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

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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 coactivates phonologically related signs, just as hearing a spoken word coactivates 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 coactivation 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 coactivate words and, conversely, how hearing a word could coactivate signs and how such cross-language coactivation patterns differ from within-language coactivation. The results revealed cross-language, cross-modal activation in both directions. Furthermore, comparison with previous findings of within-language lexical coactivation for spoken and signed language showed 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 coactivation precedes handshape coactivation)—even when the sign is seen. We provide evidence that, instead, this pattern of activation is motivated by how common in the lexicon the sublexical 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.

language coactivation | bimodal bilingualism | lexical access | sublexical competition | visual world paradigm

Words exist in relation to one another. In the mental lexicon, the activation of one word may coactivate other similar words, where similarity between words depends on common sublexical units, such as shared word onset or rhyme or a relation in meaning. For bilinguals, such coactivation extends across similar-sounding words in the other language or shared semantics, when the word of one language coactivates 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 that avails of the auditory-oral modality and a signed language that 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 sublexical 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 sublexical 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 sublexical coactivation 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, nonselective access to words in both languages is driven by phonological ambiguity in the input (10–13) (i.e., words from different languages that sound alike). Additionally, there is evidence for cross-language coactivation

Significance

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 characterized the temporal properties of language coactivation between spoken and signed languages in a sample of native bimodal bilinguals. The findings provide insights not only 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.

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between two spoken languages in the absence of overt phonological overlap ("phonologically covert coactivation") (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 coactivates the Spanish phonologically overlapping word "pala" and its English translation equivalent 'shovel.' Thus, in addition to coactivation of words that sound alike, bilinguals also coactivate 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* coactivation in bimodal bilinguals. In particular, a variety of paradigms and techniques have shown that bimodal bilinguals coactivate 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 coactivation 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 electroencephalogram responses while deaf bimodal bilinguals processed signs [American Sign Language (22), German Sign Language (23)].

Coactivation 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 coactivation 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, 25), we examined the role of sublexical 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 eye-tracker measures fixations to the different images. In Spanish, hearing a target word coactivated lexical competitors that shared onset and rhyme with the target; furthermore, the coactivation of onset was stronger and earlier than that of rhyme [in line with previous work on other spoken languages (26)]. Thus, "estrella" [star] coactivated "espada" [sword] and then "botella" [bottle]. In Spanish Sign Language (LSE; *lengua de signos española*), seeing a target sign coactivated lexical competitors that shared handshape and location with the target; coactivation of handshape was stronger, but later, than that of location. The LSE sign CARROT coactivated the sign DUCK (CARROT and DUCK have the same location) and then the sign NOOSE (CARROT and NOOSE have the same handshape).

Here, we exploited the same paradigm and stimuli to examine coactivation between a signed and a spoken language, looking specifically at the time course and the role of different sublexical 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 coactivation—coactivating words without hearing them or coactivating 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 considered cross-modal, cross-language coactivation in hearing bimodal bilinguals of Spanish and LSE, and the other two examined cross-language coactivation 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 coactivation of auditory sublexical representations is affected by the absence of a spoken linguistic signal, Experiment 1 looked at the coactivation of Spanish words while bimodal bilinguals viewed LSE signs and at the role of word onset and rhyme during this covert coactivation.

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 coactivation of auditory sublexical representations occurs independently of a spoken linguistic signal, we expected greater looks to the competitor images compared to the unrelated distractors. In terms of the relative strength and timing of the competitor effects, we expected 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 to 4, the sign videos were longer in duration and also included transitional movements. See Fig. 5B and *Materials and Methods* and for details of these stimuli. The lower accuracy rates are typical of those found in LSE lexical recognition tasks (27, 28) and reflect greater dialectal variation of a nonstandardized language.)

Fig. 1 shows the proportion of looks to onset and rhyme competitors and unrelated distractors for bimodal bilinguals, with the window of interest (200 to 1,080 ms) based on the duration of the sign stimuli.

Sublexical effects: Onset and rhyme.

Onset competitors. There was a significant effect of this competitor on the intercept term (Estimate = 0.020, SE = 0.007, $P = 0.008$), 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, $P = 0.002$), indicating a steeper slope for looks to onset competitors compared to unrelated distractors (*SI Appendix*, Table S1*A* for full results).

Table 1. Behavioral measures for responses to filler trials

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)

Target item was included in the images, and participants had to respond. SDs are shown in parentheses.

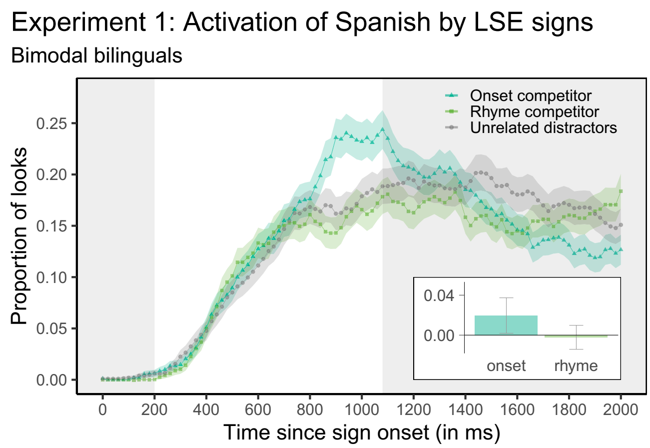

Fig. 1. Proportion of looks to onset and rhyme competitors and unrelated distractors for Spanish/LSE bimodal bilinguals (n = 28) from sign onset to the end of the trial (0–2,000 ms). Error bands show SE. The window of interest (200 to 1,080 ms) is shown by a white background. *Inset* shows the magnitude of each competitor effect (looks to competitor minus looks to unrelated distractors) over the entire window of interest; errors bars show 95% CIs.

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 (*SI Appendix*, Table S1*A* 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 = 0.005) and on both temporal terms (linear: Estimate = −0.169, SE = 0.049, P = 0.001; quadratic: Estimate = −0.096, SE = 0.043, P = 0.027), indicating a higher overall proportion and a steeper slope of looks to onset competitors compared to rhyme distractors (*SI Appendix*, Table S1*B* provides full results).

Summary of Experiment 1. Experiment 1 demonstrated cross-modal coactivation of Spanish sublexical 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 coactivation 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) coactivation depended on prior cross-language coactivation, 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 coactivation of Spanish in the absence of a spoken linguistic signal in bimodal bilinguals. To allow a comparison with covert coactivation 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 investigated onset and rhyme effects (in the same trial) in cross-language activation of spoken languages.

Our expectations were similar to those of Experiment 1: Cross-language coactivation 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. Fig. 2 shows the grand average plots for the eye gaze behavior, with the window of interest (200 to 860 ms) based on the duration of the stimuli.

Sublexical 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 = 0.025), 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 = 0.017), indicating a different time course compared to unrelated distractors (*SI Appendix*, Table S2*A* for full results).

Rhyme competitors. Significant effects of this competitor on the intercept (Estimate = 0.026, SE = 0.009, P = 0.004) and on the quadratic term (Estimate = −0.114, SE = 0.053, P = 0.031) indicated a higher proportion of looks to rhyme competitors and different time course compared to unrelated distractors (*SI Appendix*, Table S2*A* 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 (*SI Appendix*, Table S2*B*).

Summary of Experiment 2. The results of Experiment 2 show phonologically covert coactivation 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 coactivation (24, 26), we predicted stronger and earlier coactivation for onset compared to rhyme competitors. This was not the case, suggesting that sublexical coactivation might differ between within- versus cross-language contexts. In the cross-language setting, the

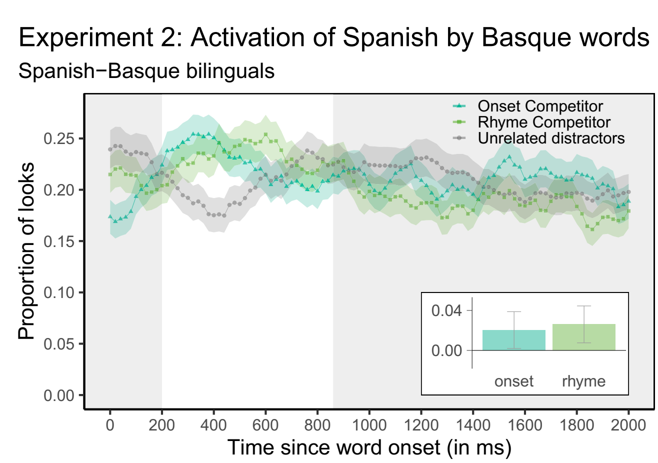

Fig. 2. Proportion of looks to onset and rhyme competitors and unrelated distractors for Spanish/Basque unimodal bilinguals (n = 33) from word onset to the end of the trial (0 to 2,000 ms). Error bands show SE. The window of interest (200 to 860 ms) is shown by a white background. *Inset* shows the magnitude of each competitor effect (looks to competitor minus looks to unrelated distractors) over the entire window of interest; errors bars show 95% CIs.

lexical item was activated without temporal structure and the spreading coactivation no longer reflected the temporal structure of the word: Onset and rhyme effects showed no differences in timing or strength.

Experiment 3: Cross-Modal, Cross-Language, Signed Lexical Access in Bimodal Bilinguals. In lexical coactivation in LSE, signs coactivate 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 coactivation of signed sublexical representations occurs independently of the presence of a signed linguistic signal, we expected 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 coactivation also held here, handshape effects would be stronger but later than location effects.

Results of Experiment 3. Accuracy rates and response times for filler trials are shown in Table 1.

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

Sublexical effects: Location and handshape.

Location competitors. A significant effect of this competitor on the intercept term (Estimate = 0.032, SE = 0.008, $P < 0.001$) indicated a higher overall proportion of looks to location competitors than to unrelated distractors (*SI Appendix*, Table S3*A* for full results).

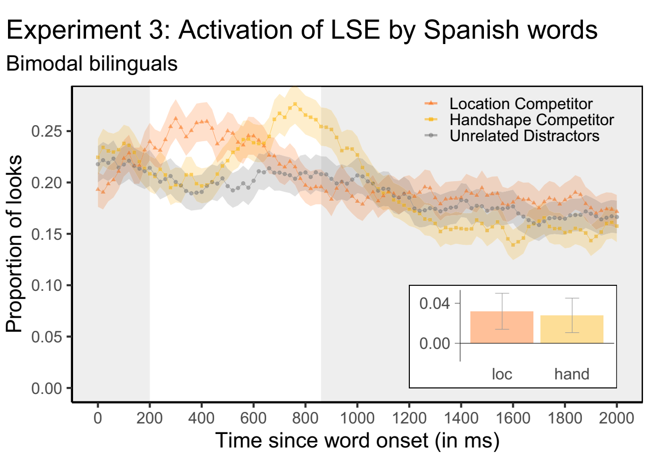

Fig. 3. Proportion of looks to location and handshape competitors and unrelated distractors for bimodal bilinguals (n = 28) from word onset to the end of the trial (0 to 2,000 ms). Error bands show SE. The window of interest (200 to 860 ms) is shown by a white background. *Inset* shows the magnitude of each competitor effect (looks to competitor minus looks to unrelated distractors) over the entire window of interest; errors bars show 95% CIs. Hand, handshape; loc, location.

Handshape competitors. The analysis showed a significant effect of Competitor on the intercept term (Estimate = 0.028, SE = 0.008, $P = 0.001$), reflecting a higher overall proportion of looks to handshape competitors than to unrelated distractors (*SI Appendix*, Table S3*A* 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, $P = 0.005$) 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 (*SI Appendix*, Table S3*B* provides full results).

Summary of Experiment 3. The results of Experiment 3 show that the coactivation of sublexical 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 sublexical unit (15–17, 19–21, 29). This increases the likelihood of finding evidence for coactivation but makes it difficult to assess the role of different sublexical units. This study showed cross-language activation of signs via a single shared parameter: either handshape or location.

In the previous study on lexical coactivation 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 noted that the preserved temporal ordering of the effects in overt and covert coactivation 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 expand further on this finding in the *Discussion*.

Experiment 4: Cross-Modal, Cross-Language, Signed Lexical Access in Sign-Naive 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 had no knowledge of LSE, we did not expect them to show any preference based on phonological similarity in LSE. Therefore, their looking behavior toward handshape and location competitors would not differ from that toward unrelated distractors.

Results of Experiment 4. Accuracy rate and response time for filler trials are shown in Table 1. Fig. 4 shows the grand average plots for the eye gaze behavior.

Sublexical 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 *SI Appendix*, Table S4 for detailed results.

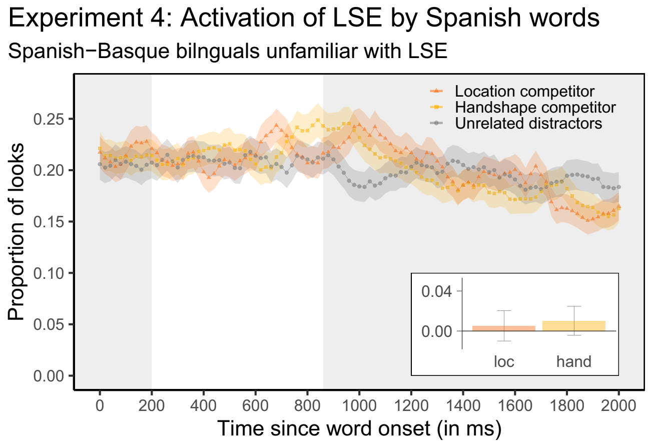

Fig. 4. Proportion of looks to handshape and location competitors and unrelated distractors for Spanish/Basque unimodal bilinguals with no knowledge of LSE (n = 25) from word onset to the end of the trial (0 to 2,000 ms). Error bands show SE. The window of interest (200 to 860 ms) is shown on a white 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% CIs. Hand, handshape; loc, location.

Summary of Experiment 4. The results of Experiment 4 confirm that individuals with no knowledge of LSE showed 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 coactivation in bilinguals to investigate how lexical access and activation of sublexical 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 sublexical units in cross-language lexical access. Specifically, Experiments 1 and 3 looked at cross-modal, cross-language coactivation and showed activation of spoken sublexical representations while viewing signs (Experiment 1) and, vice versa, activation of signed sublexical 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 sublexical representations while hearing Basque words. Experiment 4 served as a control experiment to confirm that results from Experiment 3 were not observed in nonsigners.

In contrast to spoken languages, where a word in one language can activate phonologically similar words in another 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) were all phonologically unrelated. These coactivation effects were 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 was 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 had an impact on the organization of their mental lexicon and how the two languages interacted. Nevertheless, coactivation of translation equivalents is widely reported in various bilingual populations (4, 14, 20) and falls more generally within semantic coactivation, which occurs in monolingual individuals. The sequential combination of semantic and phonological coactivation in STAR > "estrella" > "espada" has been reported for within-language contexts in the reverse direction: 'logs' > 'lock' > 'key' (30).

Experiment 1 investigated the dynamics of activation of spoken Spanish sublexical representations when the input was a visual LSE sign and provided evidence for coactivation of onset representations but not rhyme representations. Our previous study (24) on lexical coactivation in Spanish provides an informative comparison. Using the same stimuli and paradigm, the same group of participants coactivated both Spanish onset and rhyme competitors when the stimulus was presented as a Spanish word (rather than as an LSE sign). Another point of comparison comes from the results of Experiment 2, in which Spanish/Basque bilinguals coactivated 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 coactivation patterns are conditioned by whether this coactivation 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 coactivation in Spanish, hearing a (Spanish) word provides a temporally structured input that imposes sequential order on the coactivation processes: Onset comes before rhyme in the input, and as a result, onset competitors are activated earlier and more strongly than rhyme competitors are. In contrast, when coactivated through Basque, the lexical representation in Spanish is not as 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 sublexical 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 sublexical units for spoken and written words, respectively (31). 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 sublexical information becomes available by using printed words and pictures as stimuli in addition to cross-language translation equivalents.

Returning to the cross-modal findings, coactivation through LSE signs yielded onset competitor effects but no rhyme competitor effects. Given how the two coactivation effects became more homogeneous in the (within-modality) cross-language setting, the lack of a rhyme effect in the cross-modal setting was somewhat surprising. The few available studies looking at parallel activation of a spoken (or written) language by a signed language did show coactivation 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 coactivation of sublexical information in Spanish (through LSE and Basque, respectively) is the complexity of the process of coactivation: In the case of within-modal coactivation, 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 sublexical 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 (32, 33). 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 coactivation 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 coactivation 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 coactivation in LSE with the same stimuli, paradigm, and participants. When signs were seen, handshape coactivation was stronger and later than location coactivation (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 coactivation 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 sublexical units, we calculated how often a given handshape or major location appeared in a lexical database of over 2,400 LSE signs (34). This measure, which we are calling sublexical density, reflects how common a specific sublexical 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 sublexical density values. When information about the relative timing of handshape versus location is included in the stimulus sign in the analysis, the relative ordering of location and handshape coactivation was still evident (*SI Appendix*, Table S5 *A* and *B* provides full details and results). In contrast, when sublexical density was included in the analysis, there was no longer evidence of relative ordering of location and handshape coactivation (*SI Appendix*, Table S5*C* provides full details and results). Thus, the relative timing of coactivation of location and handshape when seeing a sign can be explained by differences in the sublexical density of those sublexical 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 sublexical density also account for the ordering of location and handshape coactivation 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 sublexical density was included, the analysis showed only weak evidence for a difference in the timing of location and handshape coactivation. (Additionally, sublexical density modulated the overall magnitude of coactivation. *SI Appendix*, Table S6 *A* and *B* provides full details and results.) This follow-up analysis suggests that the distribution of handshapes and locations in the sign lexicon impacts how these sublexical 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 (31). A recent neuroimaging study provides converging evidence that this temporal ordering is driven by structural linguistic properties (35). Electrocorticograph 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 coactivation occurs across linguistically disparate contexts, even when there is no possibility of phonological overlap between languages (15–17, 20, 22, 29), and furthermore demonstrate that this coactivation occurs in both directions in bimodal bilinguals.

In addition, our experimental design directly aimed to probe the time course and role of sublexical units in coactivation during lexical access across languages and modalities. By comparing these results with previous findings for sublexical coactivation in a within-language setting, the current study yields insights into how the presence of the input signal impacts the processing of sublexical information. The results provide clear evidence for differential processing of distinct sublexical 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 a marked difference between modalities in the influence of the temporal structure of the linguistic signal on lexical coactivation. For spoken language, the temporal structure of words imposes temporal order on sublexical processing: Onset competitors are activated before rhyme competitors; when the lexical item is coactivated 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 coactivation effects is not dependent on whether or not the sign itself is perceived. Instead, our results lead us to believe that distributional properties of sublexical units explain the different time course of location and handshape coactivation. 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 Basque Center on Cognition, Brain and Language Ethics Committee and were performed in accordance with the Helsinki Declaration. All participants provided informed consent.

Experiment 1.

Participants. We recruited a group of 28 native bimodal bilinguals of Spanish and LSE (22 female; mean age, 44 y). All participants were hearing and learned 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 y of experience using LSE professionally; range 4 to 29 y). 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 center 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 coactivation 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, and 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 ref. 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 320 × 296 pixels and presented in the center of the screen (25 fps). Each video started with the signer in the resting position (hands by her sides) followed by a transition movement to articulate the sign and ended with the signer 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 ms); the average onset for handshape was 387 ms, and for location it was 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 1,000 Hz 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 (1,044 × 768 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, a 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 Fig. 5*A*. 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 min.

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 to 12 per participant). After these invalid trials were removed, there were no trials with incorrect responses (i.e., false hits).

We analyzed the data using R (36) v4.0.3 with the VWPre package (37) v1.2.3 for preprocessing and the lme4 package (38) 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 coactivation, 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 ms), resulting in a 200- to 1,080-ms window for analysis after accounting for the ∼200 ms involved to program an eye movement (39) (Fig. 5*B*). 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 behavior, we performed a time series analysis: growth curve analysis (40). 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), the steepness of the slope (linear term), and the shape of the curve (quadratic and higher-order terms). This allowed us to estimate the strength of the coactivation, indexed by the proportion of looks (intercept term), and the temporal

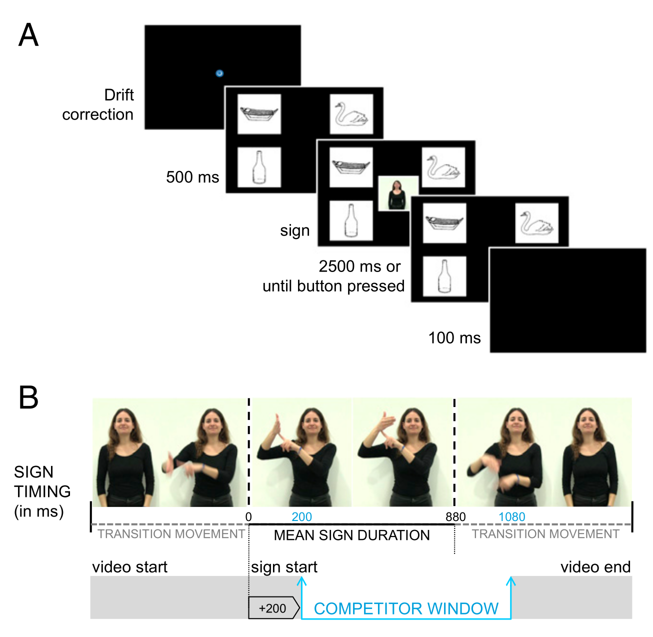

Fig. 5. (*A*) Trial sequence for Experiment 1: parallel activation of spoken Spanish. (*B*) Illustration of sign duration (in milliseconds) and the selected time window for the analysis of onset and rhyme competition effects for the LSE stimulus FLAG.

development of coactivation, revealed by changes in the looking behavior 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 (40), 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 was not possible to use growth curve analysis on participant-by-item data (41). For the model parameter estimates, normal approximation (z-distribution) was used to calculate *P* values. Fixed effects (with SE, 95% CI, *t* statistic, and *P* value) for all analyses are provided in the *SI Appendix*.

Sublexical effects. To assess the effect of the sublexical competitors, the overall time course of fixations was modeled with 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 was treated as the reference level and parameters were 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 more each participant looked 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 bar plot insets in Figs. 1–4.

Comparison of sublexical effects. To check for differences between competitors, the competitor curves were modeled 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 (acquisition for both languages before the age of 6 y) with no knowledge of LSE (mean age, 38 y; SD = 6.6 y; 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. Fig. 6*A* illustrates the trial sequence. The experiment lasted less than 10 min.

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), allowing for an additional 200 ms for the programming and executing of eye movements, resulting in a time window of 200 to 860 ms (see Fig. 6*B*). 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 coactivation in LSE using the same paradigm, with handshape and location competitors for an LSE target sign. All targets, competitors, and distractors were LSE noun signs from the Standardized LSE Dictionary (42) (available online: www.fundacioncnse.org/tesorolse/index.html) and were 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 ref. 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 ms).

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. 6*A* illustrates the trial sequence). The experiment lasted less than 10 min.

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 sign that was different from the one expected, the trial was eliminated from the analysis. Thus, 28.1% of the trials were eliminated (range per participant, 1 to 14). After these invalid trials were removed, 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), which was shifted 200 ms to allow for the programming and launching of eye movements, was selected for the analyses of handshape and location coactivation. This resulted in a window of interest between 200 ms and 860 ms after word onset (Fig. 6*B*). 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).

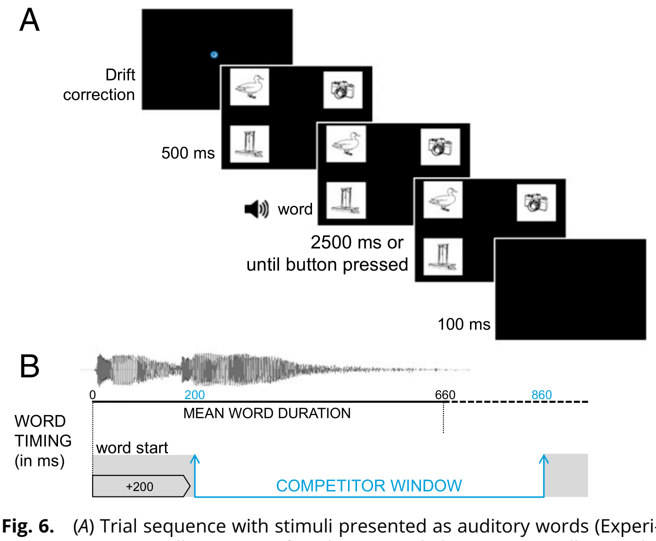

Fig. 6. (*A*) Trial sequence with stimuli presented as auditory words (Experiments 2 to 4). (*B*) Illustration of auditory word duration (in milliseconds) and the selected time window for the analysis of competition effects.

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 y; SD = 6.1 y; 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, Materials, and Software Availability. Eye-tracking data and lexical data for stimuli have been deposited in Open Science Framework repository: Eye-tracking data on cross-language (cross-modal) coactivation (https://osf.io/m2qz6) (43).

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