Main Manuscript for

Cross-modal and cross-language activation in bilinguals reveals lexical competition even when words or signs are unheard or unseen

Saul Villameriel*[1], Brendan Costello*[1], Marcel Giezen[1] and Manuel Carreiras[1,2,3].

[1]Basque Center on Cognition, Brain and Language, 20009 Donostia-San Sebastián, Spain

[2]Departamento de Lengua Vasca y Comunicación, UPV/EHU, 48940 Leioa, Spain

[3]Ikerbasque, Basque Foundation for Science, 48013 Bilbao, Spain

*Saúl Villameriel, Brendan Costello (corresponding authors and equal contribution)

Email: s.villameriel@bcbl.eu, b.costello@bcbl.eu

Author Contributions: S.V., B.C. and M.C. conceived and designed the experiment; S.V. carried out the data collection; S.V. processed and analyzed the data under the guidance of M.G.; S.V., B.C., M.G. and M.C. interpreted the data; S.V. wrote the first manuscript; B.C., M.G. and M.C. revised the manuscript. All authors reviewed the manuscript.

Competing Interest Statement: The authors declare no competing interests.

Classification: Social Sciences; Psychological and Cognitive Sciences.

Keywords: language co-activation, bimodal bilingualism, modality, lexical access, sub-lexical competition, visual world paradigm.

This PDF file includes:

Abstract
Significance Statement
Main Text with figures and tables in place
Supplementary information

Abstract

We exploit the phenomenon of cross-modal, cross-language activation to examine the dynamics of language processing. Previous within-language work showed that seeing a sign co-activates phonologically-related signs, just as hearing a spoken word co-activates phonologically-related words. In this study, we conducted a series of eye-tracking experiments using the visual world paradigm to investigate the time-course of cross-language co-activation in hearing bimodal bilinguals (Spanish-Spanish Sign Language) and unimodal bilinguals (Spanish-Basque). The aim was to gauge whether (and how) seeing a sign could co-activate words, and, conversely, hearing a word could co-activate signs, and how such cross-language co-activation patterns differ from within-language co-activation. The results revealed cross-language, cross-modal activation in both directions. Furthermore, comparison with the previous findings of within-language lexical co-activation for spoken and signed language shows how the impact of temporal structure changes in different modalities. Spoken word activation follows the temporal structure of that word only when the word itself is heard; for signs, the temporal structure of the sign does not govern the time course of lexical access (location co-activation precedes handshape co-activation) – even when the sign is seen. We provide evidence that, instead, this pattern of activation is motivated by how common in the lexicon the sub-lexical units of the signs are. These results reveal the interaction between the perceptual properties of the explicit signal and structural linguistic properties. Examining languages across modalities illustrates how this interaction impacts language processing.

Significance Statement

When a word is activated, is it like hearing that word in your head? This study broadens our understanding of the cognition of language by exploiting the phenomenon of cross-modal, cross-language activation. Using eye-tracking and analyses of looking patterns over time, we characterize the temporal properties of language co-activation between spoken and signed languages in a sample of native bimodal bilinguals. The findings provide new insight into the time-course of lexical activation in spoken and signed language, but also into the nature of language processing: the mental representation of a word/sign is not tied to the temporal structure of that word/sign. Activating a word is not the same as replaying that word in your head.

Main Text

Introduction

Words exist in relation to one another. In the mental lexicon, the activation of one word may co-activate other similar words, where similarity between words depends on common sub-lexical units, such as shared word onset or rhyme, or a relation in meaning. For bilinguals, such co-activation extends across similarsounding words in the other language or shared semantics, when the word of one language co-activates the corresponding word ('translation') in the other language. In this study, we take this one step further, by studying cross-language activation in a setting in which there is no possibility of similarity in form between a bilingual's two languages.

Bimodal bilinguals are individuals who are proficient in a spoken language, which avails of the auditory-oral modality, and a signed language, which uses the visual-gestural modality. This difference in modality impacts the phonological organization of words and signs. While spoken words are formed principally by the sequential concatenation of phonemes, the sub-lexical units of signs appear simultaneously. Signs are made up of handshapes (the form the hands adopt) and locations (the part of the upper body or the signing space in front of the signer where the hand articulates the sign), in addition to other sub-lexical units that form the phonological repertoire of sign languages(1, 2). Handshape and location are present simultaneously during the articulation of the sign. Importantly, a signed and a spoken language have no overlap in phonological form: a Japanese word may sound like an English one, but words and signs cannot sound or look like each other. Bimodal bilingualism allows us to investigate sub-lexical co-activation in the absence of any overlap in form between the languages: *what does word or sign activation look like when words or signs are not heard or seen?*

A large body of research has shown that bilinguals of two (or more) spoken languages access words in parallel in both languages when they speak or process input in one language (reading words(3, 4); reading sentences(5); hearing words(6, 7); naming pictures: (8, 9)). In many of these studies, non-selective access to words in both languages is driven by phonological ambiguity in the input(10–13), that is, words from different languages that sound alike. Additionally, there is evidence for cross-language co-activation between two spoken languages in the absence of overt phonological overlap ('phonologically covert co-activation')(14). In a visual world paradigm, English-Spanish bilinguals looked more to the image of a shovel than to unrelated distractors when asked to click on an image of a duck. The word 'duck' activates its Spanish translation 'pato', which in turn co-activates the Spanish phonologically-overlapping word 'pala' and its English translation equivalent 'shovel'. Thus, in addition to co-activation of words that sound alike, bilinguals also co-activate words in different languages that have the same meaning.

Despite the different structural and physical properties of signs and words, a growing body of studies provides evidence for *cross-modal, cross-language* co-activation in bimodal bilinguals. In particular, a variety of paradigms and techniques have shown that bimodal bilinguals co-activate sign language while hearing spoken words (American Sign Language(15, 16); Spanish Sign Language(17)) or reading words (American Sign Language(18–20); German Sign Language(21)). These studies demonstrate that a word can activate a sign with the same meaning. Evidence for co-activation in the opposite direction – activation of spoken words while perceiving signs – is still relatively scarce. However, two recent studies revealed activation of the spoken language in the EEG (electroencephalogram) responses while deaf bimodal bilinguals processed signs (American Sign Language(22), German Sign Language(23)).

Co-activation in studies with bimodal bilinguals provides strong evidence that cross-language activation can take place in the absence of overlap between languages. More generally, it lets us examine the co-activation of a word (or sign) when nothing at all is heard (or seen), and to disentangle the impact of the overt linguistic signal on lexical access of words and signs. In a previous study(24) we examined the role of sub-lexical units in word recognition and in sign recognition using the visual world paradigm. In this paradigm participants are presented with a target lexical item while viewing a screen with four images, some of which are similar in form to the target item (i.e., they are phonological competitors); an eyetracker measures fixations to the different images. In Spanish, hearing a target word co-activated lexical competitors that shared onset and rhyme with the target; furthermore, the co-activation of onset was stronger and earlier than that of rhyme (in line with previous work on other spoken languages (25)). Thus, *estrella* [star] co-activated *espada* [sword] and then *botella* [bottle]. In Spanish Sign Language (LSE – *lengua de signos española*), seeing a target sign co-activated lexical competitors that shared handshape and location with the target; co-activation of handshape was stronger, but later, than that of location. The LSE sign CARROT co-activated the sign DUCK (CARROT and DUCK have the same location) and then the sign NOOSE (CARROT and NOOSE have the same handshape).

Here, we exploit the same paradigm and stimuli to examine co-activation between a signed and a spoken language looking specifically at the time course and the role of different sub-lexical units in each language (onset and rhyme in the spoken language; handshape and location in the signed language). Does seeing the LSE sign STAR also activate the Spanish words *espada* and *botella* and in the same order? In addition, does hearing the Spanish word *zanahoria* [carrot] activate the LSE signs DUCK and NOOSE, and in what order? Examining cross-modal, cross-language co-activation – co-activating words without hearing them or co-activating signs without seeing them – can reveal how lexical access is shaped by the explicit linguistic signal in one modality or the other. We carried out four experiments. Two experiments consider cross-modal, cross-language co-activation in hearing bimodal bilinguals of Spanish and Spanish Sign Language (LSE) and the other two examine cross-language co-activation in unimodal bilinguals of Spanish and Basque.

Results

Experiment 1: Cross-Modal Cross-Language Spoken Lexical Access in Bimodal Bilinguals

To investigate how cross-language co-activation of auditory sub-lexical representations is affected by the absence of a spoken linguistic signal, Experiment 1 looked at the co-activation of Spanish words while bimodal bilinguals viewed LSE signs, and at the role of word onset and rhyme during this covert co-activation.

Participants saw an LSE sign while viewing four images on the screen. Two of the images were competitors: the corresponding Spanish word overlapped in onset or rhyme with the Spanish word corresponding to the LSE sign. The other two images were unrelated distractors: the corresponding Spanish words had no overlap with the Spanish word corresponding to the LSE stimulus. (None of the LSE signs corresponding to the images bore any relation to the stimulus sign.) For example, if the LSE stimulus was STAR ('estrella' in Spanish), the onset competitor was an image representing a sword ('espada' in Spanish) and the rhyme competitor was an image of a bottle ('botella' in Spanish).

If cross-language co-activation of auditory sub-lexical representations occurs independently of a spoken linguistic signal, we expect greater looks to the competitor images compared to the unrelated distractors. In terms of the relative strength and timing of the competitor effects, we expect the pattern found for within-language competition to be maintained: onset effects are stronger and earlier than those of rhyme.

Results of Experiment 1

Accuracy rates and response times for filler trials are shown in Table 1. (The greater response times in Experiment 1 were due to the nature of the stimuli; compared to the audio word recordings used in Experiments 2-4, the sign videos were longer in duration and also included transitional movements. See Methods section and Fig. 5B for details of these stimuli. The lower accuracy rates are typical of those found in LSE lexical recognition tasks(26, 27) and reflect greater dialectal variation of a non-standardized language.)

Table 1

Behavioural measures for responses to filler trials, in which the target item was included in the images and participants had to respond. (Standard deviations in brackets)

Experiment	Group	n	Accuracy (%)	Response time (ms)
1 (LSE signs)	Spanish-LSE	28	86.7 (7.3)	2,369 (255)
2 (Basque words)	Spanish-Basque	33	98.2 (3.0)	1,612 (171)
3 (Spanish words)	Spanish-LSE	28	99.8 (1.3)	1,580 (175)
4 (Spanish words)	Spanish-Basque	25	99.7 (1.3)	1,593 (163)

Figure 1 shows the proportion of looks to onset and rhyme competitors and unrelated distractors for bimodal bilinguals, with the window of interest (200-1080 ms) based on the duration of the sign stimuli.

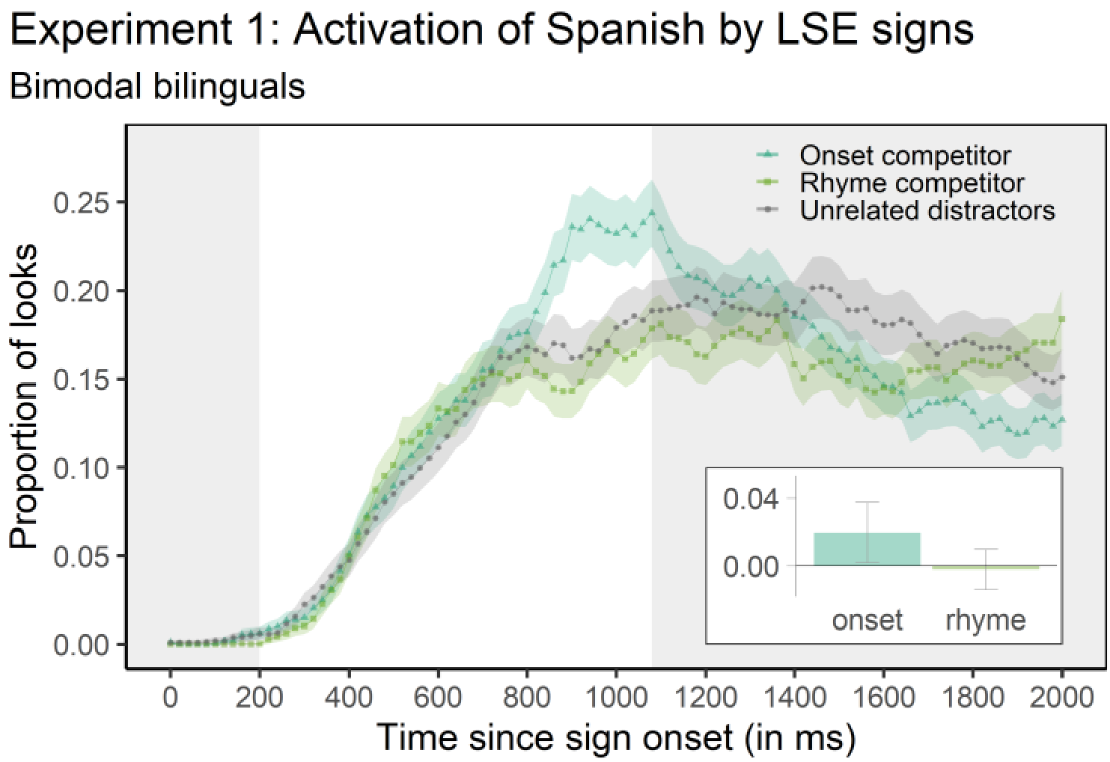

Figure 1. Proportion of looks to onset and rhyme competitors and unrelated distractors for Spanish-LSE bimodal bilinguals (n=28) from sign onset to the end of the trial (0-2000 ms). Error bands show standard error. The window of interest (200-1080 ms) is shown by a white background. Inset shows the magnitude of each competitor effect (looks to competitor minus looks to unrelated distractors) over the entire window of interest; errors bars show 95% confidence intervals.

Sub-lexical effects: onset and rhyme

Onset competitors. There was a significant effect of this competitor on the intercept term (*Estimate* = 0.020, *SE* = 0.007, *p* = .008), indicating a higher overall proportion of looks to onset competitors with respect to unrelated distractors, and on the linear term (*Estimate* = 0.137, *SE* = 0.044, *p* = .002), indicating a steeper slope for looks to onset competitors compared to unrelated distractors (see Figure 1 for model fit and Table S1a for full results).

Rhyme competitors. The analysis showed no significant effect of this competitor on the intercept or on the temporal terms, indicating that overall there was no difference in proportion of looks or in curve shape between rhyme competitors and distractors (see Figure 1 for model fit and Table S1a for full results).

Comparison of onset and rhyme competitors

There was a significant effect of Competitor type on the intercept term (Estimate = -0.022, SE = 0.008, p = .005) and on both temporal terms (linear: Estimate = -0.169, SE = 0.049, p = .001; quadratic: Estimate = -0.096, SE = 0.043, p = .027) indicating a higher overall proportion and a steeper slope of looks to onset competitors compared to rhyme distractors (see Table S1b for full results).

Summary of Experiment 1

Experiment 1 demonstrated cross-modal co-activation of Spanish sub-lexical representations in the absence of a spoken linguistic signal. While viewing LSE signs, Spanish-LSE bilinguals showed greater looks to images displaying the onset competitor of the Spanish word corresponding to the LSE sign stimulus than to unrelated images, but not to images of Spanish rhyme competitors. The previous study on within-language lexical co-activation in Spanish using the same experimental paradigm found effects for both onset and rhyme competitors(24). The absence of a rhyme effect in the current experiment could be due to the cross-language setting: in the current experiment the covert (within-language) co-activation depended on prior cross-language co-activation and this additional step may have weakened the spreading activation. In Experiment 2 we further investigated this possibility by running an adapted version of this experiment with a group of hearing Spanish/Basque bilinguals.

Experiment 2: Cross-Language Spoken Lexical Access in Unimodal Bilinguals

Experiment 1 revealed co-activation of Spanish in the absence of a spoken linguistic signal in bimodal bilinguals. To allow a comparison with covert co-activation in the presence of such a signal, in Experiment 2 we adapted the paradigm for Spanish-Basque bilinguals. Participants heard a Basque word while viewing four images on the screen. Two of the images were phonological competitors in Spanish (onset and rhyme); the other two images were unrelated distractors. (The Basque words for the four images were all unrelated to the Basque stimulus.) For example, if the Basque stimulus was 'izar' (star, 'estrella' in Spanish), the onset competitor was an image representing a sword ('espada' in Spanish) and the rhyme competitor was an image of a bottle ('botella' in Spanish). As such, this study directly investigates onset and rhyme effects (in the same trial) in cross-language activation of spoken languages.

Our expectations are similar to those of Experiment 1: cross-language co-activation will be evidenced by greater looks to competitors, with more and earlier looks to onset compared to rhyme competitors.

Results of Experiment 2

Accuracy rate and response time for filler trials are shown in Table 1. Figure 2 shows the grand average plots for the eye gaze behaviour, with the window of interest (200-860 ms) based on the duration of the stimuli.

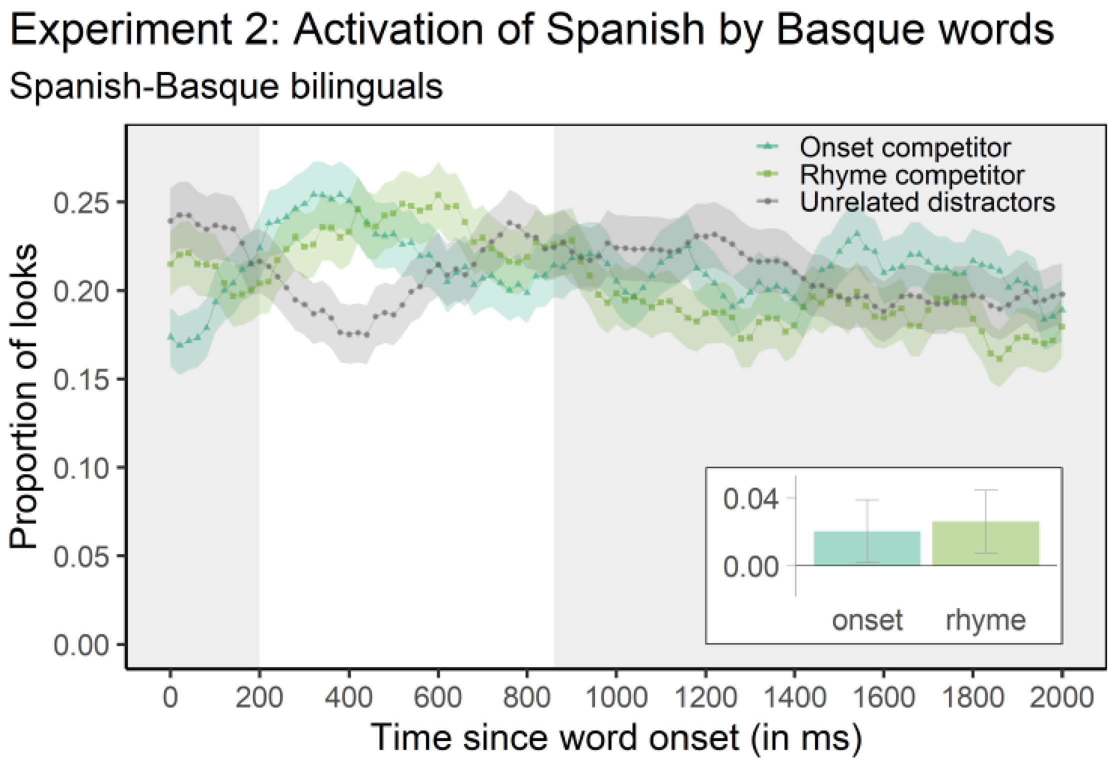

Figure 2. Proportion of looks to onset and rhyme competitors and unrelated distractors for Spanish/Basque unimodal bilinguals (n=33) from word onset to the end of the trial (0-2000 ms). Error bands show standard error. The window of interest (200-860 ms) is shown by a white background. Inset shows the magnitude of each competitor effect (looks to competitor minus looks to unrelated distractors) over the entire window of interest; errors bars show 95% confidence intervals.

Sub-lexical effects: onset and rhyme

Onset Competitors. There was a significant effect of this competitor on the intercept term (*Estimate* = 0.020, *SE* = 0.009, *p* = .025), indicating a higher overall proportion of looks to onset competitors than to unrelated distractors, and on the linear term (*Estimate* = -0.160, *SE* = 0.67, *p* = .017), indicating a different time course compared to unrelated distractors (see Figure 2 for model fit and Table S2a for full results).

Rhyme Competitors. Significant effects of this competitor on the intercept (*Estimate* = 0.026, *SE* = 0.009, *p* = .004) and on the quadratic term (*Estimate* = -0.114, *SE* = 0.053, *p* = .031), indicated a higher proportion of looks to rhyme competitors and different time course compared to unrelated distractors (see Figure 2 for model fit and Table S2a for full results).

Comparison of onset and rhyme competitors

This analysis failed to show any significant difference between looks to the onset and the rhyme competitors (see Table S2b).

Summary of Experiment 2

The results of Experiment 2 show phonologically covert co-activation between the spoken languages of unimodal bilinguals. Additionally, they provide insight into the relative strength and timing of the onset and rhyme effect: the two effects were equally strong and there was no evidence of sequentiality.

Based on previous studies of within-language co-activation(24, 25), we predicted stronger and earlier co-activation for onset compared to rhyme competitors. This was not the case, suggesting that sub-lexical co-activation might differ between within- versus cross-language contexts. In the cross-language setting, the lexical item is activated without temporal structure and the spreading co-activation no longer reflects the temporal structure of the word: onset and rhyme effects show no differences in timing or strength.

Experiment 3: Cross-Modal Cross-Language Signed Lexical Access in Bimodal Bilinguals

In lexical co-activation in LSE, signs co-activate location competitors earlier than but not as strongly as handshape competitors(24). To investigate if these findings generalize to cross-language activation of LSE, we conducted Experiment 3. Spanish-LSE bimodal bilinguals heard a Spanish word while viewing four images on the screen: two were phonological competitors in LSE (handshape and location); the other two were unrelated distractors with no overlap with the LSE sign corresponding to the Spanish word. (None of the Spanish words for the images had any overlap with the Spanish stimulus.) For example, if the Spanish stimulus was 'zanahoria' (carrot), the handshape competitor was an image of a noose (the LSE signs NOOSE and CARROT are both articulated with a closed fist handshape) and the location competitor was an image of a duck (the LSE signs DUCK and CARROT are both articulated at the mouth location).

If cross-language co-activation of signed sub-lexical representations occurs independently of the presence of a signed linguistic signal, we expect greater looks to the competitor images compared to the unrelated distractors. In terms of the relative strength and timing of the competitor effects, if the pattern found for within-language co-activation also holds here, handshape effects will be stronger but later than location effects.

Results of Experiment 3

Accuracy rates and response times for filler trials are shown in Table 1.

Figure 3 shows the proportion of looks to location and handshape competitors and unrelated distractors for bimodal bilinguals, showing the window of interest (200-860 ms) based on the duration of the stimuli.

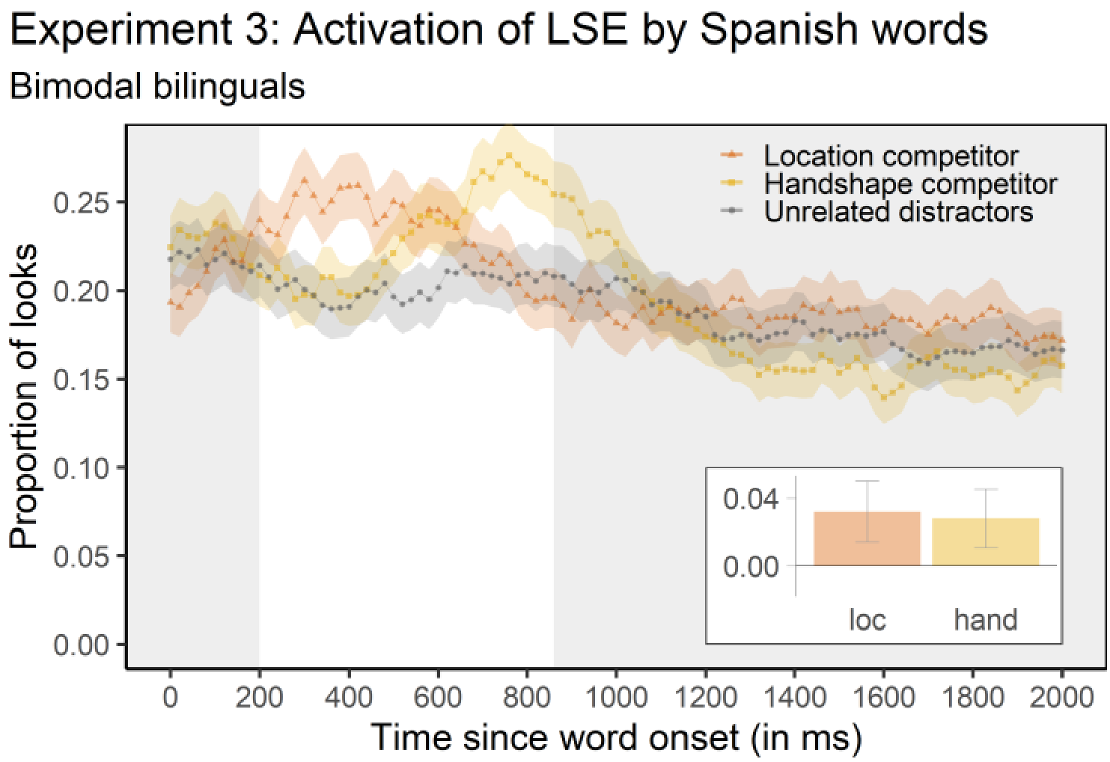

Figure 3. Proportion of looks to location and handshape competitors and unrelated distractors for bimodal bilinguals (n=28) from word onset to the end of the trial (0-2000 ms). Error bands show standard error. The window of interest (200-860 ms) is shown by a white background. Inset shows the magnitude of each competitor effect (looks to competitor minus looks to unrelated distractors) over the entire window of interest; errors bars show 95% confidence intervals.

Sub-lexical effects: location and handshape

Location competitors. A significant effect of this competitor on the intercept term (*Estimate* = 0.032, *SE* = 0.008, $p < .001$) indicated a higher overall proportion of looks to location competitors than to unrelated distractors (see Figure 3 for model fit and Table S3a for full results).

Handshape competitors. The analysis showed a significant effect of Competitor on the intercept term (*Estimate* = 0.028, *SE* = 0.008, $p = .001$), reflecting a higher overall proportion of looks to the handshape competitors than to unrelated distractors (see Figure 3 for model fit and Table S3a for full results).

Comparison of location and handshape competitors

The effect of Competitor type on the intercept term was not significant, indicating no significant difference in the proportion of looks to location and handshape competitors. The effect of Competitor type on the linear term (*Estimate* = 0.218, *SE* = 0.077, $p = .005$) indicated that looks to location competitors tended to decrease in the time window while looks to handshape competitors increased; this difference was driven by earlier looks to location relative to handshape competitors (see Table S3b for full results).

Summary of Experiment 3

The results of Experiment 3 show that the co-activation of sub-lexical presentations of the signed language is independent of the presence of an overt signed linguistic signal, and also occurs when bimodal bilinguals hear words of the spoken language. The cross-modal, cross-language activation was evidenced by greater looks to location as well as handshape competitors compared to unrelated distractors. Previous studies on parallel activation of the signed language (whether with deaf or hearing bilinguals, or whether the explicit language was written or spoken) all included sign competitors that shared more than one parameter with the target and in many cases differed in only one sub-lexical unit(15–17, 19–21, 28). This increases the likelihood of finding evidence for co-activation, but makes it difficult to assess the role of different sub-lexical units. This study shows cross-language activation of signs via a single shared parameter: either handshape or location.

In the previous study on lexical co-activation in LSE, the location effect appeared earlier than the handshape effect but was weaker(24). In the current cross-modal, cross-language experiment, the two effects showed the same relative temporal ordering (location before handshape) but did not differ in strength. Here we note that the preserved temporal ordering of the effects in overt and covert co-activation suggests that this order is not imposed by the temporal structure of the overt linguistic signal and instead likely reflects intrinsic properties of the mental lexicon. We will expand further on this finding in the Discussion section.

Experiment 4: Cross-Modal Cross-Language Signed Lexical Access in Sign Naïve Bilinguals

Our final experiment was the same as Experiment 3, but tested Spanish-Basque bilinguals with no knowledge of LSE. This served as a control to ensure that the effects we found for the bimodal bilinguals could be ascribed to cross-language activation, and not to some extraneous effect of the stimulus items.

Since the participants have no knowledge of LSE, we do not expect them to show any preference based on phonological similarity in LSE. Therefore, their looking behaviour towards handshape and location competitors should not differ from that towards unrelated distractors.

Results of Experiment 4

Accuracy rate and response time for filler trials are shown in Table 1. Figure 4 shows the grand average plots for the eye gaze behaviour.

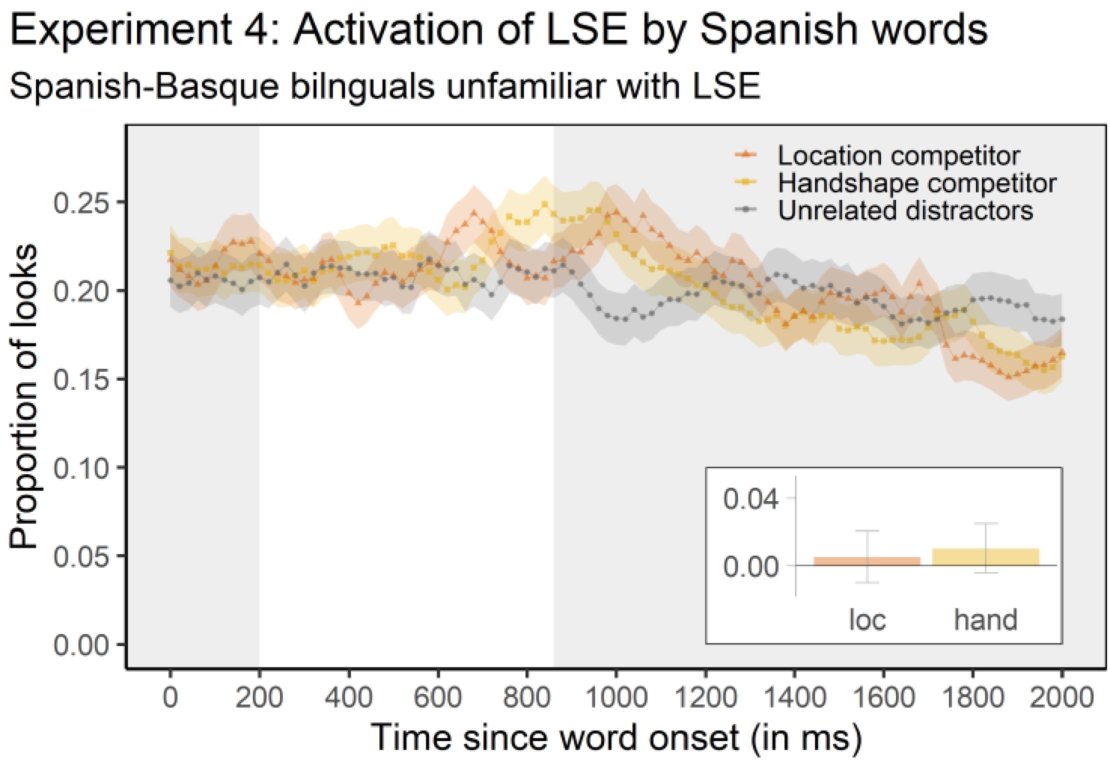

Figure 4. Proportion of looks to handshape and location competitors and unrelated distractors for Spanish/Basque unimodal bilinguals with no knowledge of LSE (n=25) from word onset to the end of the trial (0-2000 ms). Error bands show standard error. The window of interest (200-860 ms) is shown on a white background. Inset shows the magnitude of each competitor effect (looks to competitor minus looks to unrelated distractors) over the entire window of interest; errors bars show 95% confidence intervals.

Sub-lexical effects: location and handshape

The analysis did not show a significant effect of Competitor type on the intercept or on the temporal terms for either competitor, indicating that overall there was no difference in proportion of looks or in curve shapes between competitors and distractors. See Figure 4 for model fit and Table S4 for detailed results.

Summary of Experiment 4

The results of Experiment 4 confirm that individuals with no knowledge of LSE show no preference for lexical competitors based on phonological overlap in LSE. This result is self-evident – cross-language activation of a given language cannot occur if a person does not know that language – but rules out the possibility that the greater looks to competitors of the bimodal bilinguals (Experiment 3) were due to bias in the experimental material used, instead of showing cross-language activation.

Discussion

In the present study, we exploited cross-language co-activation in bilinguals to investigate how lexical access and activation of sub-lexical representations are shaped by properties of the linguistic signal and language modality. A series of experiments investigated the time course of activation of spoken and signed sub-lexical units in cross-language lexical access. Specifically, Experiments 1 and 3 looked at cross-modal cross-language co-activation, and showed activation of spoken sub-lexical representations while viewing signs (Experiment 1), and, vice versa, activation of signed sub-lexical representations while listening to spoken words (Experiment 3). Experiment 2 examined within-modal covert cross-language activation in unimodal bilinguals of Spanish and Basque, and showed activation of Spanish sub-lexical representations while hearing Basque words. Experiment 4 served as a control experiment to confirm that results from Experiment 3 were not observed in non-signers.

In contrast to spoken languages, where a word in one language can activate phonologically similar words in the other language, the phonologies of signed and spoken languages have no shared phonemes, and there is therefore no direct route from one to the other based on overlap in form. Cross-language activation between spoken languages and signed languages is instead dependent on activation of the translation equivalent of a perceived lexical item. Activation of the translation equivalent in turn leads to activation of phonologically similar items in the same language (within-language activation). Thus, the LSE sign STAR activates the Spanish word 'estrella', which can activate 'espada' (shared onset) or 'botella' (shared rhyme). Importantly, in our experimental design, the items in the explicit language (in this example, the LSE signs STAR, SWORD and BOTTLE, as well as the signs corresponding to the distractor images) are all phonologically unrelated. These co-activation effects are not the result of explicit translation strategies during the task. Each experiment included stimuli in just one of the participants' languages and in the debriefing participants were not aware of the link with the other language nor did they pick up on the cross-language competitors. The early timing of the effects also indicates that this is a fast, automatic response rather than a conscious strategy. The fact that the participants were all professional sign language interpreters (which was necessary to ensure that they were highly proficient in LSE) may have an impact on the organization of their mental lexicon and how the two languages interact. Nevertheless, co-activation of translation equivalents is widely reported in various bilingual populations(4, 14, 20) and falls more generally within semantic co-activation, which occurs in monolingual individuals. The sequential combination of semantic and phonological co-activation in STAR > 'estrella' > 'espada' has been reported for within-language contexts in the reverse direction: 'logs' > 'lock' > 'key'(29).

Experiment 1 investigated the dynamics of activation of spoken Spanish sub-lexical representations when the input was a visual LSE sign, and provided evidence for co-activation of onset representations, but not rhyme representations. Our previous study(24) on lexical co-activation in Spanish provides an informative comparison. Using the same stimuli and paradigm, the same group of participants co-activated both Spanish onset and rhyme competitors when the stimulus was presented as a Spanish word (rather than as a LSE sign). Another point of comparison comes from the results of Experiment 2, in which Basque-Spanish bilinguals co-activated both Spanish onset and rhyme competitors through Basque with no difference in magnitude or time course between the two competitors. Together, these results suggest that lexical co-activation patterns are conditioned by whether this co-activation occurs across languages or across both languages and modalities.

Similar onset and rhyme competitor effects in Spanish when activated through another spoken language (Basque) suggest that activation across languages removes the temporal ordering in lexical access. During co-activation in Spanish, hearing a (Spanish) word provides a temporally structured input that imposes sequential order on the co-activation processes: onset comes before rhyme in the input and, as a result, onset competitors are activated earlier and stronger than rhyme competitors are. In contrast, when co-activated through Basque, the lexical representation in Spanish is not incrementally activated as it would be when hearing the word itself unfolding in time. If the lexical representation of the Spanish word is activated in its entirety, such that the sub-lexical units can be simultaneously accessed, this would explain why the effects are similar in time-course and magnitude, and fits with models of lexical processing that distinguish between sequential and instantaneous activation of sub-lexical units for spoken and written words, respectively(30). This finding opens up questions about the temporal properties of lexical representations and access, and merits further exploration. Future studies could, for example, manipulate how sub-lexical information becomes available by using printed words and pictures as stimuli in addition to cross-language translation equivalents.

Returning to the cross-modal findings, co-activation through LSE signs yielded onset competitor effects but no rhyme competitor effects. Given how the two co-activation effects become more homogeneous in the (within-modality) cross-language setting, the lack of a rhyme effect in the cross-modal setting is somewhat surprising. The few available studies looking at parallel activation of the spoken (or written) language by a signed language did show co-activation of rhyme competitors(22, 23). However, these studies used very different experimental paradigms and did not directly compare onset and rhyme effects, making it difficult to compare their results to those of the current study. One possible explanation for the difference between bimodal and unimodal co-activation of sub-lexical information in Spanish (through LSE and Basque, respectively) is the complexity of the process of co-activation: in the case of within-modal co-activation, the entire process involves a single type of representation (e.g. auditory); for cross-modal activation, two distinct representational systems (auditory and visual-spatial) are activated. The increased demands of processing two representational systems in parallel may prevent some competition effects – in this case, the weaker rhyme competitors – from emerging. Some indirect support for this explanation can be found in earlier work comparing sub-lexical activation across modalities in a single language: priming experiments between the written and the spoken form of words showed an effect for shared onsets, but not for rhymes(31, 32). Alternatively, the effect may be driven by word-based mouthings that may accompany signs and reflect a modality-specific aspect of bimodal bilingualism. Although these mouthings are rarely obligatory in LSE (and were not present in the stimuli videos), they tend to incorporate the word onset and this may have facilitated the onset effect at the expense of the rhyme effect. These two explanations are not mutually exclusive; examining different bilingual populations (e.g., deaf signers) could help to delineate the contribution of cross-modal representations.

Experiment 3 investigated the time course of activation of location and handshape competitors in LSE when the input was a spoken Spanish word, providing evidence for co-activation of both competitors. The effects did not differ in magnitude, but location competitor effects preceded handshape competitor effects. (This finding was validated by the results of Experiment 4: the co-activation effects of LSE through Spanish disappeared when the participants had no knowledge of the sign language.) These results are largely similar to those found for lexical co-activation in LSE with the same stimuli, paradigm and participants. When seeing signs, handshape co-activation was stronger and later than location co-activation(24). When the input was a spoken Spanish word, the relative magnitude of the two competitor effects changed slightly, but, strikingly, the relative temporal ordering was maintained (location before handshape).

To investigate what factors could account for the relative temporal ordering of location and handshape co-activation in our findings, we performed a follow-up analysis. Specifically, we examined the role of temporal and distributional properties of the signs in a by-item analysis. First, we went back to the within-language study and extracted two properties of the target to add as factors in the models. To characterize the temporal structure of the target sign, we extracted the time point at which the handshape and the location information appeared in the stimulus video. To characterize the distributional properties of the sub-lexical units, we calculated how often a given handshape or major location appears in a lexical database over 2,400 LSE signs(33). This measure, which we are calling sub-lexical density, reflects how common a specific sub-lexical unit is in the lexicon and also indexes an important difference between location and handshape: location typically exhibits fewer contrasts than handshape and thus has higher sub-lexical density values. When including information about the relative timing of handshape versus location in the stimulus sign in the analysis, the relative ordering of location and handshape co-activation was still evident (see Tables S5a,b for full details and results). In contrast, when including sub-lexical density in the analysis there was no longer evidence of relative ordering of location and handshape co-activation (see Table S5c for full details and results). Thus, the relative timing of co-activation of location and handshape when seeing a sign can be explained by differences in the sub-lexical density of those sub-lexical units. The location competitor effects occur earlier because location has a smaller search space and is therefore computationally less demanding compared to handshape, which takes more time to be resolved.

Can sub-lexical density also account for the ordering of location and handshape co-activation when hearing a Spanish word? To test this possibility, we added this variable to the analysis comparing location and handshape competitors in the current cross-language study (Experiment 3). When including sub-lexical density, the analysis showed only weak evidence for a difference in the timing of location and handshape co-activation. (Additionally, sub-lexical density modulated the overall magnitude of co-activation. See Tables S6a,b for full details and results.) This follow-up analysis suggests that the distribution of handshapes and locations in the sign lexicon impacts how these sub-lexical units are processed. This account of the timing of sign language lexical access appeals to basic, domain-general processing mechanisms for the activation of a given representation, but is shaped by the distributional properties of the language's lexicon(30). A recent neuroimaging study provides converging evidence that this temporal ordering is driven by structural linguistic properties(34). ECoG (electrocorticography) recordings of a sign language user revealed earlier activation of linguistically-relevant features of location relative to handshape. This combination of general processing mechanisms and language-specific properties is common to both spoken and signed language processing, and also accommodates differences between the two.

Our results add to the growing evidence that cross-language co-activation occurs across linguistically disparate contexts, even when there is no possibility of phonological overlap between languages(15–17, 20, 22, 28) and, furthermore, demonstrate that this co-activation occurs in both directions in bimodal bilinguals.

In addition, our experimental design directly aimed to probe the time course and role of sub-lexical units in co-activation during lexical access across languages and modalities. By comparing these results with previous findings for sub-lexical co-activation in a within-language setting, the current study yields new insights into how the presence of the input signal impacts the processing of sub-lexical information. The results provide clear evidence for differential processing of distinct sub-lexical units in both a spoken and a signed language, revealing a common structural mechanism for lexical access independent of modality. At the same time, there is marked difference between modalities in the influence of the temporal structure of the linguistic signal on lexical co-activation. For spoken language, the temporal structure of words imposes temporal order on sub-lexical processing: onset competitors are activated before rhyme competitors; when the lexical item is co-activated via another language, onset and rhyme effects show no temporal ordering. In the sign modality, the linguistic signal is much more simultaneous. Since the input sign does not impose a sequential structure, the temporal ordering of location and handshape co-activation effects is not dependent on whether or not the sign itself is perceived. Instead, our results lead us to believe that distributional properties of sub-lexical units explain the different time course of location and handshape co-activation. More generally, these results reveal the interaction between the perceptual properties of the explicit signal and structural linguistic properties. Examining languages from different modalities brings to light how this interaction impacts language processing.

Materials and Methods

All experiments were approved by the BCBL Ethics Committee and performed in accordance with the Helsinki Declaration.

Experiment 1

Participants

We recruited a group of 28 native bimodal bilinguals of Spanish and LSE (22 female; mean age 44). All participants were hearing and learnt LSE from birth from their deaf signing parents (except one participant, who had one deaf signing parent and one hearing signing parent). All were highly proficient in LSE and Spanish and used LSE in the deaf signing community on a daily basis for professional purposes (mean self-rated competence in LSE 6.6/7; on average 20 years' experience using LSE professionally, range 4 -29 years). In terms of average weekly language use, participants reported using LSE and Spanish in approximately the same proportion (LSE 51%; Spanish 49%), although there was some variation (11 participants reported using LSE more, 10 participants reported using Spanish more, and 7 participants reported using both equally). This population represents the most proficient hearing LSE users who acquired the language natively. We recruited participants and ran the experiment at various locations in Spain (Bilbao, Burgos, Madrid, Palencia, Pamplona, San Sebastián and Valladolid).

Materials

The experimental task consisted of 45 trials with four images in the corners of the screen and a sign stimulus video presented in the centre of the screen. In critical trials ($n = 30$), the Spanish translation of the sign stimulus (the target word) was phonologically related to the corresponding word for two of the images (the phonological competitors): one competitor shared the onset with the target word, and the other competitor rhymed with the target word. The remaining two pictures were unrelated distractors (with no phonological overlap with the target word). In four trials, the LSE signs for the target, competitors and distractors had some degree of overlap, and these trials were excluded from analysis. In each of the remaining 26 critical trials, there was no overlap in LSE between target, competitors and distractors. In critical trials there was no image corresponding to the target sign. In filler trials ($n = 15$), the target image was present, and the remaining three images were unrelated distractors.

The material was adapted from a previous experiment that investigated lexical co-activation in Spanish using the same paradigm, with onset and rhyme competitors for a stimulus presented as a Spanish word. All targets, competitors and distractors were Spanish nouns matched for semantic relatedness, frequency, number of phonemes, letters and syllables; the on-screen images were black and white line drawings matched for visual complexity. (For full details and an overview of the original stimuli see (24): Experiment 1.a.) In the current experiment the target items were presented as LSE signs. The video recordings for the stimulus signs showed a female deaf signer, cropped and scaled to 320x296 pixels and presented in the center of the screen (25 fps). Each video started with the signer in resting position (hands by her sides) followed by a transition movement to articulate the sign and ended back in the resting position. Average duration of the recorded videos was 2,063 ms ($SD = 246$ ms). 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. Average sign duration was 877 ms (*SD* = 242); the average onset for handshape was 387 ms and for location 420 ms after video onset.

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. 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 LSE sign. When none of the pictures matched the sign, participants waited for the next trial to start. After watching the task instructions in LSE on the screen, nine-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. In each trial, four images appeared on the screen for 500 ms before the stimulus sign appeared. The images remained on the screen during the sign and for another 2,500 ms or until the participant pushed any of the buttons, followed by 100 ms of blank screen. The trial sequence is shown in Figure 5a. 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. The experiment lasted less than 10 minutes.

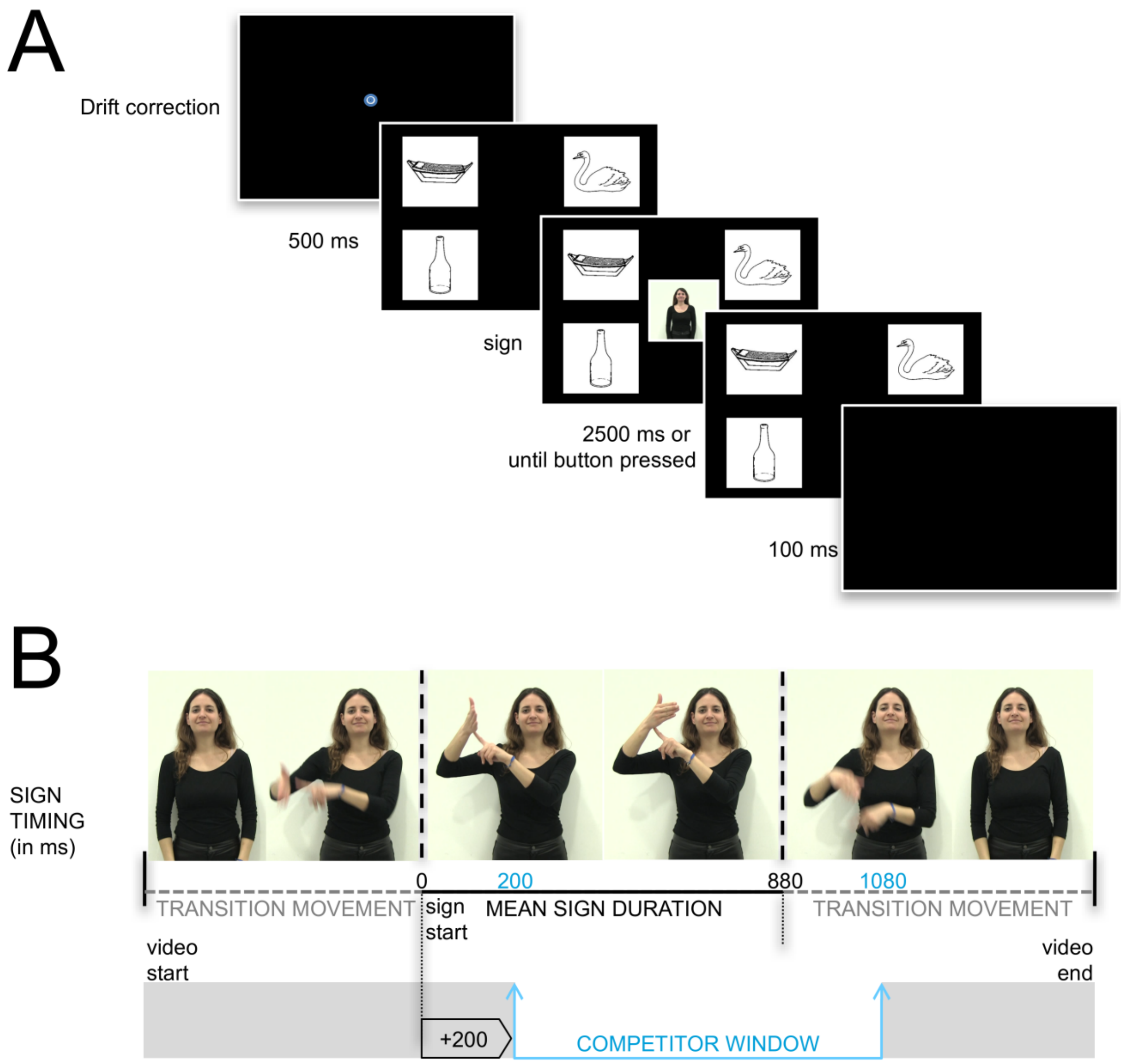

Figure 5. A: Trial sequence for Experiment 1: parallel activation of spoken Spanish. B: Illustration of sign duration (in ms) and the selected time window for the analysis of onset and rhyme competition effects for the LSE stimulus FLAG.

Analysis

To account for dialectal variation of LSE upon completing the experiment participants translated the stimulus signs they had seen into Spanish. When they did not produce the expected target Spanish word or they did not know the sign, the trial was eliminated from the analysis. In total, 25.4% of the trials were discarded (range 3-12 per participant). After removing these invalid trials, there were no trials with incorrect responses (i.e. false hits).

We analysed the data using R(35) v4.0.3 with the VWPre package(36) v1.2.3 for pre-processing and the lme4 package(37) v1.1-25 for statistical analysis. Fixations to each picture were clustered in 20 ms bins (20 samples) and averaged across trials. The proportion of looks to the two unrelated distractors was averaged together to generate a single unrelated baseline for the analysis.

For the analysis of onset and rhyme co-activation, we selected a time window determined by the duration of the sign stimuli. We used the same time window for the analyses of both competitors. The onset point for the window of analysis was adjusted to the sign onset of each individual stimulus sign (defined as the moment when both handshape and location were visibly articulated). Average sign duration was 877 ms (*SD* = 242), resulting in a 200-1080 ms window for analysis after accounting for the ~200 ms involved to programme an eye movement(38) (see Figure 5b). We excluded individual trials with more than 25% track loss in the analysis window ($n = 2$, 0.2% of the data).

To examine differences in the time course of gaze behaviour, we performed a time series analysis: Growth Curve Analysis(39). 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). This allows us to estimate the strength of the co-activation, indexed by the proportion of looks (intercept term), and the temporal development of co-activation, revealed by the changes in the looking behaviour over time (linear and quadratic term). In order to choose the polynomial order for each growth curve model we used a combination of a statistical and a theoretical approach(39), 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 on all temporal terms. 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(40). For the model parameter estimates, normal approximation (z-distribution) was used to calculate p-values. Fixed effects (with standard error, 95% confidence interval, *t* statistic and *p* value) for all analyses are provided in the Supplementary material.

Sub-lexical effects. To assess the effect of the sub-lexical competitors, the overall time course of fixations was modelled with a second-order (quadratic) orthogonal polynomial and fixed effects of Competitor type (Onset vs. Unrelated Distractor, Rhyme vs. Unrelated Distractor) on all time terms. Treatment coding was used to code the contrasts for fixed effects. 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. The Unrelated distractor was treated as the reference level and parameters were estimated for the Onset and Rhyme competitors. The model also included participant and participant-by-competitor random effects on all temporal terms. Additionally, to have a simple estimate of the magnitude of each competitor effect, we calculated how much each participant looked more at the competitor than at the unrelated distractors across the entire window of interest (i.e. proportion of looks to competitor minus proportion of looks to distractors). These values are shown in the barplot insets in figures 1-4.

Comparison of sub-lexical effects. To check for differences between competitors, the competitor curves were modelled with a second-order (quadratic) orthogonal polynomial and fixed effect of Competitor type (Onset vs. Rhyme), as well as participant and participant-by-competitor random effects on all temporal terms. Looks to the onset competitor were treated as the reference level and parameters were estimated for the rhyme competitor.

Experiment 2

Participants

A group of 33 highly proficient Spanish/Basque balanced bilinguals (age of acquisition for both languages before the age of six) with no knowledge of LSE (mean age 38, standard deviation 6.6; 9 male) performed the experiment.

Materials

The materials were the same as for Experiment 1, with target items translated into Basque. In critical trials ($n = 30$), the Spanish translation of the Basque stimulus (the target word) was phonologically related to the corresponding Spanish word for two of the images: one word shared the onset with the Spanish target word, and the other competitor word rhymed with the Spanish target word. The remaining two pictures were unrelated distractors (with no phonological overlap with the Spanish target word). Fourteen critical trials were excluded because the Basque and Spanish words for the targets were cognates. In each of the remaining 16 critical trials, there was no overlap in Basque between target, competitors and distractors. In filler trials ($n = 15$), the target image was present, and the remaining three images were unrelated distractors.

A male Basque native speaker recorded the words. The average duration of the Basque stimuli was 660 ms.

Procedure

The procedure was the same as that used for Experiment 1. However, in this version of the experiment, task instructions were shown in written Basque and, instead of seeing a sign, participants heard a Basque word through headphones on each trial. Figure 6a illustrates the trial sequence. The experiment lasted less than 10 minutes.

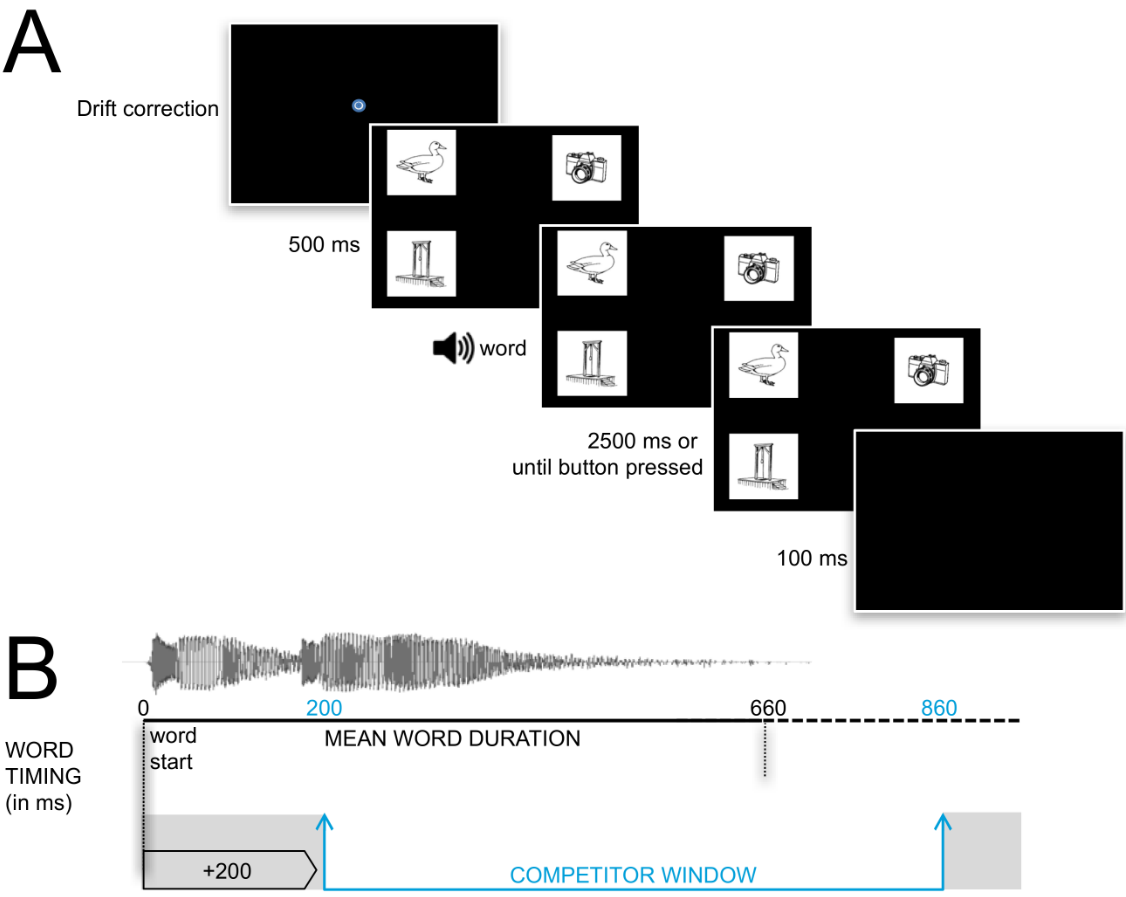

Figure 6. A. Trial sequence with stimuli presented as auditory words (Experiments 2 and 3). B. Illustration of auditory word duration (in ms) and the selected time window for the analysis of competition effects.

Analysis

The analysis was as described for Experiment 1. We defined the window of analysis based on the duration of the Basque stimulus words (average duration 660 ms), and allowing for an additional 200ms for the programming and executing of eye movements, resulting in a time window of 200-860 ms (see Fig. 6b). Experimental trials with false responses were removed from the analysis (n=7, 0.7% of the data). We excluded individual trials with more than 25% track loss in the analysis window (n = 1, 0.1% of the data).

Experiment 3

Participants

The participants were the same as those in Experiment 1.

Materials

The experimental task consisted of 45 trials with four images in the corners of the screen and an auditory Spanish word stimulus presented over headphones. In critical trials ($n = 30$), the signs corresponding to two of the pictures were phonologically related to the LSE sign translation of the Spanish word that was presented (the target sign): one competitor had the same location as the target sign (location competitor), and the other competitor shared handshape with the target sign (handshape competitor). The remaining two pictures were unrelated distractors with no phonological overlap with the target sign. In two trials, the LSE signs for the target and distractors had some degree of overlap, and these trials were excluded from analysis. In each of the remaining 28 critical trials, there was no overlap in Spanish between target, competitors and distractors. In critical trials there was no image corresponding to the Spanish word. In filler trials ($n = 15$) the target image was present and the other three images were unrelated distractors.

The material was adapted from a previous experiment that investigated lexical co-activation in LSE using the same paradigm, with handshape and location competitors for a LSE target sign. All targets, competitors and distractors were LSE noun signs from the Standardized LSE Dictionary(41) (available online: http://www.fundacioncnse.org/tesorolse/index.html) and matched for handedness, semantic relatedness, frequency and iconicity; the on-screen images were black and white line drawings matched for visual complexity. For full details and an overview of the original stimuli see (24): Experiment 2. In this experiment the target items were presented as spoken Spanish words. A male Spanish native speaker recorded the target words in Spanish. Average duration of the words was 654 ms (*SD* =116).

Procedure

The procedure was the same as that used for Experiment 1 with the following differences. Task instructions were shown in written Spanish. Instead of seeing a sign, participants heard a Spanish word through headphones on each trial. (Fig. 6a illustrates the trial sequence.) The experiment lasted less than 10 minutes.

Analysis

The analysis was as described for Experiment 1.

To account for dialectal variation in LSE, upon completing the experiment participants produced the signs they normally use for the Spanish stimulus words and for the images that served as competitors. When they used a different sign to the one expected, the trial was eliminated from the analysis. Thus, 28.1% of the trials were eliminated (range per participant: 1-14). After removing these invalid trials, there were no trials with incorrect responses (i.e. false hits).

A time window based on the mean duration of the word stimuli (654 ms) shifted 200 ms to allow for the programming and launching of eye movements, was selected for the analyses of handshape and location co-activation. This resulted in a window of interest between 200 ms and 860 ms after word onset (see Fig. 6b). Individual trials with more than 25% track loss in the time window of interest were excluded from the analysis ($n = 4$, 0.5% of the data).

In the comparison of handshape and location competitors, looks to the location competitor were treated as the reference level and parameters were estimated for the handshape competitor.

Experiment 4

Participants

A group of 25 Spanish/Basque bilinguals (mean age 40, standard deviation 6.1; 5 male) with no knowledge of LSE or any other sign language performed the experiment.

Materials

The materials were the same as for Experiment 3.

Procedure

The procedure was the same as that used for Experiment 3.

Analysis

The analysis was as described for Experiment 3. We excluded individual trials with more than 25% track loss in the analysis window (n = 2, 0.3% of the data). There were no false responses in the experimental trials.

Data availability

The data and scripts for these experiments are available at the Open Science Foundation repository: https://osf.io/m2qz6

Acknowledgments

We thank the organizations that provided staff and premises to run the experiments: CILSEM (Sign Language Interpreters Association in Madrid), ASORMADRID (Deaf Association in Madrid), Fundación CNSE (Madrid), APERSORVA (Deaf Association in Valladolid), ARANSBUR (Association of Families with Deaf Children, Burgos), APSBU (Deaf Association in Burgos), ASORNA (Deaf Association in Navarra). The University of Valladolid and the López Vicuña Vocational Institute (Palencia) provided spaces in which to run the experiment. Various colleagues have provided invaluable support: Patricia Dias, Noemi Fariña, Ainhoa Ruiz de Angulo, David Carcedo, Aina Casaponsa, Effie Kapnoula and Jim Magnuson. Finally, we are truly indebted to all our participants.

The authors acknowledge financial support from the Spanish Ministry of Economy and Competitiveness (MINECO), through the "Severo Ochoa" Programme for Centres/Units of Excellence in R&D" (CEX2020-001010-S), from the Basque Government through the BERC 2022-2025 program, from the National Research Agency [Agencia Estatal de Investigación], MINECO and European Regional Development Fund, through grants (PSI-2016-76435-P and PID2019-107325GB-I00 to M.G and B.C.; and PID2021-122918OB-I00 to M.C.), and through Juan de la Cierva Fellowships (FJCI-2017-31806 and IJC2019-038991-I to B.C.).

References

1. D. Brentari, *A Prosodic Model of Sign Language Phonology* (The MIT Press, 1998) https:/doi.org/10.7551/mitpress/5644.001.0001 (November 20, 2020).

2. W. Sandler, *Phonological Representation of the Sign* (DE GRUYTER MOUTON, 1989) https:/doi.org/10.1515/9783110250473.

3. A. I. Schwartz, J. F. Kroll, M. Diaz, Reading words in Spanish and English: Mapping orthography to phonology in two languages. *Lang. Cogn. Process.* **22**, 106–129 (2007).

4. G. Thierry, Y. J. Wu, Brain potentials reveal unconscious translation during foreign-language comprehension. *Proc. Natl. Acad. Sci. U. S. A.* **104**, 12530–5 (2007).

5. M. R. Libben, D. A. Titone, Bilingual lexical access in context: Evidence from eye movements during reading. *J. Exp. Psychol. Learn. Mem. Cogn.* **35**, 381–390 (2009).

6. V. Marian, M. Spivey, Competing activation in bilingual language processing: Within- and between-language competition. *Biling. Lang. Cogn.* **6**, 97–115 (2003).

7. M. J. Spivey, V. Marian, Cross Talk Between Native and Second Languages: Partial Activation of an Irrelevant Lexicon. *Psychol. Sci.* **10**, 281–284 (1999).

8. S. C. Bobb, K. Von Holzen, J. Mayor, N. Mani, M. Carreiras, Co-activation of the L2 during L1 auditory processing: An ERP cross-modal priming study. *Brain Lang.* **203**, 104739 (2020).

9. A. Costa, A. Caramazza, N. Sebastian-Galles, The Cognate Facilitation Effect: Implications for Models of Lexical Access. *J. Exp. Psychol. Learn. Mem. Cogn.* **26**, 1283–1296 (2000).

10. M. Ju, P. A. Luce, Falling on sensitive ears: Constraints on bilingual lexical activation. *Psychol. Sci.* **15**, 314–318 (2004).

11. V. Marian, H. K. Blumenfeld, O. V. Boukrina, Sensitivity to phonological similarity within and across languages. *J. Psycholinguist. Res.* **37**, 141–170 (2008).

12. A. Weber, A. Cutler, Lexical competition in non-native spoken-word recognition. *J. Mem. Lang.* **50**, 1–25 (2004).

13. E. Canseco-Gonzalez, *et al.*, Carpet or cárcel: The effect of age of acquisition and language mode on bilingual lexical access. *Lang. Cogn. Process.* **25**, 669–705 (2010).

14. A. Shook, V. Marian, Covert co-activation of bilinguals' non-target language. *Linguist. Approaches to Biling.* **9**, 228–252 (2019).

15. M. R. Giezen, H. K. Blumenfeld, A. Shook, V. Marian, K. Emmorey, Parallel language activation and inhibitory control in bimodal bilinguals. *Cognition* **141**, 9–25 (2015).

16. A. Shook, V. Marian, Bimodal bilinguals co-activate both languages during spoken comprehension. *Cognition* **124**, 314–24 (2012).

17. S. Villameriel, P. Dias, B. Costello, M. Carreiras, Cross-language and cross-modal activation in hearing bimodal bilinguals. *J. Mem. Lang.* **87**, 59–70 (2016).

18. G. Meade, J. Grainger, K. J. Midgley, P. J. Holcomb, K. Emmorey, ERP Effects of masked orthographic neighbour priming in deaf readers. *Lang. Cogn. Neurosci.* **34**, 1016–1026 (2019).

19. J. P. Morford, J. F. Kroll, P. Piñar, E. Wilkinson, Bilingual word recognition in deaf and hearing signers: Effects of proficiency and language dominance on cross-language activation. *Second Lang. Res.* **30**, 251–271 (2014).

20. J. P. Morford, E. Wilkinson, A. Villwock, P. Piñar, J. F. Kroll, When deaf signers read English: do written words activate their sign translations? *Cognition* **118**, 286–92

(2011).

21. O. Kubus, A. Villwock, J. P. Morford, C. Rathmann, Word recognition in deaf readers: Cross-language activation of German Sign Language and German. *Appl. Psycholinguist.* **36**, 831–854 (2015).

22. B. Lee, G. Meade, K. J. Midgley, P. J. Holcomb, K. Emmorey, ERP Evidence for Co-Activation of English Words during Recognition of American Sign Language Signs. *Brain Sci.* **9**, 148 (2019).

23. J. Hosemann, N. Mani, A. Herrmann, M. Steinbach, N. Altvater-Mackensen, Signs activate their written word translation in deaf adults: An ERP study on cross-modal co-activation in German Sign Language. *Glossa a J. Gen. Linguist.* **5**, 57 (2020).

24. S. Villameriel, B. Costello, P. Dias, M. Giezen, M. Carreiras, Language modality shapes the dynamics of word and sign recognition. *Cognition* **191**, 103979 (2019).

25. P. D. Allopenna, J. S. Magnuson, M. K. Tanenhaus, Tracking the Time Course of Spoken Word Recognition Using Eye Movements: Evidence for Continuous Mapping Models. *J. Mem. Lang.* **38**, 419–439 (1998).

26. M. Carreiras, E. Gutiérrez-Sigut, S. Baquero, D. Corina, Lexical processing in Spanish Sign Language (LSE). *J. Mem. Lang.* **58**, 100–122 (2008).

27. C. L. Rivolta, B. Costello, M. Carreiras, Language modality and temporal structure impact processing: Sign and speech have different windows of integration. *J. Mem. Lang.* **121**, 104283 (2021).

28. G. Meade, K. J. Midgley, Z. Sevcikova Sehyr, P. J. Holcomb, K. Emmorey, Implicit co-activation of American Sign Language in deaf readers: An ERP study. *Brain Lang.* **170**, 50–61 (2017).

29. E. Yee, J. C. Sedivy, Eye movements to pictures reveal transient semantic activation during spoken word recognition. *J. Exp. Psychol. Learn. Mem. Cogn.* **32**, 1–14 (2006).

30. Q. Chen, D. Mirman, Competition and cooperation among similar representations: Toward a unified account of facilitative and inhibitory effects of lexical neighbors. *Psychol. Rev.* **119**, 417–430 (2012).

31. C. M. Connine, D. G. Blasko, D. Titone, Do the Beginnings of Spoken Words Have a Special Status in Auditory Word Recognition? *J. Mem. Lang.* **32**, 193–210 (1993).

32. W. Marslen-Wilson, P. Zwitserlood, “Accessing Spoken Words: The Importance of Word Onsets” (1989).

33. E. Gutierrez-Sigut, B. Costello, C. Baus, M. Carreiras, LSE-Sign: A lexical database for Spanish Sign Language. *Behav. Res. Methods* **48** (2016).

34. M. K. Leonard, B. Lucas, S. Blau, D. P. Corina, E. F. Chang, Cortical Encoding of Manual Articulatory and Linguistic Features in American Sign Language. *Curr. Biol.* **30**, 4342-4351.e3 (2020).

35. R Core Team, R: A Language and Environment for Statistical Computing (2020).

36. V. Porretta, A.-J. Kyröläinen, J. van Rij, J. Järvikivi, “Visual World Paradigm Data: From Preprocessing to Nonlinear Time-Course Analysis” in (2018), pp. 268–277.

37. D. Bates, M. Mächler, B. Bolker, S. Walker, Fitting Linear Mixed-Effects Models Using lme4. *J. Stat. Softw.* **67** (2015).

38. E. Matin, K. C. Shao, K. R. Boff, Saccadic overhead: Information-processing time with

and without saccades. *Percept. Psychophys.* **53**, 372–380 (1993).

39. D. Mirman, *Growth Curve Analysis and Visualization Using R* (Chapman and Hall/CRC, 2017) https:/doi.org/10.1201/9781315373218.

40. D. Mirman, J. A. Dixon, J. S. Magnuson, Statistical and computational models of the visual world paradigm: Growth curves and individual differences. *J. Mem. Lang.* **59** (2008).

41. Fundación C.N.S.E, Diccionario normativo de la lengua de signos española (2008).

Supplementary Information for

Cross-modal and cross-language activation in bilinguals reveals lexical competition even when words or signs are unheard or unseen

Saul Villameriel*[1], Brendan Costello*[1], Marcel Giezen[1] and Manuel Carreiras[1,2,3].

[1]Basque Center on Cognition, Brain and Language, 20009 Donostia-San Sebastián, Spain

[2]Departamento de Lengua Vasca y Comunicación, UPV/EHU, 48940 Leioa, Spain

[3]Ikerbasque, Basque Foundation for Science, 48013 Bilbao, Spain

*Saúl Villameriel, Brendan Costello.

This PDF file includes:

Tables S1 to S6

SI References

Other supplementary materials for this manuscript include the following:

Dataset S1 https://osf.io/m2qz6

Table S1a. *Experiment 1. Parameter estimates for growth curve analysis of Onset and Rhyme Competition (compared to unrelated distractors) for native bimodal bilinguals of Spanish and LSE.*

Predictors	*Estimates*	*SE*	*CI*	*t*	*p*
Intercept	0.111	0.007	0.098 – 0.124	16.970	**<0.001**
Linear	0.397	0.032	0.335 – 0.459	12.573	**<0.001**
Quadratic	-0.078	0.029	-0.135 – -0.021	-2.674	**0.008**
Onset : Intercept	0.020	0.007	0.005 – 0.034	2.666	**0.008**
Rhyme : Intercept	-0.002	0.007	-0.017 – 0.012	-0.300	0.764
Onset : Linear	0.137	0.044	0.050 – 0.224	3.083	**0.002**
Rhyme : Linear	-0.032	0.044	-0.120 – 0.055	-0.728	0.467
Onset : Quadratic	0.050	0.040	-0.029 – 0.129	1.241	0.215
Rhyme : Quadratic	-0.045	0.040	-0.125 – 0.034	-1.124	0.261

Table S1b. *Experiment 1. Parameter estimates for growth curve analysis of onset (reference) and rhyme competitors for native bimodal bilinguals of Spanish and LSE.*

Predictors	*Estimates*	*SE*	*CI*	*t*	*p*
Intercept	0.130	0.007	0.117 – 0.144	19.201	**<0.001**
Linear	0.534	0.036	0.465 – 0.604	15.032	**<0.001**
Quadratic	-0.028	0.031	-0.088 – 0.032	-0.914	0.361
Rhyme : Intercept	-0.022	0.008	-0.037 – -0.007	-2.828	**0.005**
Rhyme : Linear	-0.169	0.049	-0.266 – -0.073	-3.428	**0.001**
Rhyme : Quadratic	-0.096	0.043	-0.180 – -0.011	-2.209	**0.027**

Table S2a. *Experiment 2. Parameter estimates for growth curve analysis of Onset and Rhyme Competitors (compared to unrelated distractors) for unimodal bilinguals of Spanish and Basque.*

Predictors	*Estimates*	*SE*	*CI*	*t*	*P*
Intercept	0.205	0.007	0.192 – 0.218	30.981	**<0.001**
Linear	0.073	0.047	-0.020 – 0.166	1.539	0.124
Quadratic	0.054	0.037	-0.019 – 0.128	1.458	0.145
Onset : Intercept	0.020	0.009	0.003 – 0.038	2.239	**0.025**
Rhyme : Intercept	0.026	0.009	0.008 – 0.044	2.864	**0.004**
Onset : Linear	-0.160	0.067	-0.291 – -0.028	-2.384	**0.017**
Rhyme : Linear	-0.066	0.067	-0.197 – 0.066	-0.978	0.328
Onset : Quadratic	-0.065	0.053	-0.168 – 0.039	-1.223	0.221
Rhyme : Quadratic	-0.114	0.053	-0.217 – -0.010	-2.154	**0.031**

Table S2b. *Experiment 2. Parameter estimates for growth curve analysis (200-860 ms time window) to compare onset (reference) and rhyme competitors for unimodal bilinguals of Spanish and Basque.*

Predictors	*Estimates*	*SE*	*CI*	*t*	*p*
Intercept	0.225	0.008	0.210 – 0.241	29.234	**<0.001**
Linear	-0.087	0.054	-0.192 – 0.018	-1.620	0.105
Quadratic	-0.010	0.041	-0.091 – 0.071	-0.244	0.807
Rhyme : Intercept	0.006	0.010	-0.014 – 0.026	0.561	0.575
Rhyme : Linear	0.094	0.076	-0.054 – 0.243	1.244	0.213
Rhyme : Quadratic	-0.049	0.058	-0.164 – 0.065	-0.840	0.401

Table S3a. *Experiment 3. Parameter estimates for growth curve analysis of Location and Handshape Competitors (compared to unrelated distractors) for native bimodal bilinguals of Spanish and LSE.*

Predictors	*Estimates*	*SE*	*CI*	*t*	*p*
Intercept	0.202	0.006	0.190 – 0.214	32.593	**<0.001**
Linear	0.015	0.050	-0.083 – 0.112	0.293	0.769
Quadratic	0.023	0.040	-0.056 – 0.101	0.567	0.571
Location : Intercept	0.032	0.008	0.016 – 0.049	3.796	**<0.001**
Handshape : Intercept	0.028	0.008	0.012 – 0.045	3.321	**0.001**
Location : Linear	-0.092	0.070	-0.229 – 0.044	-1.323	0.186
Handshape : Linear	0.125	0.070	-0.011 – 0.262	1.796	0.072
Location : Quadratic	-0.084	0.056	-0.194 – 0.027	-1.481	0.138
Handshape : Quadratic	-0.007	0.056	-0.117 – 0.104	-0.121	0.904

Table S3b. *Experiment 3. Parameter estimates in growth curve analysis to compare competition from location and handshape (reference) for native bimodal bilinguals of Spanish and LSE.*

Predictors	*Estimates*	*SE*	*CI*	*t*	*p*
Intercept	0.234	0.007	0.221 – 0.247	34.964	**<0.001**
Linear	-0.078	0.055	-0.186 – 0.031	-1.406	0.160
Quadratic	-0.061	0.045	-0.149 – 0.027	-1.358	0.175
Handshape : Intercept	-0.004	0.009	-0.022 – 0.014	-0.442	0.659
Handshape : Linear	0.218	0.077	0.066 – 0.369	2.811	**0.005**
Handshape : Quadratic	0.077	0.063	-0.048 – 0.201	1.210	0.226

Table S4. *Experiment 4. Parameter estimates for growth curve analysis of Location and Handshape Competition for unimodal bilinguals of Spanish and Basque.*

Predictors	*Estimates*	*SE*	*CI*	*t*	*p*
Intercept	0.209	0.008	0.194 – 0.224	26.723	**<0.001**
Linear	-0.001	0.039	-0.077 – 0.075	-0.029	0.977
Quadratic	0.001	0.031	-0.060 – 0.061	0.017	0.986
Location : Intercept	0.005	0.007	-0.008 – 0.018	0.763	0.445
Handshape : Intercept	0.010	0.007	-0.003 – 0.023	1.508	0.132
Location : Linear	0.026	0.053	-0.078 – 0.130	0.489	0.625
Handshape : Linear	0.050	0.053	-0.053 – 0.154	0.955	0.340
Location : Quadratic	-0.002	0.043	-0.087 – 0.083	-0.047	0.963
Handshape : Quadratic	0.026	0.043	-0.059 – 0.111	0.604	0.546

Table S5a. *By-item analysis of within-language sub-lexical co-activation in LSE based on data reported as Experiment 2 in* (1)*.*

Parameter estimates for growth curve analysis to compare condition (Location versus Handshape), which was sum coded so that results reflect main effects. The full model was:

*Proportion_of_looks ~ (ot1 + ot2) * Condition +*

(ot1 + ot2 | Item) + (ot1 + ot2 | Item:Condition)

Where ot1 and ot2 are the linear and quadratic temporal terms, respectively.

Predictors	*Estimates*	*SE*	*CI*	*t*	*p*
Intercept	0.134	0.011	0.113 – 0.156	12.206	**<0.001**
Linear	0.337	0.039	0.261 – 0.413	8.703	**<0.001**
Quadratic	-0.105	0.036	-0.176 – -0.034	-2.901	**0.004**
Condition : Intercept	0.009	0.007	-0.005 – 0.023	1.232	0.218
Condition : Linear	0.098	0.037	0.026 – 0.170	2.664	**0.008**
Condition : Quadratic	-0.039	0.029	-0.096 – 0.018	-1.348	0.178

Table S5b. *Parameter estimates for the same model as Table S5a with the addition of sub-lexical timing (i.e. the onset time of Location and Handshape in the target sign) as a fixed effect. The full model was:*

*Proportion_of_looks ~ (ot1 + ot2) * Condition * Timing +*

(ot1 + ot2 | Item) + (ot1 + ot2 | Item:Condition)

The onset time of the Location and Handshape of each target sign was measured by identifying the video frame in which the hand had reached the sign's location and the hand had adopted the sign's handshape, respectively. With respect to the sign onset (defined as the frame when the handshape was visibly articulated at the sign's location), the average Location onset was -69 ms (sd 127 ms) and the average Handshape onset was -229 ms (sd 102 ms). As has been found for other sign languages, handshape tends to precede location information(2).

Note that the interaction between Condition and the linear temporal term, which indicates the relative timing of the Location and Handshape effects, is unaffected by the addition of information about when the sub-lexical units appear in the target sign.

Predictors	*Estimates*	*SE*	*CI*	*t*	*p*
Intercept	0.134	0.012	0.110 – 0.157	11.078	**<0.001**
Linear	0.369	0.046	0.279 – 0.459	8.054	**<0.001**
Quadratic	-0.102	0.042	-0.184 – -0.019	-2.419	**0.016**
Condition : Intercept	-0.002	0.009	-0.020 – 0.017	-0.173	0.862
Timing : Intercept	-0.018	0.011	-0.039 – 0.003	-1.688	0.091
Condition : Linear	0.132	0.045	0.043 – 0.220	2.911	**0.004**
Condition : Quadratic	-0.016	0.036	-0.088 – 0.055	-0.449	0.654
Timing : Linear	0.058	0.046	-0.031 – 0.147	1.268	0.205
Timing : Quadratic	0.039	0.039	-0.038 – 0.115	0.992	0.321
Condition : Timing : Intercept	-0.001	0.010	-0.020 – 0.018	-0.087	0.930
Condition : Timing : Linear	0.055	0.045	-0.034 – 0.143	1.204	0.228
Condition : Timing : Quadratic	0.005	0.037	-0.067 – 0.078	0.147	0.883

Table S5c. *Parameter estimates for the same model in Table S5a with the addition of sub-lexical density (i.e. the proportion of signs in the LSE lexicon that have the Location/Handshape value of the target sign) as a fixed effect. The full model was:*

*Proportion_of_looks ~ (ot1 + ot2) * Condition * sub_d +*

(ot1 + ot2 | Item) + (ot1 + ot2 | Item:Condition)

Sub-lexical density was calculated using a lexical database of 2,400 LSE signs(3).

Note that the interaction between Condition and the linear temporal term, which indicates the relative timing of the Location and Handshape effects, disappears with the addition of information about the frequency of occurrence of the sub-lexical units (i.e. density) of the target sign in the lexicon.

Predictors	*Estimates*	*SE*	*CI*	*t*	*p*
Intercept	0.129	0.018	0.094 – 0.165	7.076	**<0.001**
Linear	0.308	0.074	0.164 – 0.453	4.175	**<0.001**
Quadratic	-0.113	0.065	-0.240 – 0.014	-1.749	0.080
Condition : Intercept	0.014	0.015	-0.015 – 0.043	0.929	0.353
Sub_d : Intercept	0.007	0.017	-0.026 – 0.039	0.392	0.695
Condition : Linear	0.071	0.072	-0.069 – 0.212	0.993	0.321
Condition : Quadratic	-0.057	0.058	-0.171 – 0.058	-0.969	0.333
Sub_d: Linear	-0.033	0.077	-0.185 – 0.119	-0.428	0.668
Sub_d : Quadratic	-0.022	0.064	-0.147 – 0.103	-0.347	0.729
Condition : Sub_d : Intercept	-0.006	0.018	-0.042 – 0.030	-0.327	0.744
Condition : Sub_d : Linear	-0.036	0.079	-0.190 – 0.118	-0.460	0.645
Condition : Sub_d : Quadratic	-0.010	0.067	-0.141 – 0.122	-0.142	0.887

Table S6a. *Experiment 3. By-item analysis. Parameter estimates for growth curve analysis to compare condition (Location versus Handshape), which was sum coded so that results reflect main effects. The full model was:*

*Proportion_of_looks ~ (ot1 + ot2) * Condition +*

(ot1 + ot2 | Item) + (ot1 + ot2 | Item:Condition)

Where ot1 and ot2 are the linear and quadratic temporal terms, respectively.

Note that the interaction between Condition and the linear temporal term (also present in the by-subject analysis in Table S3b) indicates the relative timing of the Location and Handshape effects.

Predictors	*Estimates*	*SE*	*CI*	*t*	*p*
Intercept	0.228	0.011	0.206 – 0.250	19.952	**<0.001**
Linear	0.058	0.054	-0.047 – 0.163	1.080	0.280
Quadratic	-0.007	0.036	-0.079 – 0.064	-0.203	0.839
Condition : Intercept	0.002	0.011	-0.020 – 0.024	0.168	0.866
Condition : Linear	-0.118	0.054	-0.223 – -0.013	-2.207	**0.027**
Condition : Quadratic	-0.065	0.036	-0.137 – 0.006	-1.782	0.075

Table S6b. *Parameter estimates for the same model Table S6a with the addition of sub-lexical density (i.e. the proportion of signs in the LSE lexicon that have the Location/Handshape value of the target sign) as a fixed effect. The full model was:*

*Proportion_of_looks ~ (ot1 + ot2) * Condition * sub_d +*

(ot1 + ot2 | Item) + (ot1 + ot2 | Item:Condition)

Note that the interaction between Condition and the linear temporal term, which indicates the relative timing of the Location and Handshape effects, is weakened by the addition of information about the frequency of occurrence of the sub-lexical units (i.e. density) of the target sign in the lexicon. Additionally, there is a significant effect of sub-lexical density on the intercept term.

Predictors	*Estimates*	*SE*	*CI*	*t*	*p*
Intercept	0.227	0.021	0.187 – 0.268	10.970	**<0.001**
Linear	-0.027	0.100	-0.224 – 0.170	-0.269	0.788
Quadratic	0.001	0.070	-0.136 – 0.138	0.019	0.985
Condition : Intercept	-0.036	0.021	-0.077 – 0.004	-1.748	0.080
Sub_d : Intercept	0.048	0.022	0.004 – 0.092	2.160	**0.031**
Condition : Linear	-0.182	0.100	-0.378 – 0.015	-1.808	0.071
Condition : Quadratic	-0.002	0.070	-0.139 – 0.135	-0.030	0.976
Sub_d : Linear	0.081	0.108	-0.131 – 0.293	0.746	0.456
Sub_d : Quadratic	-0.080	0.075	-0.227 – 0.068	-1.059	0.290
Condition : Sub_d : Intercept	0.001	0.022	-0.042 – 0.045	0.063	0.950
Condition : Sub_d : Linear	0.108	0.108	-0.104 – 0.320	0.998	0.319
Condition : Sub_d : Quadratic	-0.012	0.075	-0.159 – 0.136	-0.154	0.878

SI References

1. S. Villameriel, B. Costello, P. Dias, M. Giezen, M. Carreiras, Language modality shapes the dynamics of word and sign recognition. *Cognition* **191** (2019).

2. J. Hosemann, A. Herrmann, M. Steinbach, I. Bornkessel-Schlesewsky, M. Schlesewsky, Lexical prediction via forward models: N400 evidence from German Sign Language. *Neuropsychologia* **51**, 2224–2237 (2013).

3. E. Gutierrez-Sigut, B. Costello, C. Baus, M. Carreiras, LSE-Sign: A lexical database for Spanish Sign Language. *Behav. Res. Methods* **48** (2016).