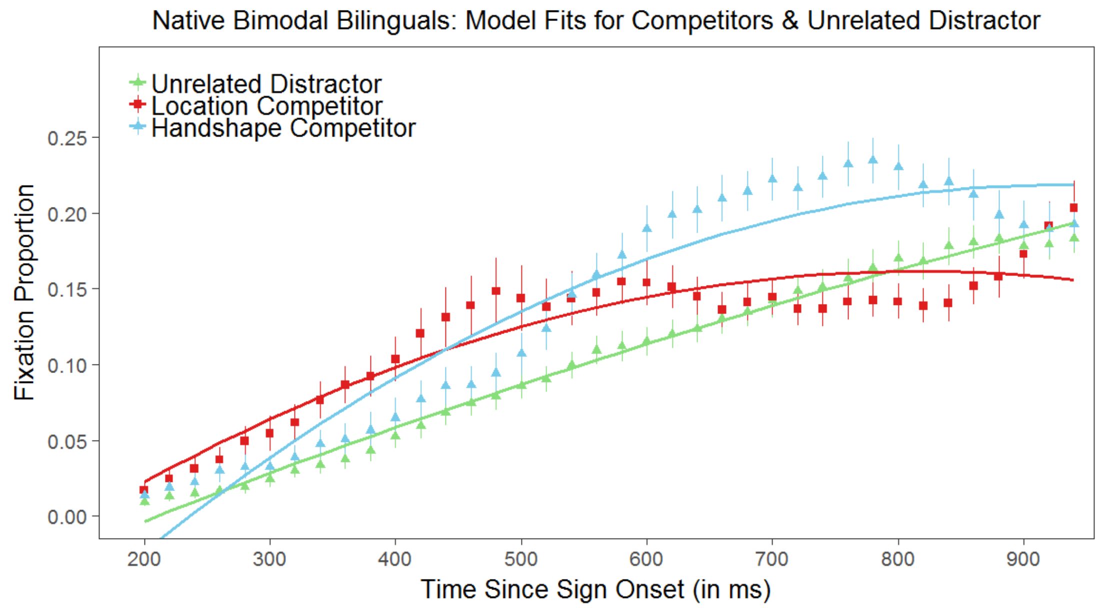


Figure 9. Model fit for looks to location (red) and handshape (blue) competitors and unrelated distractors (green) for native bimodal bilinguals in Experiment 2: signs. Error bars show standard errors.

3.2.3 L2 learners of LSE

Figure 10 shows the proportion of looks to location and handshape competitors and unrelated distractors from sign onset and for the specific time window of interest (200-940 ms) for L2 learners of LSE.

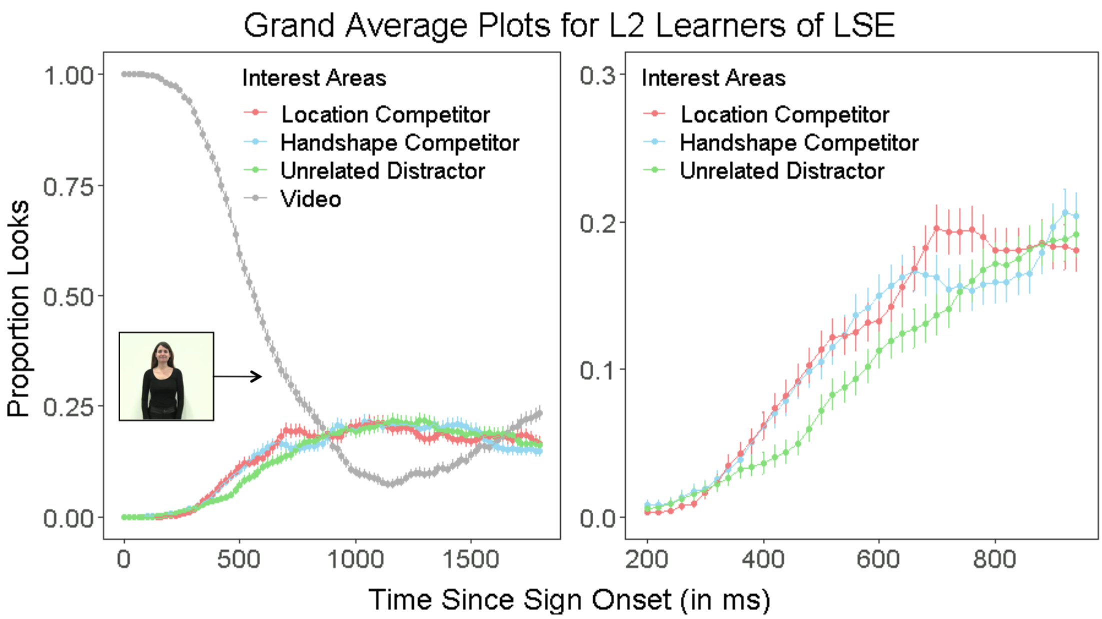


Figure 10. Proportion of looks to location and handshape competitors and unrelated distractors for L2 learners of LSE from sign onset (0-1800 ms) including looks to the stimulus video (left) and for the window of interest (200-940 ms) (right) in Experiment 2: signs.

The same growth curve analysis previously described for the native bimodal bilinguals was applied to the gaze data of the hearing L2 learners of LSE.

Location competitors. A significant effect of Competitor type on the intercept term was found (*Estimate* = 0.020, *SE* = 0.007, $p = 0.004$), reflecting a higher overall proportion of looks to location competitors than to unrelated distractors. There was also a significant effect of Competitor type on the quadratic term (*Estimate* = -0.107, *SE* = 0.034, $p = 0.001$), indicating a sharper peak for looks to location competitors compared to unrelated distractors. See Figure 11 for model fit.

Handshape competitors. A significant effect of Competitor type was found on the intercept term (*Estimate* = 0.014, *SE* = 0.007, $p = 0.036$), indicating a higher overall proportion of looks to handshape competitors than to unrelated distractors. There was a significant effect of Competitor type on the quadratic term (*Estimate* = -0.074, *SE* = 0.034, $p = 0.029$), indicating a sharper peak for handshape competitors relative to unrelated distractors (see Figure 11 for model fit).

Comparison of location and handshape competitors. As was done for the native signers, we directly compared the two competitor fixation curves for the L2 learners of LSE. A growth curve analysis with looks to the handshape competitor as reference did not show any significant effects, indicating a similar effect with the same time course for both competitors.

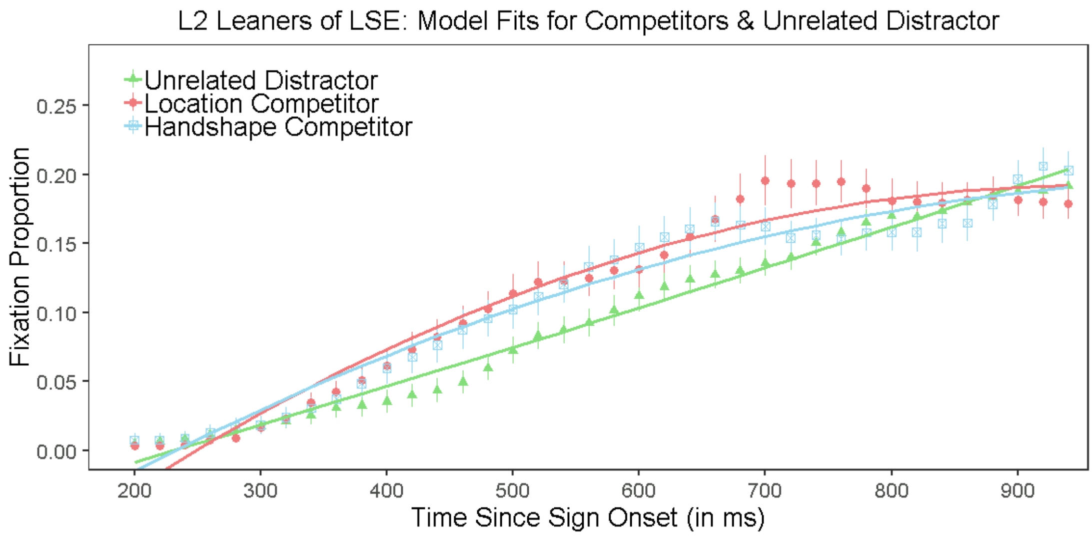


Figure 11. Model fit for looks to location (red) and handshape (blue) competitors and unrelated distractors (green) for L2 learners of LSE in Experiment 2: signs. Error bars show standard errors.

3.2.4 Comparison between native bimodal bilinguals and L2 learners for each competitor

To compare location and handshape competitor effects between the two groups, we relied on the use of two difference curves, as earlier described for the group comparison. These difference curves were modeled with a second-order (quadratic) orthogonal polynomial and fixed effects of Group on all time terms. The native group was treated as reference and parameters were estimated for the L2 learners of LSE. The model also included random effects of Participants on all time terms.

Location competitors. There was no effect of Group on the intercept, and thus no evidence of a difference in the overall proportion of looks to location competitors between native signers and L2 learners of LSE. However, there was a significant effect of Group on the linear term (*Estimate* = 0.127, *SE* = 0.061, $p = 0.038$), indicating a more positive slope for looks to location competitors over distractors in

L2 learners of LSE compared to native bimodal bilinguals, motivated by an earlier effect in the native bilinguals (see Figure 12, left panel).

Handshape competitors. There was a significant effect on the intercept (*Estimate* = -0.021, *SE* = 0.008, *p* =0.012), indicating an overall lower proportion of looks to handshape competitors by L2 learners of LSE compared to native bimodal bilinguals. There were no significant group differences on any of the time terms (see Figure 12, right panel).

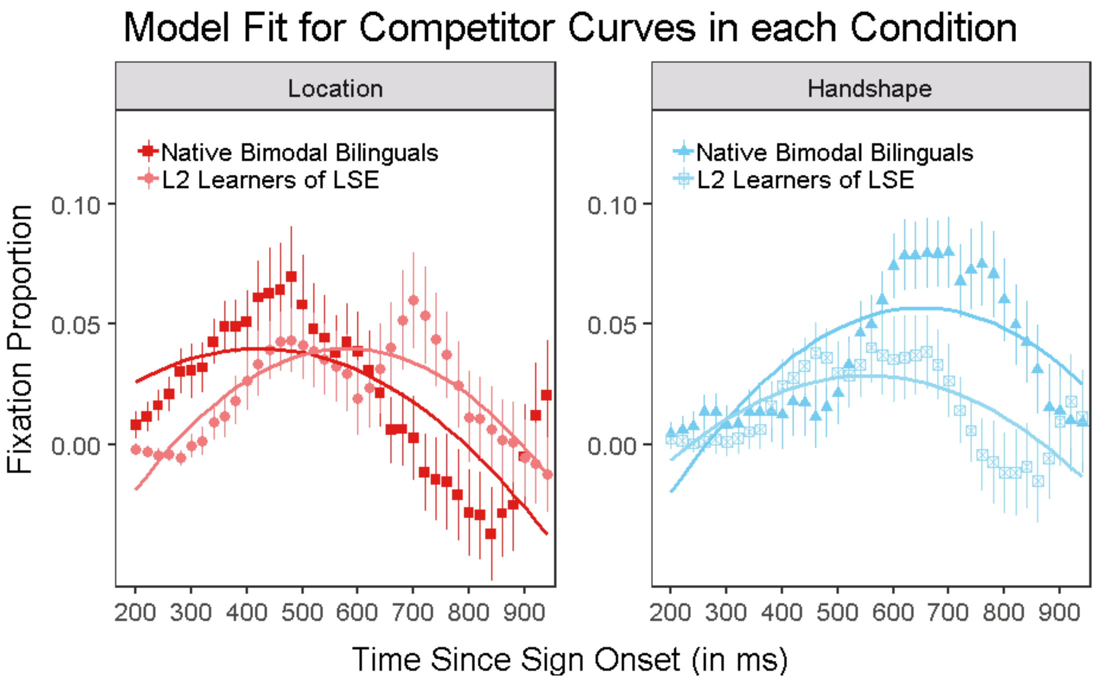


Figure 12. Model fit for location (left) and handshape (right) competitor effects in Experiment 2: signs. Error bars show standard errors.

4. General discussion

This study investigated the impact of modality-specific aspects of sub-lexical organization on spoken word and sign recognition in hearing bimodal bilinguals whose dominant language was spoken Spanish and who acquired LSE as a native language from birth or as a second language as adults.

In Experiment 1 we investigated the dynamics of spoken word recognition and found significant effects from onset and rhyme competitors compared to unrelated distractors. In line with our predictions, as the words unfolded in time increased looks were initially directed at onset competitors, and only later, towards the end of the word, were increased looks directed to rhyme competitors. In Experiment 2 we investigated the dynamics of sign recognition. Again, our expectations of competition from location and handshape were borne out by the results, with greater looks to both types of competitor compared to unrelated distractors. For native bimodal bilinguals, the results showed stronger effects for handshape compared to location; the location effect appeared earlier than the handshape effect, in line with our predictions. Although evidence for competition from both sign parameters was found for native signers as well as L2 learners of LSE, there were differences in the relative strength and the time courses of the effects between the two groups. Specifically, compared to native bimodal bilinguals, L2 learners of LSE showed later effects for location competitors and weaker effects for handshape competitors. For the L2 group, there were no reliable differences in the strength or timing of handshape and location effects.

4.1 Impact of language modality on lexical access

The results of native bimodal bilinguals across the two experiments largely confirm our central hypothesis that lexical access is conditioned by the nature of the input signal. Onset competitor effects precede (and are stronger than) rhyme competitor effects during spoken word recognition, while the co-articulation of handshape and location yields more concurrent activation of both sub-lexical parameters during sign recognition. This clearly demonstrates that language modality and the temporal dynamics of the linguistic signal impact primary recognition processes. Nevertheless, in native signers, location effects slightly preceded handshape effects, suggesting that additional factors play a role: we return to this point at the end of this section.

Our results for spoken word recognition are in line with previous findings showing earlier and stronger effects for competitors that overlap with the target in onset than in rhyme (Allopenna et al., 1998). There have been relatively few comparable studies investigating incremental processing in sign recognition. Emmorey and Corina (1990) found that deaf signers accessed location information before handshape information in a gating study. In contrast, Morford and Carlson (2011) found no differences in the number of non-target responses with the correct handshape or location in native signers in a gating task.

Recent eye-tracking studies using the visual world paradigm have further confirmed that deaf children and adults process signs incrementally and use partial information to constrain lexical recognition processes (Lieberman et al., 2014; MacDonald, LaMarr, Corina, Marchman, & Fernald, 2018; Thompson et al., 2013), despite having to divide their visual attention between the stimulus video and visual objects on the screen. However, none of these studies manipulated phonological overlap between single parameters in signs, which makes it impossible to independently assess the time course of location and handshape identification. Instead, they relied on combinations of shared parameters between target and competitors, for example, signs sharing handshape *and* location, or location *plus* movement. The unique contribution of the current study, therefore, is that we investigated the dynamics of spoken word processing and sign processing by independently manipulating onset and rhyme overlap in the spoken modality (cf. Allopenna et al., 1998; Magnuson et al., 2007), and handshape and location overlap in the signed modality. In addition, a particularly strong feature of our design is that we limited potential confounding stimulus and participant artefacts in the results by using the same experimental paradigm (visual world paradigm), group of participants (hearing bimodal bilinguals), and the same set of target items for within-modality phonological overlap (target-absent design with two competitors on the screen).

Despite the broadly simultaneous nature of the sign language signal, lexical processing appears to be incremental: location effects occurred earlier than handshape effects in hearing native bimodal bilinguals, in line with evidence from gating studies that location is identified before handshape (Emmorey & Corina, 1990). Furthermore, the temporal precedence in our results of location over handshape competitor effects reveals that the temporal course of sign processing may not follow the temporal order of the signal. In our stimuli, handshape appeared slightly before location during the production of the signs (by around 80 ms on average – see section 2.2.2) and this temporal order has been reported for other sign languages (Hosemann, Herrmann, Steinbach, Bornkessel-Schlesewsky, & Schlesewsky, 2013). In the remainder of the discussion, we will consider several other differences between the two phonological parameters that may account for this finding.

4.2 The role of different phonological parameters in sign recognition

Another aim of the current study was to gain further insight into the role of handshape and location information in sign recognition. Several previous studies have found contrasting effects for phonological overlap in handshape and location in psycholinguistic tasks, for example, phonological priming studies in comprehension (e.g., Carreiras et al., 2008; Corina & Emmorey, 1993: Dye & Shih, 2006; Gutiérrez et al., 2012; Mayberry & Witcher, 2005) and picture-word interference studies in production (e.g., Corina & Hildebrandt, 2002; Baus, Gutiérrez-Sigut, Quer, & Carreiras, 2008, Baus, Gutiérrez, & Carreiras, 2014). A common pattern across these studies is the observation of facilitatory effects for handshape overlap, but inhibitory effects for location overlap. Unfortunately, methodological differences between these studies have made it difficult to explain the divergent results, such as the language profile of the participants (deaf native signers or late first language learners), how the phonological parameters were manipulated (independently or in combination), and variation in stimulus timing and control.

A notable exception is a recent computational study by Caselli and Cohen-Goldberg (2014). Based on an existing computational model, they simulated the activation dynamics of sub-lexical units in a lexical network while varying 1) the temporal order of sign perception; 2) the robustness of location and handshape encoding (indexed through the level of resting activation); and 3) the number of lexical neighbors sharing handshape or location units. Their simulations showed that earlier perception and a higher resting activation of location could both account for the often-reported combination of facilitatory effects of handshape overlap and inhibitory effects of location overlap in phonological priming, respectively.

In line with the observations by Caselli and Cohen-Goldberg (2014), our results provide empirical support for earlier activation of location information than handshape information in native signers during sign recognition. Conversely, our results do not appear to corroborate higher resting activation of location; on the contrary, handshape competitors showed a stronger effect. This is not incompatible with Caselli and Cohen-Goldberg's claims: their findings suggest that either factor could account for the pattern of activation, and our results point toward one factor but not the other. Nevertheless, we cannot fully rule out higher resting activation of location: the model aims to explain differential priming effects of location and handshape, and our data come from a very different task and experimental paradigm. Greater looks to handshape competitors may reflect the facilitatory nature of handshape, and thus this particular finding could represent a replication of the facts that Caselli and Cohen-Goldberg attempt to explain rather than insight into the underlying mechanism. Reconciling and integrating findings from different paradigms is a goal for future research.

Higher resting activation for location information in signs could be due to higher sub-lexical frequency (in most sign languages there are fewer possible sign locations than hand configurations) or enhanced perceptual saliency of location information. As mentioned in section 4.1, perceptual saliency has been proposed as a motivating factor in the lexical processing of signs to explain differences between phonological parameters. Handshape is not very prominent perceptually, whereas location, especially in combination with movement, is perceptually more salient (Brentari, 2006; Corina & Hildebrandt, 2002; Hildebrandt & Corina, 2002; Dye & Shih, 2006; Thompson et al., 2013). A study in BSL using the visual world paradigm found evidence of effects only from competitors that shared both location and movement with the target sign (Thompson et al., 2013). In contrast, competitors that shared location and handshape or handshape and movement did not yield reliable effects. Since movement and location are the most salient parameters of the visual signal, the authors concluded that sign language processing is driven by saliency constraints and not by temporal factors relating to the order in which each parameter appears or is perceived in the signal.

Our results do not fully align with this interpretation: hearing bimodal bilinguals (including the L2 learners) showed effects from handshape competitors, contrary to the BSL findings. Nonetheless, there are differences between the two studies that might account for the divergent findings. Firstly, Thompson and colleagues paired sub-lexical units as competitors while we examined the effect of each parameter separately. Furthermore, the two studies tested different groups of signers (deaf vs. hearing) and languages (BSL vs. LSE), which further makes a direct comparison of the findings difficult. However, our study clearly demonstrates that lexical access in a sign language is not always driven by the saliency of the sub-lexical units.

4.3 Age of acquisition effects in sign recognition

Hearing second language learners of sign language showed effects for both types of phonological competitor (location and handshape), and these effects were modulated by age of acquisition when compared to those of the native bimodal bilinguals.

Firstly, native bimodal bilinguals showed significantly stronger handshape competitor effects compared to L2 learners of LSE. This may reflect differences in phonological processing conditioned by age of acquisition, and is in line with previous work that demonstrates that handshape is particularly problematic for L2 learners of the signed language (Carreiras et al., 2008; Orfanidou et al., 2009). This apparent complexity of handshape compared to location is also reflected in acquisition and learning studies. During infant acquisition, location is acquired before handshape, whether the child is deaf or hearing (Conlin, Mirus, Mauk, & Meier, 2000; Karnopp, 2002; Marentette & Mayberry, 2000; Meier, 2000; Morgan, Barrett-Jones, & Stoneham, 2007; Siedlecki & Bonvillian, 1993). In adult second language learning, a similar pattern appears, with handshape being more difficult to learn than location (Bochner, Christie, Hauser, & Searls, 2011; Ortega, 2013; Ortega & Morgan, 2015).

Handshape is also the most affected parameter in sign language aphasia (Corina, 2000). All this evidence points to the fact that the acquisition and/or processing of handshape is somehow more challenging than the processing of location, and benefits from native experience. The difficulty associated with handshape may be due to various reasons. Firstly, handshape is made up of more complex information: phonological models (such as Brentari, 1998) posit more features to specify handshape in comparison with location, and those features tend to have a larger set of possible values for handshape compared to location. This has a knock-on effect for the other properties of these sub-lexical units which are also relevant to processing. The wider range of values for handshape features means that a larger number of handshapes exist in the phonological repertoire of a given language. As a result, handshapes tend to have lower sub-lexical frequencies than locations.

Secondly, handshape involves smaller articulators, namely, the fingers and their joints, compared to location, which takes in the head, the upper body and the non-dominant hand. This leads to greater articulatory complexity in production and reduced perceptual saliency during comprehension. This factor may account for the challenging nature of handshape during developmental acquisition. However, the finding that L2 signers discriminate more handshapes but have less categorical perception compared to native signers (Morford et al., 2008) suggests that their difficulty with handshape is related to mapping the visual signal onto phonological categories over and above perceiving the visual signal itself. Results from our study also point away from the role of perceptual saliency: one might expect L2 learners to make greater use of location as a perceptually more salient parameter, yet the L2 learners did not show any greater reliance on location (either with respect to handshape, or compared to native signers).

The second characteristic of L2 signers is that effects from location competitors occurred later compared to native bimodal bilinguals. One possible explanation for this may lie in the visual nature of the sign signal and the predictive abilities of native signers. In the linguistic signal of a signed language, the hands move through space as they articulate different signs. Transition movements take the hands from the location of one sign to that of the next. As already noted, during such transition movements, the new handshape is often fully formed before the hand reaches the new location: in our stimuli, the average onset of handshape was around 80 ms prior to that of location. Thus, handshape appears in the signal before location does. However, before the hand arrives at the new location, information about that location may be available from the direction of the transition movement. This allows the observer to predict the location of the sign and to integrate this information during lexical access. Our results for native signers concur with previous gating work in showing that the order of processing does not match the temporal ordering of the signal (see section 4.1), and this may occur because of the information that is available during the transition movement. Location itself appears after handshape, but cues about location are available earlier. Furthermore, recent ERP work (on German Sign Language) has shown that native signers use the transition movement to create predictive models of the upcoming signs (Hosemann et al., 2013), including information about location (Hänel-Faulhaber et al., 2014). While native signers may generate predictions about location based on the transition movement, leading to early location effects, L2 learners of the signed language may not be able to make use of this information, perhaps because of an inability to capture the cues in the transition movement or reduced phonological sensitivity.

We propose that processing during sign recognition is driven by an interaction between linguistic principles (such as knowledge of the phonological categories of the language) and characteristics of the visual signal (such as relatively long and informative transitions into signs) rather than purely perceptual properties such as saliency. This accounts for native bimodal bilinguals' strong handshape effects (due to natively acquired phonological categories) and early location effects (due to the ability to create predictions from transitional cues) compared with L2 learners.

Finally, our findings come with a caveat: the possibility that there were confounding differences between the native bilinguals and L2 learners, a somewhat unavoidable characteristic of the special population under study. Specifically, the age of acquisition effects found in the current study could also be partly driven by proficiency differences. There is currently no objective measure to assess LSE proficiency and instead we had to rely on self-evaluations by the participants. To ensure that our participants were highly proficient in LSE, we recruited professionals who used LSE on an everyday basis, mostly as sign language interpreters. Furthermore, two measures from the study indicate no differences in the performance of the two groups: the response times on the filler trials (for which a target was present) and the amount of time spent looking at the video before moving eye gaze to the images.

5. Conclusions

Our results demonstrate that the dynamics of language modality impact lexical access. Sequentiality in the unfolding spoken signal is evident in the word recognition process, as onset and rhyme effects follow each other and are conditioned by the auditory information as it becomes available. The availability of simultaneous sub-lexical information in signed languages influences sign recognition, but other factors enter into play, namely, differences between location and handshape processing arising from the linguistic properties of these sub-lexical parameters and from affordances of the visual modality, in which transition movements are informative. These mechanisms are coherent with the effects of age of acquisition on signed lexical access. Compared to native signers, second language learners of LSE showed weaker effects from handshape competitors, reflecting less robust phonological representations of this complex parameter, and later effects from location competitors, due to reduced sensitivity to early location cues during the transition movements.

Supplementary Material

Raw data and scripts for the analysis are available in an online repository (DOI 10.17605/OSF.IO/XS9EN)

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participants. The experiment was approved by the BCBL Ethics Review Board and complied with the guidelines of the Helsinki Declaration.

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Appendix A. Critical trials

Table A1

Target words, onset and rhyme competitors in critical trials from Experiment 1: Spanish (English translations in brackets)

Target Word	Onset Competitor	Rhyme Competitor
papa (pope)	pala (shovel)	mapa (map)
hueso (bone)	huella (fingerprint)	queso (cheese)
tejado (roof)	tetera (teapot)	cuadrado (square)
policía (police)	pozo (well)	sandía (watermelon)
galleta (cookie)	gallina (chicken)	raqueta (tennis racket)
dinero (money)	dinosaurio (dinosaur)	sombrero (hat)
tacón (heel)	taladro (drill)	limón (lemon)
sopa (soup)	sobre (envelope)	copa (glass)
mesa (table)	médico (doctor)	fresa (strawberry)
cuñado (brother-in-law)	cuchara (spoon)	pescado (fish)
paso (step)	pavo (turkey)	vaso (glass)
estrella (star)	espada (sword)	botella (bottle)
palabra (word)	patín (roller-skate)	cabra (goat)
maleta (suitcase)	marinero (sailor)	cometa (kite)
bota (boot)	bolo (bowling pin)	gota (drop)
manzana (apple)	manguera (hose)	campana (bell)
noche (night)	novia (bride)	coche (car)
piscina (swimming pool)	pistola (gun)	cocina (stove)
persona (person)	perchero (coat stand)	fregona (mop)
cerilla (match)	cebra (zebra)	bombilla (lightbulb)
foto (photo)	foca (seal)	moto (motorcycle)
cama (bed)	caja (box)	rama (branch)
cielo (sky)	ciego (blind man)	pelo (hair)
patata (potato)	paraguas (umbrella)	corbata (tie)
calculadora (calculator)	calcetines (socks)	batidora (beater)
lazo (bow)	lata (can)	brazo (arm)
toalla (towel)	tobogán (slide)	medalla (medal)
nudo (knot)	nube (cloud)	embudo (funnel)

Table A2

Target signs, location and handshape competitors in critical trials from Experiment 2: Spanish Sign Language

For Type: T = target, HS = handshape competitor, LOC = location competitor.

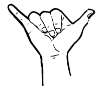
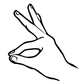
For handshape, the images show the shared handshape of the target and competitor (left) and the handshape of location competitor (right).

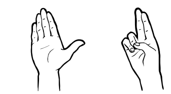
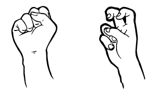
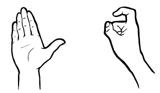
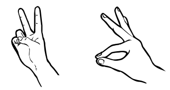
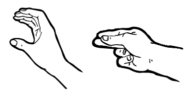
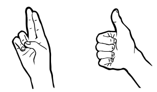
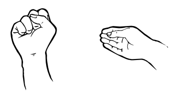
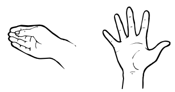
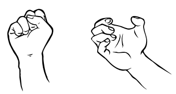
The handshape font was created by CSLDS, CUHK, and is available on-line: http://www.cslds.org/v3/resources.php?id=1.

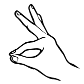
For selected fingers: i=index, m=middle, r=ring, p=pinkie, t=thumb.

Phonological coding is based on Brentari (1998).

Type	Sign	English	Location		Handshape				Movement	
			Major	Minor		Selected fingers	Joints	Flex	Path	Internal
T	PAYASO	clown	Head	Nose	 	imrp	BASE+NONBASE	Ø	Straight	No
HS	PIE	foot	Head	Nose		im	Ø	Ø	Straight	Yes
LOC	GRIFO	faucet	Neutral-space	-		imrp	BASE+NONBASE	Ø	-	Yes
T	RAYO	lightning	Passive-hand	Finger-tip	 	i	Ø	Ø	Zig-zag	No
HS	MOLINO	windmill	Passive-hand	Finger-tip		imrp	spread	Ø	-	Yes
LOC	MÚSICA	music	Neutral-space	-		i	Ø	Ø	Curved	No
T	PERIÓDICO	newspaper	Passive-hand	Palm	 	imrp	Ø	Ø	Straight	No
HS	TENEDOR	fork	Passive-hand	Palm		im	spread	Ø	Straight	No
LOC	MARIPOSA	butterfly	Neutral-space	-		imrp	Ø	Ø	-	Yes
T	TORTUGA	turtle	Passive-hand	Back	 	imrp	Ø	Ø	-	Yes
HS	TANQUE	tank	Passive-hand	Back		i	Ø	Ø	Straight	No
LOC	ÁNGEL	angel	Body	Upper		imrp	Ø	Ø	-	Yes
T	GATO	cat	Passive-hand	Back	 	imrp	NONBASE	Ø	Curved	Yes
HS	PUERTA	door	Passive-hand	Back		imrp	Ø	Ø	-	Yes
LOC	GUITARRA	guitar	Body	Mid		imrp	NONBASE	Ø	Curved	No

T	VINO	wine	Head	Nose			t	Ø	Ø	Straight	Yes
HS	BRUJA	witch	Head	Nose			imrp	BASE+NONBASE	flex	Curved	Yes
LOC	BOLSO	purse	Body	Shoulder			t	Ø	Ø	Curved	No
T	BURRO	donkey	Head	Top			imrp	Ø	Ø	-	Yes
HS	CUERNOS	horns	Head	Top			p	spread	Ø	Straight	Yes
LOC	CASA	house	Neutral-space	-			imrp	Ø	Ø	Straight	No
T	SETA	mushroom	Passive-hand	Finger-tip			imrp	BASE+NONBASE	Ø	Straight	No
HS	CRUZ	cross	Passive-hand	Finger-back			i	Ø	Ø	Straight	No
LOC	RADIO	radio	Head	Ear			imrp	BASE+NONBASE	Ø	-	Yes
T	MUJER	woman	Head	Ear			i	BASE	flex	-	Yes
HS	MÓVIL	cell phone	Head	Ear			i	Ø	Ø	Straight	No
LOC	TÉ	tea	Neutral-space	-			i	BASE	flex	Straight	No
T	LUPA	magnifying glass	Head	Eye			i	cross	Ø	Straight	No
HS	LÁGRIMA	tear	Head	Eye			i	Ø	Ø	Straight	Yes
LOC	CREMALLERA	zipper	Body	Mid			i	cross	Ø	Straight	Yes
T	PIPA	pipe	Head	Mouth			p	spread	Ø	Straight	No
HS	PÁJARO	bird	Head	Mouth			i	BASE	flex	-	Yes
LOC	AVIÓN	airplane	Neutral-space	-			p	spread	Ø	Straight	No
T	COLEGIO	school	Head	Mouth			imrp	Ø	Ø	Circular	No
HS	DIENTE	tooth	Head	Mouth			i	BASE+NONBASE	Ø	Straight	No
LOC	JAMÓN	ham	Body	Lower			imrp	Ø	Ø	Curved	Yes
T	VIRGEN	virgin	Body	Upper			m	BASE	Ø	Straight	No
HS	GORILA	gorilla	Body	Upper			imrp	Ø	flex	Straight	No
LOC	ARROZ	rice	Passive-hand	Palm			m	BASE	Ø	-	Yes
T	HELADO	ice cream	Head	Mouth			i	cross	Ø	Circular	No
HS	PERRO	dog	Head	Mouth			imrp	BASE	flex	Straight	Yes
LOC	PEINE	comb	Head	Top			i	cross	Ø	-	Yes

T	CERVEZA	beer	Passive-hand	Radial		imrp	∅	∅	Curved	No
HS	TOMATE	tomato	Passive-hand	Radial		im	∅	∅	Circular	No
LOC	FALDA	skirt	Body	Waist		imrp	∅	∅	Straight	No
T	FRUTA	fruit	Head	Cheek		imrp	∅	flex	-	Yes
HS	MAQUINILLA	razor	Head	Cheek		im	NONBASE	∅	Straight	No
LOC	PLANCHA	iron	Neutral-space	-		imrp	∅	flex	Straight	No
T	BANDERA	flag	Passive-hand	Finger-tip		imrp	∅	∅	-	Yes
HS	PERCHA	hanger	Passive-hand	Finger-front		i	BASE+NONBASE	∅	Straight	No
LOC	LIBRO	book	Neutral-space	-		imrp	∅	∅	-	Yes
T	CEREZA	cherry	Head	Ear		im	spread	∅	Straight	No
HS	PENDIENTE	earring	Head	Ear		i	BASE	∅	0	Yes
LOC	CIGARRO	cigarette	Head	Mouth		im	spread	∅	Straight	No
T	ASCENSOR	elevator	Passive-hand	Palm		imrp	BASE+NONBASE	∅	Straight	No
HS	RANA	frog	Passive-hand	Palm		im	BASE	flex	Straight	Yes
LOC	AUTOBÚS	bus	Neutral-space	-		imrp	BASE+NONBASE	∅	Straight	No
T	CHOCOLATE	chocolate	Head	Cheek		im	BASE	∅	-	Yes
HS	EMBARAZO	pregnancy	Head	Cheek		t	∅	∅	Curved	No
LOC	PEZ	fish	Neutral-space	-		im	BASE	∅	Straight	Yes
T	ZANAHORIA	carrot	Head	Mouth		imrp	∅	flex	Straight	No
HS	PATO	duck	Head	Mouth		imrp	BASE	flex	-	Yes
LOC	HORCA	gallows	Body	Neck		imrp	∅	flex	Straight	No
T	CAMELLO	camel	Neutral-space	-		imrp	BASE	flex	Circular	No
HS	ÁRBOL	tree	Neutral-space	-		imrp	spread	∅	-	Yes
LOC	PLÁTANO	banana	Passive-hand	Finger-tip		imrp	BASE	flex	Curved	Yes
T	FARMACIA	pharmacy	Passive-hand	Palm		imrp	∅	flex	Circular	No
HS	FLAN	crème caramel	Passive-hand	Palm		imrp	BASE+NONBASE	∅	-	Yes
LOC	PANTALÓN	pants	Body	Waist		imrp	∅	flex	Curved	No

T	DEPORTE	sport	Arm	Forearm-back	 	i	Ø	Ø	Straight	No
HS	BEBÉ	baby	Arm	Forearm-front		imrp	BASE	flex	Curved	No
LOC	BRÚJULA	compass	Passive-hand	Palm		i	Ø	Ø	-	Yes
T	VENTANA	window	Arm	Forearm-ulnar	 	imrp	Ø	flex	Straight	No
HS	REGLA	ruler	Arm	Foreram-back		i	BASE	flex	Straight	No
LOC	ESCOBA	broom	Neutral-space	-		imrp	Ø	flex	Curved	Yes
T	BORRACHO	drunkard	Head	Nose	 	imrp	Ø	flex	-	Yes
HS	RINOCERONTE	rhinoceros	Head	Nose		p	spread	Ø	Straight	No
LOC	CINTURÓN	belt	Body	Waist		imrp	Ø	flex	Straight	No
T	HELICÓPTERO	helicopter	Passive-hand	Finger-tip	 	imrp	spread	Ø	-	Yes
HS	ANTENA	antenna	Passive-hand	Finger-tip		im	spread	Ø	Straight	No
LOC	CIERVO	deer	Head	Top		imrp	spread	Ø	Straight	No
T	GORRA	cap	Head	Forehead	 	i	NONBASE+cross	Ø	Straight	No
HS	VACA	cow	Head	Forehead		ip	Ø	Ø	-	Yes
LOC	LLAVES	key	Neutral-space	-		i	NONBASE+cross	Ø	-	Yes

Appendix B: Results

Experiment 1: words

All participants

See main article for a description of the results for this group.

Table S1

Parameter estimates for growth curve analysis of onset competitor (200-420ms time window) for native bimodal bilinguals and L2 learners of LSE

	Estimate	*Std. Error*	*t*	*p*
Intercept	0.212	0.008	25.749	0.000
Linear	-0.042	0.016	-2.630	0.009
Onset : Intercept	0.035	0.011	3.281	0.001
Onset : Linear	0.102	0.023	4.527	0.000

Table S2

Parameter estimates for growth curve analysis of rhyme competitor (440-820ms time window) for native bimodal bilinguals and L2 learners of LSE

	Estimate	*Std. Error*	*t*	*p*
Intercept	0.203	0.006	35.863	0.000
Linear	0.053	0.021	2.531	0.011
Rhyme : Intercept	0.025	0.007	3.375	0.000
Rhyme : Linear	0.064	0.030	2.181	0.029

Table S3

Parameter estimates for growth curve analysis (200-820ms time window) to compare onset (reference) and rhyme competitors for all participants

	Estimate	*Std. Error*	*t*	*p*
Intercept	0.238	0.006	42.244	0.000
Linear	-0.084	0.031	-2.706	0.007
Quadratic	-0.119	0.024	-4.892	0.000
Rhyme : Intercept	-0.030	0.007	-4.173	0.000
Rhyme : Linear	0.255	0.042	6.108	0.000
Rhyme : Quadratic	0.169	0.034	4.921	0.000

Experiment 2: signs

See main article for a description of the results for this experiment.

Group comparison

Table S4

Parameter estimates for growth curve analysis including Competitor type (location versus handshape) and Group (native bimodal bilinguals versus L2 learners of LSE). This analysis uses sum coding to show main effects of each contrast.

	Estimate	*Std. Error*	*t*	*p*
Intercept	0.022	0.003	6.857	0.000
Linear	-0.008	0.024	-0.348	0.727
Quadratic	-0.089	0.021	-4.213	0.000
Competitor : Intercept	0.002	0.002	0.959	0.337
Group : Intercept	0.005	0.003	1.546	0.121
Competitor : Linear	0.043	0.015	2.739	0.006
Competitor : Quadratic	0.002	0.016	0.131	0.895
Group : Linear	-0.008	0.024	-0.328	0.742
Group : Quadratic	0.001	0.021	0.063	0.949
Competitor : Group : Intercept	0.005	0.002	1.901	0.057
Competitor : Group : Linear	0.055	0.015	3.521	0.000
Competitor : Group : Quadratic	-0.014	0.016	-0.862	0.388

Native bimodal bilinguals

Table S5

Parameter estimates for growth curve analysis of Location and Handshape Competitors (compared to unrelated distractors) for native bimodal bilinguals

	Estimate	*Std. Error*	*t*	*p*
Intercept	0.102	0.007	14.438	0.000
Linear	0.359	0.032	11.069	0.000
Quadratic	-0.020	0.029	-0.715	0.474
Location : Intercept	0.019	0.006	3.007	0.002
Handshape : Intercept	0.036	0.006	5.503	0.000
Location : Linear	-0.115	0.045	-2.556	0.010
Handshape : Linear	0.082	0.045	1.821	0.068
Location : Quadratic	-0.076	0.039	-1.941	0.052
Handshape : Quadratic	-0.100	0.039	-2.553	0.010

Table S6

Parameter estimates in growth curve analysis to compare location and handshape (reference) competitors for native bimodal bilinguals

	Estimate	*Std. Error*	*t*	*p*
Intercept	0.138	0.007	18.249	0.000
Linear	0.441	0.035	12.275	0.000
Quadratic	-0.121	0.034	-3.528	0.000
Location : Intercept	-0.016	0.007	-2.166	0.030
Location: Linear	-0.197	0.047	-4.174	0.000
Location : Quadratic	0.024	0.046	0.512	0.608

L2 learners of LSE

Table S7

Parameter estimates for growth curve analysis of Location and Handshape competitors (compared to unrelated distractors) for L2 learners of LSE

	Estimate	*Std. Error*	*t*	*p*
Intercept	0.095	0.006	14.116	0.000
Linear	0.388	0.025	15.113	0.000
Quadratic	0.005	0.026	0.219	0.829
Location : Intercept	0.020	0.007	2.854	0.004
Handshape : Intercept	0.014	0.007	2.097	0.036
Location : Linear	0.011	0.036	0.329	0.741
Handshape : Linear	-0.012	0.036	-0.357	0.720
Location : Quadratic	-0.107	0.034	-3.140	0.001
Handshape : Quadratic	-0.074	0.034	-2.182	0.029

Table S8

Parameter estimates for growth curve analysis to compare location and handshape (reference)competitors for L2 learners of LSE

	Estimate	*Std. Error*	*t*	*p*
Intercept	0.110	0.007	14.935	0.000
Linear	0.375	0.028	13.260	0.000
Quadratic	-0.068	0.027	-2.471	0.013
Location : Intercept	0.005	0.008	0.658	0.510
Location: Linear	0.024	0.038	0.637	0.524
Location : Quadratic	-0.032	0.034	-0.942	0.346

Comparison between groups for each competitor

Table S9

Parameter estimates for growth curve analysis of location competitors comparing native bimodal bilinguals (reference level) and L2 learners of LSE

	Estimate	*Std. Error*	*t*	*p*
Intercept	0.019	0.006	3.070	0.002
Linear	-0.115	0.043	-2.647	0.008
Quadratic	-0.076	0.042	-1.808	0.070
L2 learners of LSE : Intercept	0.000	0.009	0.066	0.946
L2 learners of LSE : Linear	0.127	0.061	2.064	0.038
L2 learners of LSE : Quadratic	-0.031	0.059	-0.521	0.602

Table S10

Parameter estimates for growth curve analysis of handshape competitors comparing native bimodal bilinguals (reference level) and L2 learners of LSE

	Estimate	*Std. Error*	*t*	*p*
Intercept	0.036	0.005	6.051	0.000
Linear	0.082	0.038	2.125	0.033
Quadratic	-0.100	0.033	-3.001	0.002
L2 learners of LSE : Intercept	-0.021	0.008	-2.507	0.012
L2 learners of LSE : Linear	-0.095	0.054	-1.737	0.082
L2 learners of LSE : Quadratic	0.025	0.047	0.543	0.586