Brain & Language 259 (2024) 105495

Contents lists available at ScienceDirect

Brain and Language

journal homepage: www.elsevier.com/locate/b&l

Neural changes in sign language vocabulary learning: Tracking lexical integration with ERP measures

Marc Gimeno-Martínez [a,*], Eva Gutierrez-Sigut [b], Cristina Baus [c]

[a] Center for Brain and Cognition (CBC), Universitat Pompeu Fabra, Spain
[b] Department of Psychology, University of Essex, Essex, UK
[c] Department of Cognition, Development and Educational Psychology, Institut de Neurociències, Universitat de Barcelona, Spain

ARTICLE INFO

Keywords:
N400
Lexical integration
Bimodal bilingualism
Sign learning

ABSTRACT

The present study aimed to investigate the neural changes related to the early stages of sign language vocabulary learning. Hearing non-signers were exposed to Catalan Sign Language (LSC) signs in three laboratory learning sessions over the course of a week. Participants completed two priming tasks designed to examine learning-related neural changes by means of N400 responses. In a semantic decision task, participants evaluated whether written Catalan word pairs were semantically related or not. The experimental manipulation included prime-target phonological overlap (or not) of the corresponding LSC sign translations. In a LSC primed lexical decision task, participants saw pairs of signs and had to determine if the targets were real LSC signs or not. The experimental design included pairs of signs that were semantically related or unrelated. The results of the LSC lexical decision task showed N400 lexicality and semantic priming effects in the third session. Also in the third session, N400 effects related to the activation of LSC phonology were observed during word processing in the semantic decision task. Overall, our findings suggest rapid neural changes occurring during the initial stages of intensive sign language vocabulary training. The results are discussed in relation to the temporality of lexicality and semantic effects, as well as their potential relation to linguistic features of sign languages.

1. Introduction

Vocabulary learning is a fast and efficient process, essential for building a lexicon and ultimately mastering a language (see Qian & Lin, 2020 for a review). The significance of vocabulary acquisition is evident for individuals learning new words in their first language, and even more so for second language (L2) learners (Nation & Nation, 2001). For beginners in an L2, minimal exposure can suffice for new vocabulary to be assimilated into memory (e.g., Bisson et al., 2014), which denotes a dynamic lexical system that constantly adapts to accommodate new lexical entries. This adaptability also involves establishing connections between new L2 and existing L1 lexical entries, influencing the processing of both languages (see Kroll & Ma, 2017 for a review). In the present study, we focused on exploring the neural dynamics occurring during vocabulary learning of a sign language in a particular subgroup of L2 learners, hearing sign language learners. Our primary objective is to investigate how a new lexical system is built and how newly acquired L2 signs are connected to existing L1 words.

For hearing non-signers, learning a sign language represents a special case in L2 learning since the acquisition of new vocabulary involves a different language modality (second modality-second language —M2L2— learners, Pichler & Koulidobrova, 2016).[1] The perceptual and articulatory channels engaged in oral languages (in written or spoken format; auditory-vocal) differ from those engaged in sign languages (visual-manual). As such, learning a new sign vocabulary involves encoding novel linguistic features such as the shape of the hand(s), where it is positioned and what orientation it has in relation to the body, how it moves, and possible non-manual movements (e.g., facial

* Corresponding author at: Universitat Pompeu Fabra, Ramon Trías Fargas, 25-27, 08005, Barcelona, Spain.
E-mail addresses: marc.gimeno@ub.edu (M. Gimeno-Martínez), eva.gutierrez@essex.ac.uk (E. Gutierrez-Sigut), cbaus@ub.edu (C. Baus).

[1] We adopt the term M2L2, as used by Pichler and Koulidobrova (2016), which is commonly employed to describe adult hearing learners of sign language. It is important to note that by using this term, we do not intend to present a dichotomous view of language. In this study we use the term M2 to indicate that hearing non-signers lack experience with sign language in the visual/manual modality not with the whole modality. Hearing non-signers often use gestures in their communication and their expertise could serve as a valuable foundation for sign language acquisition (e.g., Ortega et al., 2020). Similarly, deaf signers incorporate mouthings when signing, evidencing the multimodal nature of language.

https://doi.org/10.1016/j.bandl.2024.105495
Received 2 July 2024; Received in revised form 14 October 2024; Accepted 18 October 2024
Available online 24 October 2024
0093-934X/

expressions or body positions) that are performed along with the sign. Importantly, although these features of signs lack direct correspondence with features of words, cross-linguistic interactions between the signed and the oral lexicon have been reported for proficient signers (e.g., Gimeno-Martínez & Baus, 2023; Kubus et al., 2015; Morford et al., 2011; Villameriel et al., 2016). In contrast, little is known about the neural dynamics between lexical systems in the first stages of adult L2 sign vocabulary learning. Next, we briefly review research on oral languages and discuss whether the dynamics between the lexical systems of bimodal learners might differ from those of unimodal (oral) learners' lexical systems.

1.1. Stages and neural markers of lexical integration

In the process of learning, a word is considered to be fully integrated into the lexicon when its processing resembles existing words, and it is able to interact with other words in the lexicon. In many paradigms, lexical integration is revealed by behavioral and neural evidence of interaction, such as interference patterns between new words and existing phonological neighbors (Gaskell & Dumay, 2003) or facilitation patterns with existing semantic-related words (Borovsky et al., 2010). At the neural level, the N400 component has been a particularly sensitive marker of lexical and semantic integration in word learning. This negative component, peaking around 400 ms after the stimulus onset presentation, is generally associated with automatic lexical-semantic processing (Kutas & Federmeier, 2011). In the context of word learning, modulations of the N400 have been considered a reliable measure of the lexical status of newly acquired words (Bentin, 1987) and their integration into the existing lexico-semantic network (Holcomb, 1993). The fact that the N400 response reduces for known words relative to unknown words, makes it an ideal marker of word learning, with newly learned words resembling N400-patterns of existing words (Batterink & Neville, 2011; Borovsky et al., 2010; McLaughlin et al., 2004; Mestres-Missé et al., 2007).

In the context of L2 word learning, McLaughlin et al. (2004) revealed both lexical and semantic N400 priming effects as a marker of L2 integration. In a priming lexical decision task, L2 French learners judged whether the second of a pair of letter strings was a real French word or a pseudoword. In each pair, the first letter string was always a real French word, semantically related or unrelated to the target word. After fourteen hours of formal instruction, a lexicality effect was observed with a reduction of the N400 for real words in comparison to pseudoword targets. This result showed that learners were sensitive to plausible form combinations of the language to be learned after a few hours of L2 instruction. It was not until a posterior testing session, after sixty-three hours of instruction, that semantic priming effects emerged. The N400 was reduced for semantically related pairs in comparison to unrelated pairs, reflecting the development of semantic connections between words in the lexicon. Altogether, these findings were interpreted as showing that a certain level of knowledge of word forms is required as a prerequisite for semantic access of newly acquired L2 words. Or, in other words, N400 modulations reflected a two-stage process of L2 vocabulary learning, with novel words integrated into the lexicon revealing first ERP patterns of existing words (lexicality effects), followed by the development of semantic connections with other words in the lexicon (semantic effects).

One critical issue in the literature on word learning is the role of offline consolidation (e.g., overnight sleep). It is generally agreed that only after a number of meaningful exposures to novel words, including at least one period of consolidation, word memory traces can be integrated into the lexicon (e.g., Bakker et al., 2014; Bakker et al., 2015a; Bakker et al., 2015b; Bakker-Marshall et al., 2018; Born & Wilhelm, 2012; Dumay & Gaskell, 2007; Gais et al., 2006; Stickgold & Walker, 2007; for a review of behavioral studies, see Palma & Titone, 2021). By comparing lexical and semantic priming effects before and after a consolidation period, Bakker et al. (2015b) reported reliable lexicality N400 effects, but not semantic effects after one learning session and one period of sleep. ERPs associated with novel words learned in two sessions, separated by twenty-four hours, were compared to existing words. The N400 lexicality effect (the difference between novel and existing words) diminished with offline consolidation. Initially, recently learned words (i.e., minutes before the test) elicited a large N400 response compared to existing words. After a twenty-four-hour consolidation period, this effect reduced, leading to N400 responses for learned words no longer differing from that of existing words. These results suggested that at a first stage, novel words are processed similarly to pseudowords (difficult to discard), but after a consolidation period, their processing becomes more akin to that of existing words (see Yum et al., 2014, for similar results with English learners acquiring words of a different script). However, relative to the observation of rapid lexicality effects, the integration of novel words into the semantic network seems to be a more gradual process. Bakker et al. (2015b) did not observe semantic integration effects within the N400 time range but with a later latency, during the Late Positive Complex (LPC) phase. The LPC is interpreted as strategic semantic processing in the early stages of word learning, becoming more automatic with some training sessions and periods of consolidation. N400 semantic priming effects have been reported with extended periods of offline consolidation (Pu et al., 2016; Tamminen & Gaskell, 2013; but see Liu & van Hell, 2020, for LPC semantic priming and absence of N400 effects). Importantly, studies testing novel word learning, both in laboratory-sessions and during natural L2 instruction (McLaughlin et al., 2004), seem to converge in showing that newly acquired words become lexicalized before being integrated into the semantic network of learners.

When considering the lexical integration of signs, some relevant features of the signed language modality should be mentioned. Relative to words, sign forms often hold a tighter relationship with their meanings. For example, some meaning-related signs share specific locations (e.g., mind-related signs are located on the forehead, Zwitserlood et al., 2023), and some handshapes are associated with particular semantic categories (i.e., classifier systems). Moreover, lexical and iconic form-meaning mappings are much more prominent in sign languages than in oral languages. Iconicity is broadly defined as the resemblance between the linguistic form and its meaning (e.g., Dingemanse et al., 2020). In sign languages, iconicity refers to the visual resemblance between the form of a sign and the meaning that it represents. For instance, in Catalan Sign Language (*Llengua de Signes Catalana*, LSC), the sign for scissors is performed extending the index and middle fingers to represent the blades of a pair of scissors and moving them to mimic the cutting motion. Iconicity has been shown to influence sign processing in signers (Gimeno-Martínez & Baus, 2022; Gutiérrez et al., 2012) and especially affects learning rates of hearing non-signers (Marshall et al., 2021; Pichler & Koulidobrova, 2016). In this context, the closer form-meaning mappings of signs (relative to words) could influence the early stages of M2L2 sign lexical and semantic processing. Specifically, under the assumption that it is easier to create correspondences between a referent and the visual-gestural properties of signs compared to the acoustic properties of vocal productions, and that visual features boost semantic conceptualization (Grote et al., 2001), semantic effects could emerge earlier compared to the later appearance observed in the oral modality. Furthermore, although non-signers lack experience with sign languages, they often use some gestures to accompany their oral productions. These gestures, which can reinforce the oral message or serve as emblems (gestures used to convey meaning and could be produced independently of speech), provide experience in producing and perceiving hand forms and movements. This gesture experience has been found to facilitate sign vocabulary learning in hearing non-signer adults (Ortega et al., 2019; 2020). Thus, gesture experience could also influence the early stages of sign form processing in sign learners.

To investigate the developmental stages underlying M2L2 sign learning, a sign lexical decision task (task 1) was employed to explore N400 changes as an index of signs' lexical and semantic integration.

Consistent with neural markers of word integration, reduced N400 amplitudes for signs compared to non-signs would be expected after at least a period of consolidation, reflecting lexicalization of new signs. Regarding semantic effects, we anticipate reduced N400 amplitudes for semantically related signs compared to semantically unrelated signs. Following previous results in oral languages, we expect lexicality effects to precede semantic effects (McLaughlin et al., 2004). However, if semantic processing is enhanced by the characteristics of the sign modality, we might expect semantic effects to appear simultaneously with, or even before, lexicality effects.

Additionally, we categorized non-signs into phonotactically legal signs (where the original handshape was replaced with a handshape from the LSC phonological repertoire) and phonotactically illegal signs (where the original handshape was replaced with a made-up handshape not belonging to the LSC phonological repertoire, nor used as gesture). The inclusion of the phonotactically illegal condition aimed to introduce an additional dimension to explore the lexicality effect. By including legal and illegal forms, we aimed to assess participants' sensitivity to the phonotactics of LSC and the possible influence of gesture experience in their performance. This involved determining not only whether a given combination of parameters constituted a genuine LSC sign (i.e., lexicality effect), but also whether participants were aware that certain handshapes were not part of the LSC. If participants distinguish between legal and illegal handshapes, we should expect reduced N400 amplitudes for phonotactically illegal non-signs compared to phonotactically legal non-signs, similar to the effects reported for non-words and pseudowords (Holcomb & Neville, 1990).

Taking a different approach, a second experimental task (word semantic decision task; task 2) was designed to further explore the integration of M2L2 novel signs into the lexicon by testing whether L2 connections influenced the processing of the L1. Most studies on the topic of vocabulary learning in the oral modality explored this issue by having both languages involved in the task (e.g., prime including the new word and target including the existing word; Bakker et al., 2015b). Behavioral and neural effects while processing the L1 target have been taken as evidence that new words are integrated into the lexicon and interact with existing words. Relevant here, Bice and Kroll (2015) revealed effects of L2 learned words when the task was restricted to the L1 of the participant. In a lexical decision task, two groups of learners, beginners and intermediate learners, were asked to respond to whether a letter string was a real English word or not (their L1). Importantly, half of their words were L1 English – L2 Spanish cognates (e.g., crude-crudo), while the remaining were non-cognates. As revealed, a certain level of language proficiency must be attained for L2 words being activated during L1 processing. Only those learners attaining sufficient L2 proficiency (i.e., intermediate learners) revealed a reduced N400 for cognate words relative to non-cognates, which was interpreted as evidence that L2 attainment produces changes to the existing lexical network (Cook, 2003).

In the present study, we explored whether the L2 (signs) is active during L1 (words) processing after an intensive L2 laboratory training, using a semantic decision task involving a hidden phonological manipulation (Thierry and Wu, 2007). In their study, Chinese – English bilinguals made judgements about the semantic relation of English (L2) word pairs that could be phonologically related in Chinese (L1) or not. Results showed phonological effects of the bilingual's L1 (Chinese) when processing their L2 (English), as evidenced by the N400 ERP component. Adaptations of Thierry and Wu's (2007) paradigm to the signed modality have also shown linguistic interactions across modalities in proficient bimodal bilinguals (those who use both an oral language and a sign language; Kubus et al., 2015; Mendoza & Jackson-Maldonado, 2020; Morford et al., 2011; Morford et al., 2019; Morford, Kroll, Piñar, & Wilkinson, 2014; Morford, Occhino-Kehoe, Piñar, Wilkinson, & Kroll, 2017). Generally, the observation of cross-linguistic effects has been explained through parallel distribution accounts, in which the presentation of a stimulus in one language modality (signs or words) activates its corresponding translation via vertical connections between lexical representations and semantics, as well as lateral connections between lexical representations of sign and oral languages. This, in turn, activates a phonologically related lexical entry (e.g., Morford et al., 2017; Ormel et al., 2012; Shook & Marian, 2012). Like these studies, we presented participants with a word semantic priming task in their L1 (Catalan) and manipulated the phonological relationship of the prime and target sign's translations, having phonologically related LSC (L2) translation pairs and phonologically unrelated translation pairs. If sign learners are sensitive to the phonological properties of sign forms while performing the task in their L1 (Catalan), we should observe differences comparing word pairs that are phonologically related through their LSC translations compared to those word pairs with unrelated LSC translations. Specifically, similar to other studies involving phonological manipulations, we expect to observe reduced N400 amplitudes for LSC phonologically related word pairs compared to LSC unrelated word pairs (Gutierrez et al., 2012).

In sum, in two tasks we explored the neural dynamics underlying the early stages of M2L2 sign learning. Three laboratory sessions were conducted within the same week, including two consolidation periods, to examine the integration of newly acquired signs into the learner's lexicon and the interaction between these signs and the learner's first language (L1). The behavioral and neural learning effects were tracked in two laboratory training sessions, each followed by a consolidation period of 24 to 48 h. Changes in priming effects (LSC lexical decision task, task 1), including lexicality and semantic effects, were analyzed across sessions to evaluate lexical integration. The cross-language interaction between newly acquired signs and existing words (word semantic decision task; task 2) was assessed by measuring the phonological priming effects in written stimuli. In the following, we describe first the participants and the general training procedure and then the two experimental tasks employed.

2. Training procedure

2.1. Participants

Thirty-two hearing Catalan speakers with no previous knowledge of LSC were recruited to participate in the study (twenty-one females, M_{age} = 22 years, range = 18–26 years). All participants were proficient bilinguals in Catalan and Spanish, with Catalan being their first acquired language. Additionally, they reported having a good command of English. As our study was exploratory in nature, we were unable to obtain reliable measures to determine the appropriate sample size. Nonetheless, the number of participants in our study exceeds those of other studies that have investigated priming effects in M2L2 sign learners (Mott et al., 2020; Ortega et al., 2019). Participants were recruited from the Center for Brain and Cognition database (Universitat Pompeu Fabra, Barcelona). All methods were in accordance with the guidelines of the ethics committee at Pompeu Fabra University and approval of the experimental protocol was obtained from the University's ethics committee. Participants were informed that to participate in the experiment they would have to attend three experimental sessions on different days within the same week. They all completed and signed an informed consent form before the experiment and were paid for their participation. From the initial pool of participants, as exclusion criteria, participants with high artifact rejection rates (>15 %) in one session were excluded from the analysis of that session (one participant in the second and one participant in the third session). In addition, those participants (n = 2) with high artifact rejection rates in two or more sessions were excluded from the analysis of all sessions.

2.2. Materials

The complete set of video stimuli consisted of individual one hundred and fifty LSC lexical signs. Signs were performed by a proficient signer and were produced without accompanying mouth movements. It is important to note that, although mouthing is proposed to be an integral part of lexical access for expert signers, we removed the accompanying mouth movements to prevent conveying partial phonological information from their oral translations. Video stimuli included the transitional movement of the hand(s) from the signer's lap (rest position) to the sign onset, and the transitional movement back to the rest position (see also Mott et al., 2020). In this way, we could consider the processes involved in early sign recognition (Emmorey et al., 2022), and avoid possible distracting effects on participants due to the sudden appearance of the signs in different locations. Videos were clipped to start approximately 1000 ms before the sign onset ($M = 1000.3$ ms, $SD = 156.4$ ms), and to end approximately 2000 ms after sign onset, resulting in a total video duration of 3000 ms. Sign onsets were determined as the first frame in which the fully formed handshape contacted the body or, for non-contact signs, when the hand reached the target location. Sign offsets were determined as the last frame in which the handshape was no longer in contact with the body or had moved away from the target location. Together, the sign onset and offset frames were used to calculate the duration of each sign. On average, duration of target signs was 813 ms (SD = 327 ms). ERPs were time-locked to the onset of the sign video, and the N400 time range was calculated starting from the sign onset. Further, to gauge the potential iconicity of the signs to be learned, we collected iconicity ratings from a group of nineteen non-signers. Raters were asked to evaluate how well the sign resembled the related concept on a scale from 1 (not iconic) to 7 (highly iconic). The mean iconicity rating across the selected stimuli was $M = 3.4$, with a standard deviation of $SD = 1.73$. Specifically, out of the total one hundred and fifty signs, fifty-six signs received ratings equal to or above four (indicating high iconicity), while ninety-four signs received ratings below four (indicating low iconicity). This indicates that approximately two thirds of the stimuli were considered low-iconic (see Caselli & Pyers, 2017 for a similar threshold).

2.3. Procedure

Participants attended the lab in three sessions within the same week. In all three sessions, participants were tested individually in a sound attenuated dimly lit room, while behavioral and EEG measurements were recorded. Each session was twenty-four to forty-eight hours apart and began with two experimental tasks: a word semantic decision task and a LSC lexical decision task. The two experimental tasks were followed by a training procedure and two learning evaluation tasks: a forced-choice task and a cross-modal translation task (see Table 1). Due to the structure of the experimental sessions, the initial session involved the presentation of the two experimental tasks prior to the learning phase. This arrangement ensured that participants were not exposed to any sign language vocabulary beforehand. All sessions followed the same structure, with the only difference being the exclusion of the forced-choice task in the third session. This decision was based on pilot testing results, where participants achieved an accuracy rate of over 90 % in the second session.

It should be noted that although the word semantic decision task was tested first and it was followed by the LSC lexical decision task, in this manuscript we present these tasks in the reverse order for the sake of logical coherence from a theoretical standpoint. Our focus was to first examine participants' sensitivity to the properties of newly learned signs through the lexical decision task. Subsequently, we investigated whether these signs are activated during the processing of Catalan words in the semantic decision task.

Table 1
Task Structure and Duration (in Minutes) Across the Three Sessions. The Duration of Each Task Varied Depending on The Participant, the Desired Rest Time Between Blocks, and the Session Number. The tasks presented in this manuscript are the two experimental tasks: the word semantic decision task and the LSC lexical decision task.

Block	Session			Task Duration
	1	2	3	
ExperimentalTasks	Semantic Decision	Semantic Decision	Semantic Decision	15′
	Lexical Decision	Lexical Decision	Lexical Decision	30′
TrainingProcedure	Associative Learning	Associative Learning	Associative Learning	20′ – 40′
Evaluation ofLearning Outcomes	Forced-choice	Forced-choice		20′ – 40′
	Cross-modal Translation	Cross-modal Translation	Cross-modal Translation	15′ – 20′

2.3.1. Training procedure and learning assessment tasks

As mentioned, the experimental tasks were followed by a training procedure in which participants completed an associative learning task and two tasks that evaluate the learning outcomes: a forced-choice task and a cross-modal translation task (see also Mott et al., 2020, for a similar learning protocol).

In the *associative learning task*, printed Catalan words were displayed on the screen, followed by the presentation of the corresponding video of the LSC translation of the word. Once the video finished, the Catalan translation reappeared on the screen until the participant pressed the space bar on the keyboard, indicating their readiness to learn the next sign. Participants were instructed to take as much time as necessary to process each Catalan-LSC pair, and they were also given the opportunity to practice reproducing the sign. Importantly, each of the one hundred and fifty word-sign pairs appeared only once throughout this task.

For the *forced-choice task*, LSC sign videos were shown on the screen, followed by two printed Catalan words. One of the word choices corresponded to the correct translation, while the other word corresponded to a translation for a different LSC sign used in the associative learning task. Participants indicated their choice by pressing designated keys on the keyboard to specify whether the correct translation of the LSC sign was presented on the left or right side of the screen. After the participants' response, they received feedback in the form of the correct translation displayed in the center of the screen. This task allowed us to provide immediate feedback and thus obtain a learning index, while also using the task as a training tool. Responses were not analysed beyond checking accuracy.

In the *cross-modal translation task*, a printed word was briefly displayed (50 ms), followed by a video displaying an LSC sign. Participants were required to verbally report the Catalan translation of the sign. This task was part of a different study; however, it is included here to provide a comprehensive overview of the experimental sessions and to offer an additional measure of the learning progress.

2.3.2. Evaluation of learning outcomes

We evaluated the learning progress of the participants as an indicator of their adherence to the training. The accuracy percentage in the forced-choice task showed improvement across sessions, with session one at 94.52 % and session two at 97.48 % ($t(31) = 3.3$, $p = 0.002$). Likewise, in the cross-modal translation task, the accuracy percentage increased across sessions, with session one at 64.16 %, session two at 84.45 %, and session three at 89.42 % ($F(2,56) = 173.04$, $p < 0.001$; all pairwise comparisons between sessions $p < 0.004$).

3. Task 1. Lexico-semantic processing in M2L2 sign learning

3.1. Methods

3.1.1. Materials

For the LSC lexical decision task, half of the one hundred and fifty LSC signs were selected as primes and the remaining half as targets. For each of the seventy-five target signs, we created two non-existing sign variants: one phonotactically legal and the other phonotactically illegal. Phonotactically legal non-signs were created by replacing the handshape of the original sign with a similar handshape from the LSC phonological repertoire (see Williams & Newman, 2016 for a similar procedure). Phonotactically illegal non-signs were created replacing the handshape of the original sign with a pronounceable hand configuration not belonging to the LSC handshape repertoire. Alongside the comparison between signs and non-signs, the division within the non-sign condition based on phonotactically probability served as an additional measure to investigate lexicality effects. By incorporating both legal and illegal LSC handshapes, we were able to further explore whether participants developed sensitivity about the phonotactics of LSC. This involved not only discerning whether a specific combination of handshapes, movement, and location constituted a genuine LSC sign (i.e. lexicality effects) but also whether they were sensitive to that certain handshapes were not part of the LSC phonological repertoire. As an example, for the LSC sign CAMEL a phonotactically legal non-sign was created changing the *flat O*-handshape for the *A*-handshape, that is present in other LSC signs such as PHARMACY. The related phonotactically illegal non-sign involved a handshape that does not belong to the usual LSC phonological repertoire (see Fig. 1). In both phonotactically legal and phonotactically illegal non-signs, the other sign parameters (i.e., movement, location, orientation) were kept the same as in the original sign. Furthermore, the target signs, the phonotactically legal, and the phonotactically illegal, had similar sign onset times ($F(1.88, 139.11) = 0.04$, $p = 0.95$), and total durations (F $(1.64, 121.61) = 0.58$, $p = 0.53$).

Primes and targets were selected so that they were not phonologically related in LSC. Through the experiment, primes appeared twice, once preceding a target sign and once preceding a non-sign (either a phonotactically legal or a phonotactically illegal) based on the same target sign. Two experimental lists were created, one including the phonotactically legal variant of the sign target and the other the phonotactically illegal variant. The first list consisted of seventy-five signs, thirty-eight phonotactically legal and thirty-seven phonotactically illegal non-sign variants, while the second one consisted of seventy-five signs, thirty-seven phonotactically legal and thirty-eight phonotactically illegal non-signs. For instance, if the prime ELEPHANT appeared with the sign CAMEL and its phonotactically legal version in the first list, it appeared with the sign CAMEL and its phonotactically illegal version in the second list. From each list, twenty-four order versions were generated. In these lists, the trial presentation was pseudorandomized with the constraint that a minimum of five trials separated the two presentations of the same prime and the presentation of the two similar targets (the real LSC sign and its non-sign variant). Presentation lists were counterbalanced across participants and sessions, so one participant saw the first list in the first and third sessions and the second list in the second session, and another participant saw the second list in the first and third sessions and the first list in the second session.

Critical for the semantic manipulation, thirty-eight of the prime-target sign pairs were semantically related whereas thirty-seven were semantically not related. Semantic ratings for the Catalan translations of the prime-target sign pairs were obtained from twenty-nine participants that did not take part in the experiment. Raters were asked to evaluate the semantic relatedness of each word pair on a scale from 1 (unrelated) to 7 (related). Pairs with semantic ratings below four were included in the semantically unrelated condition ($M = 1.82$; $SD = 1.24$), and pairs with mean ratings above four were included in the semantically related condition ($M = 5.68$; $SD = 1.33$). Additionally, primes and targets' Catalan translations were controlled for lexical frequency and word length according to the Catalan metrics obtained from the NIM database (Soskey et al., 2016; Yum et al., 2014), in both related and unrelated conditions.

In sum, in the LSC lexical decision task, each list contained one hundred and fifty video pairs, a prime video and a target video. Target videos were categorized in two groups: seventy-five signs (comprising thirty-eight semantically related signs and thirty-seven semantically unrelated signs) and seventy-five non-signs (consisting of thirty-seven phonotactically legal and thirty-eight phonotactically illegal in the first list and thirty-eight phonotactically legal and thirty-seven phonotactically illegal in the second list).

3.1.2. *Procedure*

In the lexical decision task, participants were presented with one hundred and fifty trials, in which they saw two videos in succession and had to decide whether or not the second video was an existing LSC sign or a non-sign. Before the presentation of the sign prime, a green asterisk (900 ms) was presented, followed by a white asterisk (500 ms) and a blank screen (500 ms). Primes were presented followed by a blank screen (500 ms), and the presentation of the target sign. The trial ended when the participant responded or 8000 ms after the onset of the target sign video. Response times were measured from the onset of the target sign until participants responded by pressing designated keys on the keyboard. Participants were instructed to blink when the green asterisk was displayed on the screen and/or after the response. The task was divided into three blocks of fifty trials, and participants could rest if needed between blocks.

3.1.2.1. EEG procedure. EEG activity was recorded from thirty Ag-AgCl electrodes (see Fig. 2), mounted on an elastic cap (ActiCap) with a common FCz reference. Additional electrodes were placed below the right eye and on the outer canthus of the left eye to identify blink and horizontal eye movement artifacts, respectively. The EEG signal was amplified with BrainAmp (Brain Vision) with a bandpass of the hardware filter of 0.1 to 125 Hz and was sampled continuously at 500 Hz.

EEG data was processed offline using the EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) MATLAB toolboxes. Signals were filtered with a bandpass filter of 0.1–30 Hz and re-referenced offline to the average activity of the two mastoids. Eye blinks and motor artifacts were corrected by the Infomax ICA decomposition algorithm of Brain Analyzer 2.1 (number of ICA steps: 512; number of computed components: 20, classic sphering). Epochs with amplitudes above or below 100 μV or with a difference between the maximum and the minimum amplitude exceeding 75 μV were considered artifacts and discarded from the analysis.

3.1.2.2. Data analysis. Lexical sensitivity in the behavioral data was assessed by deriving d-prime sensitivity measures by computing the proportion of hits and false alarms for each subject at each session. D-prime measures were analyzed with linear mixed-effect models. Models included fixed effects for the number of session (first, second, third), and subjects as random effects. Models were fitted in R (R Core Team, 2019) using the package lme4 (Bates et al., 2015). ERPs were computed for each participant in each condition (semantically related, semantically unrelated, phonotactically legal non-signs, and phonotactically illegal non-signs) and session (first, second, third) across twenty-two electrode sites. Trials with incorrect behavioral responses were excluded from the analyses. ERP amplitude was obtained averaging the activity across time points within the N400 time window, time-locked to the onset of the target stimuli presentation.

To objectively determine the time window related to the N400 component, we estimated its chronometry by computing the mean peak latency of the Cz electrode between 0 ms and 1000 ms after sign onset, considering all subjects, conditions and sessions ($M = 385$ ms after sign onset). This approach allowed us to estimate the consistent timing of the N400 component without focusing on specific pairwise comparisons or individual sessions. Then, we rounded the result to the nearest fifty (400 ms) and calculated 100 ms before and after resulting in the final 300–500 ms time window after sign onset, consistent with previous sign language studies (Gutierrez et al., 2012; McGarry et al., 2021). The 200 ms pre-video period served as a baseline.

Fig. 1. Still images of the sign onset of the videos corresponding to the three variants of the LSC sign CAMEL.

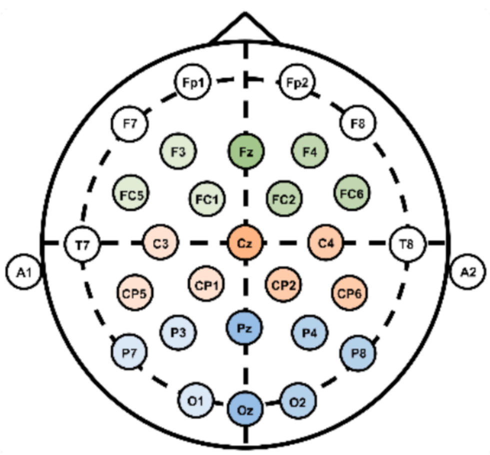

Fig. 2. Electrode montage with the twenty-two sites (filled circles) used in analyses. The greenish color refers to the electrode sites on the frontal region, the orangish color to those on the central region, and the blueish color to those on the posterior region. The light shading corresponds to the electrode sites on the left side, the medium shading to those on the right side, and the dark shading to those on the midline.

To compare mean amplitudes across conditions, we analyzed the data by fitting linear mixed models in R (R Core Team, 2019) using the lme4 package (Bates et al., 2015). Model selection was based on fit statistics (AIC, BIC and Likelihood ratio tests), and in cases where models exhibited equal statistical fit, the more simplified model was selected. The final model encompassed fixed effects for condition (semantically related, semantically unrelated, phonotactically legal non-signs, and phonotactically illegal non-signs), session (first, second, third), laterality (left, midline, right), anteriority (anterior, central, posterior), as well as all the possible interactions among this factors (for a similar approach, Holcomb & Neville, 1990). Subjects and target items were included as cross-random factors, accounting for potential variability in ERP responses due to individual differences and item-specific effects. In all analyses, the significance of the fixed effects estimates was assessed using the Satterthwaite approximation for degrees of freedom provided by the lmerTest package[2] (Kuznetsova et al., 2014). Significant effects of condition (semantically related, semantically unrelated, phototactically legal non-signs, and phonotactically illegal non-signs) were followed by pairwise analyses to examine the three specific comparisons of interest: lexicality effects (signs [semantically related and unrelated] vs. non-signs [phonotactically legal and illegal]), semantic effects (semantically related vs. semantically unrelated), and differences between the two non-sign targets (phonotactically legal vs. phonotactically illegal. Corrected p-values, controlling for the family-wise error rate, were applied using the multivariate t-distribution (mvt) method. Regarding lexicality effects, we compared the two conditions that had sign targets (semantically related/unrelated) against the two conditions with non-sign targets (phonotactically legal/illegal). Additionally, we explored phonotactic probability by comparing the two non-sign targets (phonotactically legal and phonotactically illegal). As for semantic effects, we compared the two sign targets (semantically related and semantically unrelated). As a complementary statistical analysis, we conducted t-tests for each time point (i.e., every 2 ms), corrected for False Discovery Rate (FDR).

3.2. Results

3.2.1. Lexical decision task: Behavioral results

Focusing on our analyses of interest, regarding the lexical decision task, analysis of d-prime scores (see Table 2) showed significant differences considering sessions ($F(2,55.98) = 223.19$, $p < 0.001$, $\eta^2_p = 0.89$).

Table 2
Mean (M) D-prime Scores and Standard Deviation (SD) Across Sessions for the Likelihood of Recognizing a Real Target Sign.

D-prime scores					
session 1		session 2		session 3	
M	SD	M	SD	M	SD
0.42	0.29	1.78	0.67	2.42	0.61

[2] Data in this study was analysed using Linear Mixed Models (LMM) due to their capacity to account for both fixed and random effects. However, while LMM summaries provide detailed information on individual regression coefficients and their significance, it is challenging interpreting the results in the context of interaction effects involving multiple factors, which was the case for most models in our study. Therefore, to facilitate a more intuitive understanding of the effects and their relative importance, we report the F-statistics obtained from the Satterthwaite approximation provided by the 'anova' function from package 'lmerTest' (Kuznetsova et al., 2014) in R (Luke, 2017).

Comparisons across sessions revealed that d-prime scores significantly improved between the first and second sessions ($t(56) = 13.946$, $p < 0.001$, $\eta_p^2 = 0.78$) and between the second and third sessions ($t(56.3) = 6.36$, $p < 0.001$, $\eta_p^2 = 0.42$).

3.2.2. Lexical decision task: ERP results

Only significant results related to our factors of interest are described in this section. The analysis of the mean amplitudes revealed main effects for condition ($F(3, 217) = 2.73$, $p = 0.04$, $\eta_p^2 = 0.04$), session ($F(2, 199686) = 176.65$, $p < 0.001$, $\eta_p^2 = 0.002$), anteriority ($F(2, 199817 = 2221.34$, $p < 0.001$, $\eta_p^2 = 0.02$), and laterality ($F(2, 199817 = 24.15$, $p < 0.001$, $\eta_p^2 = 0.0003$). Significant interactions were observed between condition and session ($F(6, 199495) = 6.12$, $p < 0.001$, $\eta_p^2 = 0.0002$), condition and anteriority ($F(6, 199817) = 6.25$, $p < 0.001$, $\eta_p^2 = 0.0002$), and a triple interaction between condition, session and anteriority ($F(12, 199817) = 2.37$, $p = 0.005$, $\eta_p^2 = 0.0001$).

Given the significant triple interaction between condition, session, and anteriority, follow-up comparisons were performed to assess the contrasts of lexicality (signs and non-signs), semantic relatedness (semantically related and semantically unrelated), and the phonotactic probability conditions (phonotactically legal and phonotactically illegal), across all three sessions and scalp distribution.

First session (Fig. 3 and Figure S1). None of the comparisons showed significant effects in the first session. It is important to note that no learning had occurred by this ERP session; therefore, participants made their judgments without any LSC knowledge, merely guessing whether a form could be a real LSC sign or not.

Second session (Fig. 4 and Figure S2). The contrast between the phonotactic probability conditions was significant in anterior ($t(667) = 2.76$, $p = 0.02$, $\eta_p^2 = 0.01$) and central ($t(667) = 2.39$, $p = 0.0501$, $\eta_p^2 =$

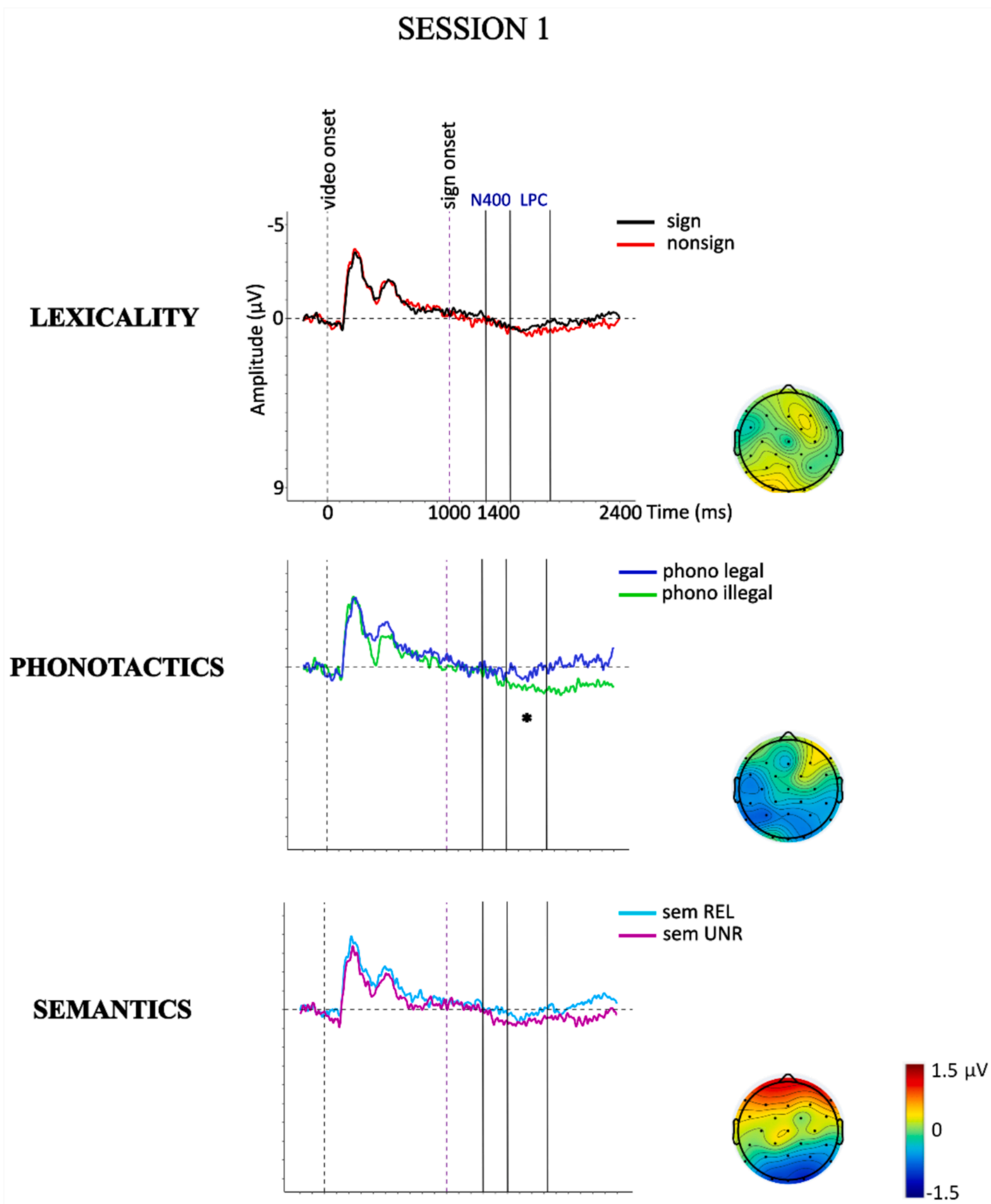

Fig. 3. Lexical decision task. Session 1. Grand average ERP over all the electrodes included in the analyses for the anterior region. ERPs are shown for the contrasts of lexicality (sign and non-sign), non-sign conditions (phonotactically legal and phonotactically illegal), and semantic relatedness (related and unrelated), all time-locked to the onset of the target video. Asterisks indicate significant effects between conditions. Voltage maps illustrate the scalp distribution of the effects depicting the differences in the N400 time window between non-sign minus sign conditions, phonotactically legal minus phonotactically illegal conditions, and semantically unrelated minus semantically related conditions. For a more detailed figure, including all regions involved in the analyses, standard errors, and difference waves between conditions, see Figure S1 in the supplementary materials.

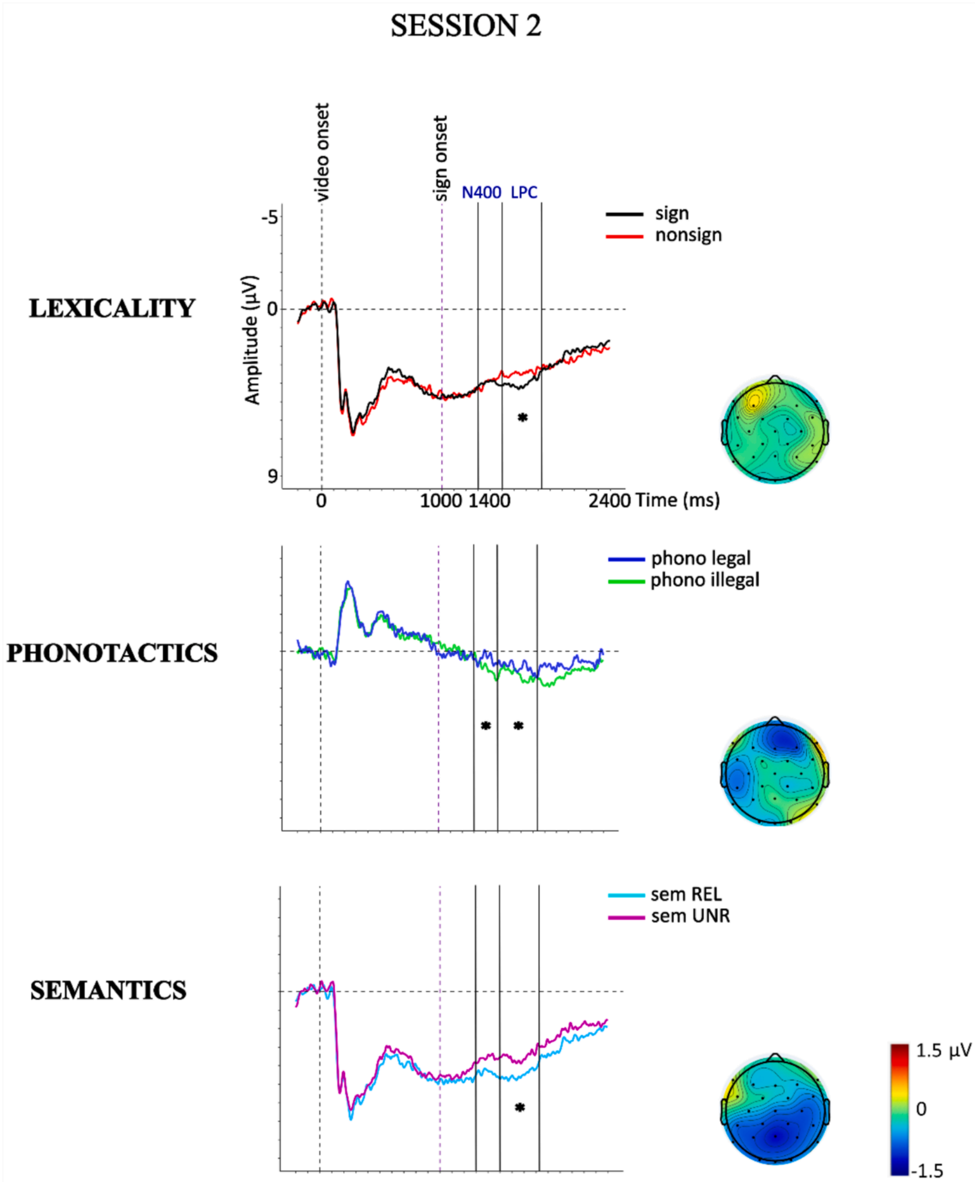

Fig. 4. Lexical decision task. Session 2. Grand average ERP over all the electrodes included in the analyses for the anterior region (phonotactic effects) and the posterior region (lexicality and semantic effects). ERPs are shown for the contrasts of lexicality (sign and non-sign), non-sign conditions (phonotactically legal and phonotactically illegal), and semantic relatedness (related and unrelated), all time-locked to the onset of the target video. Asterisks indicate significant effects between conditions. Voltage maps illustrate the scalp distribution of the effects depicting the differences in the N400 time window between non-sign minus sign conditions, phonotactically legal minus phonotactically illegal conditions, and semantically unrelated minus semantically related conditions. For a more detailed figure, including all regions involved in the analyses, standard errors, and difference waves between conditions, see Figure S2 in the supplementary materials.

0.008) sites, with phonotactically legal non-signs eliciting a more negative mean amplitude compared to phonotactically illegal non-signs. Also in the second session, semantic effects approach significance at posterior sites ($t(280) = 2.3$, $p = 0.06$, $\eta_p^2 = 0.02$), with semantically unrelated signs eliciting a more negative mean amplitude compared to semantically related signs. Although the semantic effect was marginally significant in the N400 time-range, reporting significant paired *t*-test (FDR corrected), in centro-posterior regions within the N400 time-range allowed us to consider that N400 semantic effects could be reliable in session two (see Figure S2).

Third session (Fig. 5 and Figure S3). The results showed significant effects for the three contrasts of interest, only at posterior sites. Regarding lexicality effects, non-signs elicited a more negative mean amplitude compared to signs ($t(323) = 3.23$, $p = 0.003$, $\eta_p^2 = 0.03$). For the semantic contrast, in line with results in the second session, semantically unrelated signs elicited a more negative mean amplitude compared to semantically related signs ($t(272) = 2.9$, $p = 0.02$, $\eta_p^2 = 0.03$). The comparison within the non-sign condition based on phonotactic probability showed that phonotactically legal non-signs elicited a more negative mean amplitude compared to phonotactically illegal non-signs ($t(438) = 3.04$, $p = 0.007$, $\eta_p^2 = 0.02$).

To further determine whether lexicality effects in session two were not absent but delayed (LPC), as shown in Bakker et al., (2015), we analyzed the time window between 1500 – 1828 ms. This time window corresponds to the period following the N400 time window and includes the average duration of sign endings (828 ms). Notably, lexical and semantic effects were observed within the LPC time-range in session two (see Table 3). Surprisingly, phonotactic effects were observed in session one in the LPC time window, despite participants not having undergone any LSC training at that point. These results are commented further in

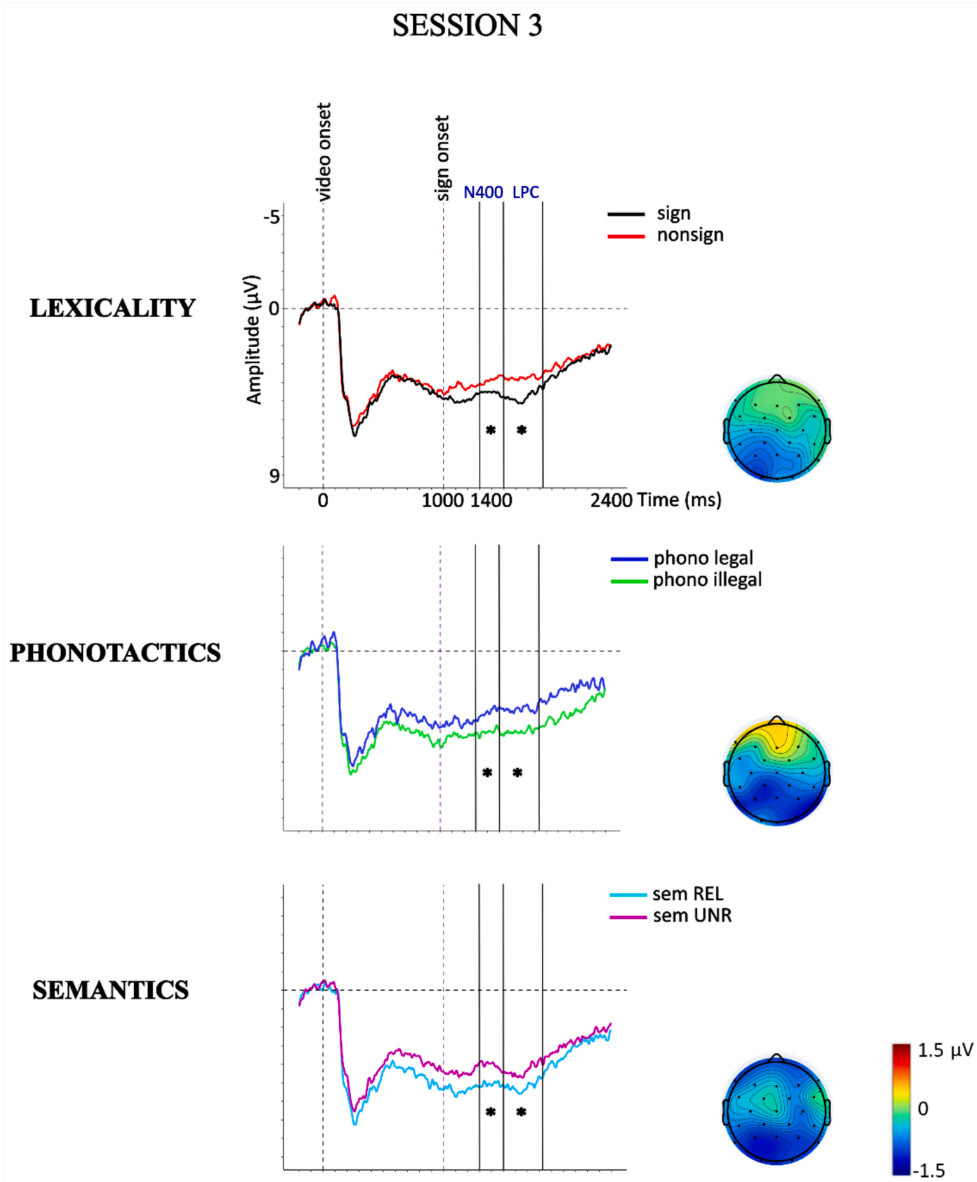

Fig. 5. Lexical decision task. Session 3. Grand average ERP over all the electrodes included in the analyses for the posterior region. ERPs are shown for the contrasts of lexicality (sign and non-sign), non-sign conditions (phonotactically legal and phonotactically illegal), and semantic relatedness (related and unrelated), all time-locked to the onset of the target video. Asterisks indicate significant effects between conditions. Voltage maps illustrate the scalp distribution of the effects depicting the differences in the N400 time window between non-sign minus sign conditions, phonotactically legal minus phonotactically illegal conditions, and semantically unrelated minus semantically related conditions. For a more detailed figure, including all regions involved in the analyses, standard errors, and difference waves between conditions, see Figure S3 in the supplementary materials.

the discussion section.

4. Task 2. Neural changes indexing L2 sign activation

4.1. Methods

4.1.1. Materials

Stimuli consisted of one hundred and fifty printed words corresponding to the Catalan translation of the signs described in the Methods section. Words were divided in two groups: targets and primes, with each target word paired with two different primes (e.g., *sword – key*, *cod – key* or *airplane – motorbike*, *car – motorbike*; see Table S2). The primes and their corresponding targets could either be semantically related or semantically unrelated (e.g., *sword – key* and *cod – key* are semantically unrelated, whereas *airplane – motorbike* and *car – motorbike* are semantically related). Out of the initial pool of one hundred and fifty trials, thirty-five target words and their corresponding two word primes were semantically unrelated, and fifteen target words had semantically related primes. To balance the number of trials across semantic conditions, a set of twenty untrained target words and their corresponding two primes were included in the semantically related condition. Thus, the complete set of stimuli consisted of seventy semantically unrelated pairs (i.e., two presentations of each of the thirty-five target words with different primes) and seventy semantically related pairs, for a total of one hundred and forty trials.

Semantically related and unrelated targets were controlled for lexical frequency and word length according to the Catalan metrics obtained from the NIM database (Guasch et al., 2013). Semantic ratings were obtained from fifty-seven participants that did not take part in the experiment. Raters were asked to evaluate the semantic relatedness of

Table 3
Contrast Analyses in the N400 and LPC Time Windows. Significant Effects Are Highlighted in Bold.

Session	Region	N400	LPC
Nonsigns vs Signs			
1	anterior	p = 0.99	p = 0.99
	central	p = 0.70	p = 0.24
	posterior	p = 0.95	p = 0.06
2	anterior	p = 0.33	p = 0.88
	central	p = 0.31	p = 0.08
	posterior	p = 0.55	**t(352) = -3.08; p = 0.007**
3	anterior	p = 0.95	p = 0.08
	central	p = 0.08	p = 0.28
	posterior	**t(323) = -3.28; p = 0.003**	**t(328) = -4.54; p < 0.001**
Semantically Related vs Semantically Unrelated			
1	anterior	p = 0.69	p = 0.70
	central	p = 0.99	p = 0.99
	posterior	p = 0.25	p = 0.10
2	anterior	p = 0.79	p = 0.76
	central	p = 0. 12	p = 0.68
	posterior	p = 0.06	**t(283) = 2.74; p = 0.02**
3	anterior	p = 0.82	p = 1.00
	central	p = 0.53	p = 0.98
	posterior	**t(272) = 2.91; p = 0.01**	**t(275) = 2.43; p = 0.05**
Phonotactically Illegal vs Phonotactically Legal			
1	anterior	p = 0.65	**t(891) = 3.06; p = 0.007**
	central	p = 0.46	**t(891) = 2.46; p = 0.04**
	posterior	p = 0.34	p = 0.52
2	anterior	**t(667) = 2.76; p = 0.02**	**t(687) = 2.55; p = 0.03**
	central	p = 0.05	p = 0.055
	posterior	p = 0.26	p = 0.11
3	anterior	p = 0.98	p = 0.99
	central	p = 0.16	p = 0.10
	posterior	**t(438) = 3.04, p = 0.007**	**t(447) = 3.79; p < 0.001**

each word pair on a scale from 1 (unrelated) to 7 (related). Pairs with semantic ratings below three were included in the semantically unrelated condition (M = 1.71; SD = 1.19), and pairs with mean ratings above five were included in the semantically related condition (M = 6.1; SD = 1.15).

Within each group of semantic relatedness, half of the pairs were considered phonologically related via their LSC translations. Phonological relatedness was considered as sign pairs that shared a minimum of two of the three main sign parameters (handshape, location, and movement; Morford et al., 2011, 2014). Thus, of the total seventy pairs in each semantic condition, thirty-five pairs were related via their LSC translation (e.g., *sword* – *key* share handshape and location, see Fig. 6) and thirty-five pairs had unrelated LSC translations (e.g., *cod* – *key* do not share any parameters). Primes across phonological conditions were controlled for lexical frequency, word length, and semantic similarity. That is, mean ratings for semantic unrelated pairs with related LSC translations (M = 1.8; SD = 1.29) did not significantly differ from those with unrelated LSC translations (M = 1.62; SD = 1.1). Likewise, mean ratings for semantically related pairs with related LSC translations (M = 6.15; SD = 1.17) did not differ from those with unrelated LSC translations (M = 6.05; SD = 1.13). For each participant, a different list was created in which the trial order was pseudorandomized, including a minimum of five trials between the two presentations of the same target word.

4.1.2. Procedure

Regarding the word semantic decision task, participants were asked to decide whether pairs of printed words were semantically related or not. Trials followed a similar design as in Meade et al. (2017). Before the presentation of the word prime, a green asterisk (900 ms) was presented, followed by a white asterisk (500 ms) and a blank screen (500 ms). Primes were presented for 500 ms, followed by a blank screen (500 ms), and the presentation of the target word (until response or a maximum of 2500 ms). Participants were instructed to blink when the green asterisk was displayed on the screen and/or after the response. The task was divided into three blocks: the first two blocks consisted of fifty trials each, while the last block consisted of forty trials. Participants were allowed to take a rest between blocks if needed.

4.1.2.1. EEG procedure. The EEG procedure was the same as described in the LSC lexical decision task (task 1) with the exception that the mean amplitudes were calculated between 250–450 ms after target word onset. We objectively determined the N400 time window by computing the mean peak latency of the Cz electrode between 250 ms and 600 ms, across conditions and sessions (M = 364 ms after word onset). We rounded the result to the nearest fifty (350 ms) and calculated 100 ms before and after, resulting in the final 250–450 ms N400 time window, consistent with previous studies exploring lexical-semantic access (Dell'Acqua et al., 2010). The 100 ms period before stimuli presentation served as a baseline. Due to the excessive number of artifacts, recordings from two participants in the first session and one participant in the third session were discarded. One participant was discarded from all sessions due to the excessive number of artifacts in all sessions. One participant was discarded from the second session due to technical failure.

4.1.2.2. Data analysis. Response times were analyzed by fitting linear mixed models, treating participants and target items nested within primes as crossed random factors. The models were fitted in R (R Core Team, 2019) using the package lme4 (Bates et al., 2015). Semantic and phonological effects (within the semantically unrelated condition) were analyzed separately in two models, each including fixed effects for condition (either semantic or phonologically related versus unrelated), number of session, (first, second, third), and their interaction. Trials with incorrect responses were excluded from the analyses. The significance of the fixed effects estimates was determined using the Satterthwaite approximation for degrees of freedom provided by the lmerTest package (Kuznetsova et al., 2014).

Regarding electrophysiological measurements, for the analyses of semantic effects, mean amplitudes were submitted to linear mixed effect models, with semantic relatedness (related, unrelated), the number of session (first, second, third), laterality (left, midline, right), anteriority (anterior, central, posterior), and their interactions as fixed effects, and subjects and target items nested within primes as cross-random factors. Trials with incorrect behavioral responses were excluded from the analyses. LSC phonological effects were analyzed comparing ERPs for LSC-related and unrelated targets within the semantically unrelated condition. Mean amplitudes were submitted to linear mixed-effect models, including phonological relatedness (related, unrelated), session (first, second, third), laterality (left, midline, right), anteriority (anterior, central, posterior), and their interactions as fixed effects, and subjects and target items nested within primes as cross-random factors. In all analyses, the significance of fixed effects was assessed with Satterthwaite's degrees of freedom method using the lmerTest package (Kuznetsova et al., 2014) in R. Pairwise analyses were conducted in cases of significant interactions between the fixed effects of interest. Corrected p-values, controlling for the family-wise error rate, were computed using the mvt (multivariate t-distribution) method.

4.2. Results

4.2.1. Word semantic decision task: Behavioral results

Regarding semantic effects (see Table 4), response times were significantly faster for semantically related word pairs compared to unrelated pairs ($F(1, 47.6) = 53.29$; $p < 0.001$, $\eta_p^2 = 0.22$), and, overall, participants responded faster across sessions ($F(2, 7740.6) = 393.48$; $p < 0.001$, $\eta_p^2 = 0.03$). In addition, it was observed a significant interaction between semantic relatedness and session ($F(2, 7736.9) = 3.89$; $p = 0.02$, $\eta_p^2 = 0.0003$). Follow-up comparisons revealed a reduction of the effect of semantic relatedness across sessions (session 1: $t(101.4) = 7.55$, $p < 0.001$, $\eta_p^2 = 0.36$; session 2: $t(94.9) = 5.56$, $p < 0.001$, $\eta_p^2 = 0.25$;

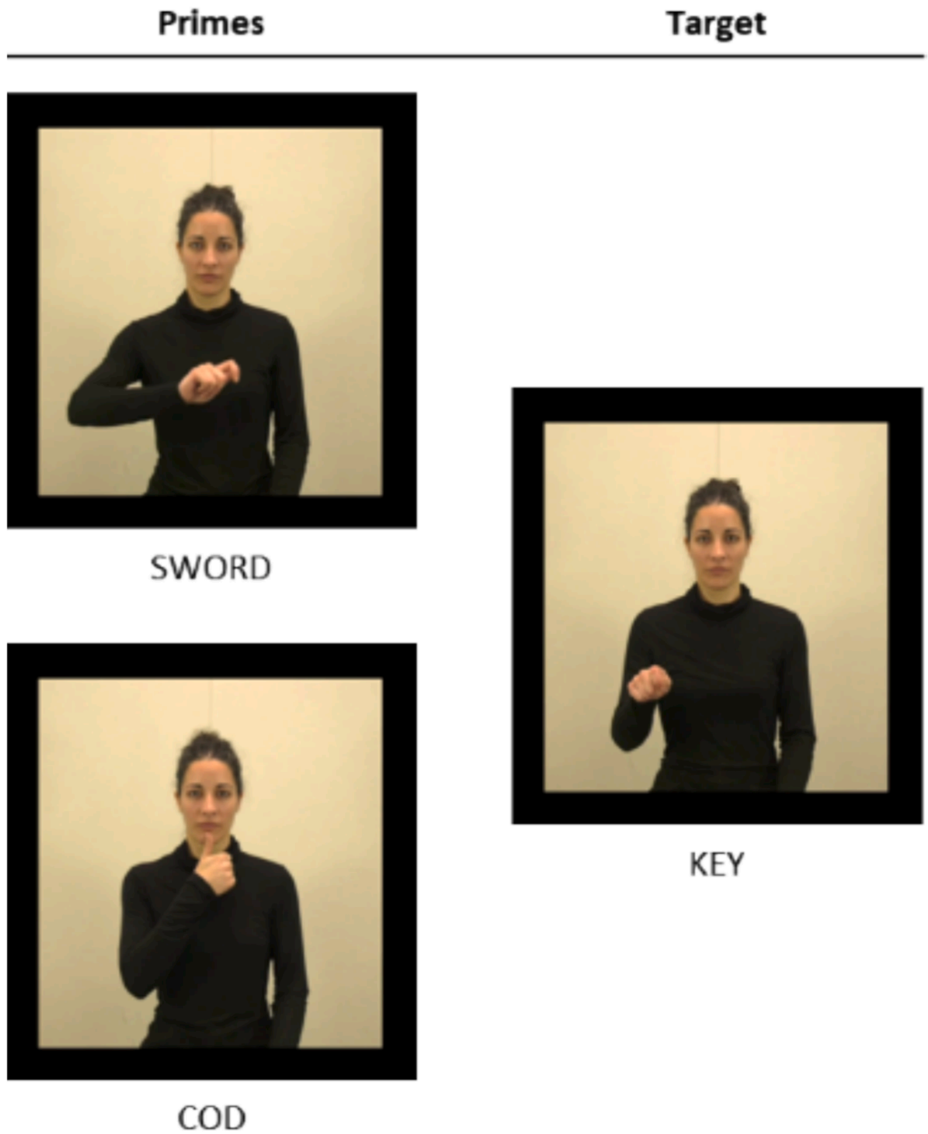

Fig. 6. Still images of the LSC signs corresponding to words in the semantically unrelated condition. The word prime *sword* and the target word *key* are semantically unrelated and phonologically related through their signed translations, while the word prime *cod* and the target word *key* and are both semantically and phonologically unrelated.

session 3: $t(95.1) = 5.18$, $p < 0.001$, $\eta_p^2 = 0.22$).

Regarding LSC phonological effects (see Table 4), no effect was obtained comparing LSC-related and LSC-unrelated pairs ($F(1, 33.5) = 0.98$; $p = 0.33$, $\eta_p^2 = 0.03$). A main effect of session was observed ($F(2, 5423.3) = 397.5$; $p < 0.001$, $\eta_p^2 = 0.97$), but no interaction between phonological condition and session was reported ($F(2, 5420.2) = 0.45$; $p = 0.64$, $\eta_p^2 = 0.00004$).

4.2.2. *Word semantic decision task: ERP results*

Only significant results related to our factors of interest are described in this section. Regarding the semantic contrast (semantically related and semantically unrelated), the analysis of the mean amplitudes revealed significant effects for semantic condition ($F(1, 81) = 48.20$, $p < 0.001$, $\eta_p^2 = 0.37$), and session ($F(2, 176438) = 278.04$, $p < 0.001$, $\eta_p^2 = 0.003$). Significant interactions were observed between semantic condition and session ($F(2, 176413) = 82.6$, $p < 0.001$, $\eta_p^2 = 0.0009$), a triple interaction between semantic condition, session and anteriority ($F(4, 176406) = 2.47$, $p = 0.04$, $\eta_p^2 = 0.000006$), and a triple interaction between semantic condition, anteriority and laterality ($F(4, 176406) = 5.33$, $p < 0.001$, $\eta_p^2 = 0.0001$). Follow-up comparisons considering the interaction between semantic condition and session revealed that the effect of semantic relatedness was significant in all three sessions (all $p \leq 0.001$), in which semantically unrelated pairs elicited a more negative mean amplitude compared to semantically related pairs. Considering the triple interaction between semantic condition, session and anteriority, in the first session (Fig. 7 and Figure S4), semantically unrelated pairs elicited a more negative mean amplitude compared to semantically related pairs at anterior ($t(125) = 3.56$, $p < 0.001$, $\eta_p^2 = 0.09$), and central regions ($t(125) = 4.03$, $p < 0.001$, $\eta_p^2 = 0.11$). In the second (Fig. 8 and Figure S5) and third session (Fig. 9 and Figure S6), significant effects were observed in all regions (all $p < 0.001$). Considering the triple interaction between semantic condition, anteriority and laterality, analyses revealed significant results in all levels of anteriority and laterality (all $p \leq 0.01$).

Concerning phonological effects, results showed no significant effect of phonological condition ($F(1, 35) = 0.44$, $p = 0.51$, $\eta_p^2 = 0.01$), but significant effects of session ($F(2, 124052) = 64.7$, $p < 0.001$, $\eta_p^2 = 0.001$), the interaction between phonological condition and session ($F(2, 124026) = 19.73$, $p < 0.001$, $\eta_p^2 = 0.0003$), and the triple interaction between phonological condition, session and anteriority ($F(4, 124017)$

Table 4
a) Displays the Mean (M) Response Times and Standard Deviations (SD) in Milliseconds for the Semantic and Phonological Conditions Across Sessions. b) Shows the Mean (M) Percentage of Accuracy and Standard Deviations (SD) for the Semantic and Phonological Conditions Across Sessions.

3.a)							
	Response Times						
	Condition	Session 1		Session 2		Session 3	
		M	SD	M	SD	M	SD
		Semantic Relation					
	Sem Rel	765	261	656	235	618	246
	Sem Unr	876	340	729	262	687	278
	Difference	−111		−73		−69	
		Phonological Relation					
	LSC Rel	880	334	733	268	685	287
	LSC Unr	872	347	725	257	689	270
	Difference	8		8		−4	
3.b)							
	Accuracy						
	Condition	Session 1		Session 2		Session 3	
		M	SD	M	SD	M	SD
		Semantic Relation					
	Sem Rel	93.7	24.4	93.8	24.2	93.8	24.2
	Sem Unr	95.2	21.3	95.1	21.7	95.0	21.9
	Difference	−1.5		−1.3		−1.2	
		Phonological Relation					
	LSC Rel	94.2	23.5	93.8	24.2	93.0	25.5
	LSC Unr	96.3	18.3	96.3	18.8	96.9	17.2
	Difference	−2.1		−2.5		−3.9	

$= 3.14$, $p = 0.014$, $\eta_p^2 = 0.0001$). Follow-up comparisons considering the interaction between phonological condition and session revealed that the effect of phonological relatedness was only significant in the third session (session 1: $t(88.2) = 1.14$, $p = 0.26$, $\eta_p^2 = 0.03$; session 2: $t(87.5) = 0.32$, $p = 0.75$, $\eta_p^2 = 0.003$; session 3: $t(87.2) = 2.44$, $p = 0.02$, $\eta_p^2 = 0.14$), in which phonologically LSC-unrelated pairs elicited a more negative mean amplitude compared to LSC-related pairs. This effect was modulated by a triple interaction between phonological condition, session and anteriority. Analyses revealed significant effects of phonological condition in the third session, at the anterior ($t(166) = 2.83$, $p = 0.005$, $\eta_p^2 = 0.08$) and central ($t(166) = 2.53$, $p = 0.01$, $\eta_p^2 = 0.07$) regions (Fig. 8 and Figure S5).

5. General discussion

In the present study, we sought to broaden the current understanding of how new lexical entries are integrated into the mental lexicon by exploring vocabulary acquisition in a different language modality. Specifically, we explored the neural changes associated with M2L2 sign vocabulary learning over three sessions within a week. Data showed lexicality, semantic, and cross-language effects in the third session (after two periods of training and consolidation). These results suggest that meaningful encounters with new signs, along with at least a period of consolidation, are necessary for these signs to become integrated into the mental lexicon and interact with existing words. Interestingly, our results revealed different timings in the process of lexicalization and integration of new signs into the existing lexicon.

In the primed lexical decision task (task 1), results showed N400 modulations associated to lexicality and semantic processing. These findings replicate prior studies reporting N400 priming effects after a brief training period (Bakker et al., 2015b; Pu et al., 2016) and suggest the lexicalization and integration of trained signs into the mental lexicon after a limited number of meaningful exposures. Notably, while N400 lexicality effects emerged in the third session, results showed LSC phonotactic effects in the second session. These effects, mainly frontally

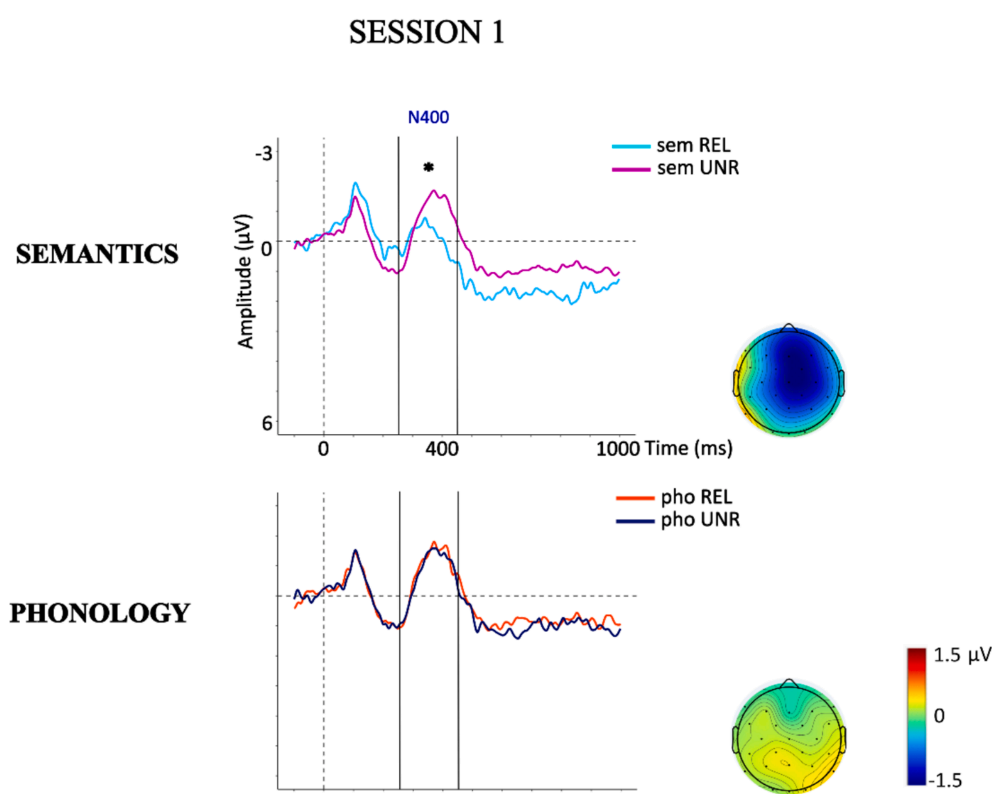

Fig. 7. Word semantic decision task. Session 1. Grand average ERP over all the electrodes included in the analyses for the anterior region. ERPs are shown for the contrasts of semantic relatedness (related and unrelated), and phonological relatedness (related and unrelated), all time-locked to the stimuli onset. Asterisks indicate significant effects between conditions. Voltage maps illustrate the scalp distribution of the effects depicting the differences in the N400 time window between semantically unrelated minus semantically related conditions, and phonologically unrelated minus phonologically related. For a more detailed figure, including all regions involved in the analyses, standard errors, and difference waves between conditions, see Figure S4 in the supplementary materials.

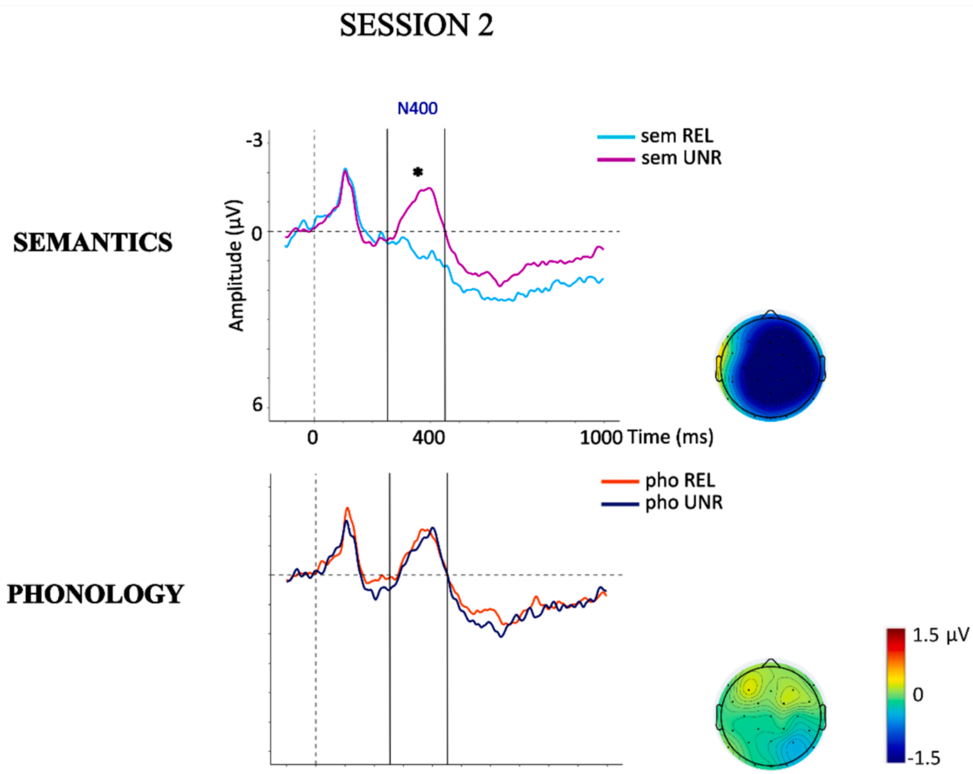

Fig. 8. Word semantic decision task. Session 2. Grand average ERP over all the electrodes included in the analyses for the anterior region. ERPs are shown for the contrasts of semantic relatedness (related and unrelated), and phonological relatedness (related and unrelated), all time-locked to the stimuli onset. Asterisks indicate significant effects between conditions. Voltage maps illustrate the scalp distribution of the effects depicting the differences in the N400 time window between semantically unrelated minus semantically related conditions, and phonologically unrelated minus phonologically related. For a more detailed figure, including all regions involved in the analyses, standard errors, and difference waves between conditions, see Figure S5 in the supplementary materials.

distributed, suggest that participants may have primarily processed the form of the signs rather than their lexical validity. Unexpectedly, in the late time window (LPC, 1500 – 1828 ms), phonotactic effects were also fronto-centrally distributed in the first session (see Table 4). The frontal distribution of the phonotactic effects, along with its presence in session one before participants received any LSC training, may indicate a familiarity effect of memory (i.e., FN400) rather than a lexical effect (see Bridger et al., 2012). Previous research has shown that M2L2 learners rely on their gestural experience when acquiring signs (Karadöller et al., 2024; Ortega et al., 2020). In our study, phonotactically illegal non-signs were constructed with hand configurations that were neither part of the LSC repertoire, nor commonly used as hand gestures conveying associated meaning (e.g., handshapes like a flexed ring finger while the other fingers are extended, which is physically feasible but not typically observed in gestures). Consequently, participants might have based their lexical decisions on their gesture experience, perceiving hand configurations similar to hand gestures as part of the sign language repertoire (and thus possible LSC signs), and those dissimilar to hand gestures as non-LSC signs. Indeed, considering the *D-prime* scores, participants were above chance in categorizing LSC signs and non-signs. In this regard, gesture experience could have served as a resource for deciding the lexical validity of the presented sign forms prior to any sign language training.

In the second session, while semantic and lexical effects were evident in the LPC time window, semantic effects started earlier, in the N400 time window. This pattern of results suggests that participants were able to infer meaning following global processing without relying on the processing of formational parameters as individual units (analytic processing). The pattern of our results in the present study deviates somewhat from the findings reported by McLaughlin et al. (2004) in the oral modality. In their study, participants first showed sensitivity to lexicality (L2 word forms), and then to semantics (word meaning). In contrast, in our study, participants could derive sign meaning from global processing, without noticing whether the combination of plausible parameters conveyed a real sign. One possible explanation is that, among the formational parameters of the sign, handshape is the most difficult to perceive (Luchkina et al., 2020), which was the parameter manipulated in the present study. In this sense, in the second session, participants could have underweighted the cues provided by sub-lexical (handshape) information, putting their cognitive resources into guessing the signs' meaning. In other words, given that participants in each trial were first exposed to real signs (primes), they could have allocated their efforts to inferring the target sign's meaning without relying on its sub-lexical information. Subsequently, in the third session, these processes became more automatic, as indexed by the N400 effects, reflecting the integration of learned signs into the lexicon. Whether the change in priming effects from LPC to N400 from session two to session three resulted from a latency change, with semantic and lexical effects in the second session reflecting a delayed integration as demonstrated in the L2 comprehension literature (e.g., Hahne & Friederici, 2001) or a change from controlled to automatic process of novel signs (Bakker et al., 2014) cannot be determined with the present data.

In addition to gesture experience, one might argue that participants attempted to guess the meaning of signs based on form-meaning similarities (i.e., iconicity). Iconic signs, when learned, function as manual cognates with the participant's gestural repertoire (Ortega et al., 2020). However, in the current experiment, only about one-third of the stimuli could be considered highly iconic, making it unlikely that the observed semantic effects were driven by the high-iconicity of the stimuli. Furthermore, hearing learners can correctly identify the meaning of some non-iconic signs even before any formal training (Akers et al., 2023). Interestingly, non-iconic signs for which the meaning was

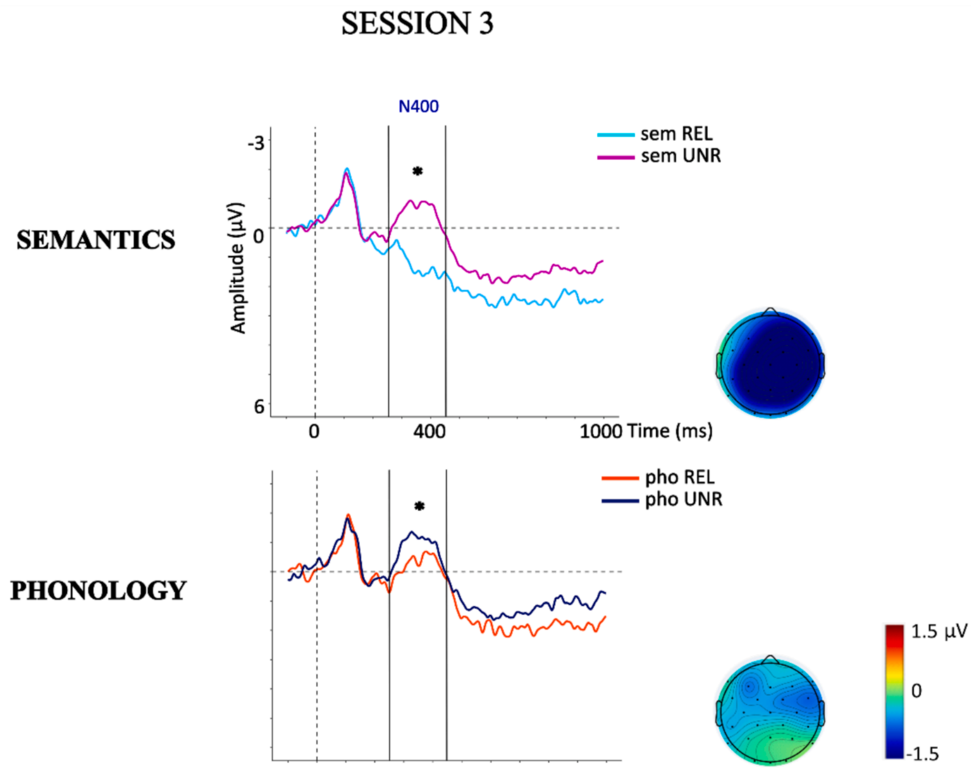

Fig. 9. Word semantic decision task. Session 3. Grand average ERP over all the electrodes included in the analyses for the anterior region. ERPs are shown for the contrasts of semantic relatedness (related and unrelated), and phonological relatedness (related and unrelated), all time-locked to the stimuli onset. Asterisks indicate significant effects between conditions. Voltage maps illustrate the scalp distribution of the effects depicting the differences in the N400 time window between semantically unrelated minus semantically related conditions, and phonologically unrelated minus phonologically related. For a more detailed figure, including all regions involved in the analyses, standard errors, and difference waves between conditions, see Figure S6 in the supplementary materials.

correctly guessed showed a similar ERP pattern to that of iconic signs. This suggests that it may not be sign iconicity per se, but rather the ability to attach meaning to sign forms, that drives semantic effects. While the current data do not allow for a deeper exploration of the role of iconicity in semantic and lexicality effects, this opens an interesting avenue for future research.

Electrophysiological data from the word semantic decision task (task 2), which involved phonological relations within the signs' word translations, provided additional support for the idea that signs were not integrated into the lexicon until after two training sessions and two periods of offline consolidation. It was not until the third session that cross-language effects based on the phonological relations within signs were observed. Research on cross-language effects in both unimodal and bimodal bilingualism has traditionally characterized the reduced N400 response triggered by translation primes that are form-related, compared to those that are form-unrelated, as an indication of automatic activation of the non-target language (Hosemann et al., 2020; Lee et al., 2019; Meade et al., 2017; Thierry & Wu, 2007). In line with those studies, we could interpret results in the third session as an indication that learners were activating LSC translations when processing written words. However, our study differs from those ones in that participants were not bimodal bilinguals but underwent two closely grouped L2 learning sessions and were explicitly prompted with the direct association between words and signs. In this context, the N400 effects reported here might be of a different nature than the ones reported for long-life bilinguals (i.e., implicit translation, Thierry and Wu, 2007) and may be associated with learning processes (Costa et al., 2017, 2019). Under this account, the present data may reflect the reorganization of the L1 oral language lexicon because of the connections formed with learned L2 signs. For instance, words that were previously unrelated in the oral lexicon such as *sword* and *key*, could end up related due to their phonological similarity in LSC (see Gimeno-Martínez & Baus, 2023).

With respect to the behavioral results in the word semantic decision task (task 2), where no LSC phonological effects were observed when judging written word pairs, bimodal bilingual studies have consistently reported that sign-phonological relations interfere when making semantically unrelated judgments (Kubus et al., 2015; Mendoza & Jackson-Maldonado, 2020; Morford et al., 2011, 2014, 2017; Villameriel et al., 2016). When evaluating whether or not a pair of words is semantically unrelated, participants are slower when the word pair is related through the sign translation compared to when the word pair is not related. Meade et al. (2017) argued that reduced N400 in form-related primes, combined with behavioral interference, reflected pre-activation of the target sign translation and subsequent conflict at the response decision level. Since bimodal bilinguals do not require high control demands in their communicative interactions (Emmorey et al., 2016), the non-target language would not be strongly inhibited and thus weaker suppression of signs during word processing would cause the behavioral interference effect. Notably, although previous studies involving phonological manipulations in semantic decision tasks have included deaf and hearing populations with varying levels of sign language proficiency, none, to our knowledge, have focused on a population of hearing non-signers. The hearing learners in our study had no prior experience with sign languages. Our results suggest that some experience in using a sign language is necessary to observe cross-language effects at the behavioral level (but see Karadöller et al., 2024; Ortega et al., 2020 for the effect of gestures in sign learning among non-signers). However, it is not surprising for studies of semantic priming tasks to reveal N400 effects in the absence of response time effects (Heil et al., 2004; Küper & Heil, 2009; McLaughlin et al., 2004; Thierry & Wu, 2007), particularly in tasks where the effects are relatively small. Thus, it is also possible that the phonological effects through translation were too subtle to lead to both N400 and behavioral effects.

6. Conclusion

In two experiments we reported evidence of the rapid neural changes that occur when learners begin to learn a new language in a different language modality. Lexicality and priming effects —semantic and phonological— were observed after a brief laboratory-training period including two learning sessions and two periods of post-training offline consolidation. These results contribute to research on bimodal bilingual language processing by showing that few exposures to new M2L2 sign entries are sufficient to establish lexico-semantic links between signs and words. Concretely, we observed that effects of lexicality and L2 cross-modal activation originate in the early stages of sign vocabulary learning. Of note, even though data in the present study suggest fast cross-linguistic interaction between languages, more than just one exposure to the new language was needed. Only in the third session, after two training sessions, did we observed sensitivity to the phonological form of signs when signs were not overtly presented (word semantic decision task; task 2). Therefore, although minimal, a certain level of exposure to new M2L2 signs, along with periods of offline consolidation, appears to be necessary for the formation of sign lexical representations and the establishment of connections with existing L1 words.

CRediT authorship contribution statement

Marc Gimeno-Martínez: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Eva Gutierrez-Sigut:** Writing – review & editing, Methodology. **Cristina Baus:** .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandl.2024.105495.

Data availability

Data will be made available on request.

References

Akers, E. M., Midgley, K. J., Holcomb, P. J., Meade, G., & Emmorey, K. (2023). Neural effects differ for learning highly iconic versus non-iconic signs in hearing adults. *Bilingualism: Language and Cognition, 1*(13). https://doi.org/10.1017/S1366728923000809

Bakker, I., Takashima, A., van Hell, J. G., Janzen, G., & McQueen, J. M. (2014). Competition from unseen or unheard novel words: Lexical consolidation across modalities. *Journal of Memory and Language, 73*(1), 116–130. https://doi.org/10.1016/j.jml.2014.03.002

Bakker, I., Takashima, A., Van Hell, J. G., Janzen, G., & McQueen, J. M. (2015). Changes in theta and beta oscillations as signatures of novel word consolidation. *Journal of Cognitive Neuroscience, 27*(7), 1286–1297. https://doi.org/10.1162/jocn_a_00801

Bakker, I., Takashima, A., van Hell, J. G., Janzen, G., & McQueen, J. M. (2015). Tracking lexical consolidation with ERPs: Lexical and semantic-priming effects on N400 and LPC responses to newly-learned words. *Neuropsychologia, 79*, 33–41. https://doi.org/10.1016/j.neuropsychologia.2015.10.020

Bakker-Marshall, I., Takashima, A., Schoffelen, J. M., Van Hell, J. G., Janzen, G., & McQueen, J. M. (2018). Theta-band oscillations in the middle temporal gyrus reflect novel word consolidation. *Journal of Cognitive Neuroscience, 30*(5), 621–633. https://doi.org/10.1162/jocn_a_01240

Bates, D., Mächler, M., Bolker, B. M., & Walker, S. C. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1). https://doi.org/10.18637/jss.v067.i01

Batterink, L., & Neville, H. (2011). Implicit and explicit mechanisms of word learning in a narrative context: An event-related potential study. *Journal of Cognitive Neuroscience, 23*(11), 3181. https://doi.org/10.1162/JOCN_A_00013

Bentin, S. (1987). Event-related potentials, semantic processes, and expectancy factors in word recognition. *Brain and Language, 31*(2), 308–327. https://doi.org/10.1016/0093-934X(87)90077-0

Bice, K., & Kroll, J. F. (2015). Native language change during early stages of second language learning. *NeuroReport, 26*(16), 966–971. https://doi.org/10.1097/WNR.0000000000000453

Bisson, M. J., van Heuven, W. J. B., Conklin, K., & Tunney, R. J. (2014). The role of repeated exposure to multimodal input in incidental acquisition of foreign language vocabulary. *Language Learning, 64*(4), 855–877. https://doi.org/10.1111/lang.12085

Born, J., & Wilhelm, I. (2012). System consolidation of memory during sleep. *Psychological Research, 76*(2), 192–203. https://doi.org/10.1007/S00426-011-0335-6

Borovsky, A., Kutas, M., & Elman, J. (2010). Learning to use words: Event-related potentials index single-shot contextual word learning. *Cognition, 116*(2), 289–296. https://doi.org/10.1016/j.cognition.2010.05.004

Bridger, E. K., Bader, R., Kriukova, O., Unger, K., & Mecklinger, A. (2012). The FN400 is functionally distinct from the N400. *Elsevier, 63*, 1334–1342. https://doi.org/10.1016/j.neuroimage.2012.07.047

Caselli, N. K., & Pyers, J. E. (2017). The road to language learning is not entirely iconic: Iconicity, neighborhood density, and frequency facilitate acquisition of sign language. *Psychological Science, 28*(7), 979–987. https://doi.org/10.1177/0956797617700498

Costa, A., Pannunzi, M., Deco, G., & Pickering, M. J. (2017). Do bilinguals automatically activate their native language when they are not using it? *Cognitive Science, 41*(6), 1629–1644. https://doi.org/10.1111/cogs.12434

Costa, A., Pannunzi, M., Deco, G., & Pickering, M. J. (2019). Does bilingualism alter lexical structure? Response to Oppenheim, Wu, and Thierry (2018). *Cognitive Science, 43*(2), e12707.

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods, 134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dingemanse, M., Perlman, M., & Perniss, P. (2020). Construals of iconicity: Experimental approaches to form-meaning resemblances in language. *Language and Cognition, 12*(1), 1–14. https://doi.org/10.1017/langcog.2019.48

Dumay, N., & Gareth Gaskell, M. (2007). *Psychological Science Sleep-Associated Changes in the Mental Representation of Spoken Words.*. https://doi.org/10.1111/j.1467-9280.2007.01845.x

Emmorey, K., Giezen, M. R., & Gollan, T. H. (2016). Psycholinguistic, cognitive, and neural implications of bimodal bilingualism. *Bilingualism: Language and Cognition, 19*(02), 223–242. https://doi.org/10.1017/S1366728915000085

Emmorey, K., Midgley, K. J., & Holcomb, P. J. (2022). Tracking the time course of sign recognition using ERP repetition priming. *Psychophysiology, 59*(3), e13975.

Gais, S., Lucas, B., & Born, J. (2006). Sleep after learning aids memory recall. *Learning & Memory, 13*(3), 259–262. https://doi.org/10.1101/lm.132106

Gaskell, M. G., & Dumay, N. (2003). Lexical competition and the acquisition of novel words. *Cognition, 89*(2), 105–132. https://doi.org/10.1016/S0010-0277(03)00070-2

Gimeno-Martínez, M., & Baus, C. (2022). Iconicity in sign language production: Task matters. *Neuropsychologia, 167*, Article 108166. https://doi.org/10.1016/j.neuropsychologia.2022.108166

Gimeno-Martínez, M., & Baus, C. (2023). Unravelling cross-language effects in bimodal bilingualism. In M. Santesteban, C. Baus, & J. A. Duñabeitia (Eds.), *Bilingualism through the Prism of Psycholinguistics. In honour of Albert Costa* (pp. 159–180). John Benjamins Publishing Company. doi: doi: 10.1075/bpa.17.

Grote, K. A. E., Linz, E., & Grote, K. (2001). The influence of Sign Language Iconicity on Semantic Conceptualization. https://www.researchgate.net/publication/309585278.

Guasch, M., Boada, R., Ferré, P., & Sánchez-Casas, R. (2013). NIM: A Web-based Swiss army knife to select stimuli for psycholinguistic studies. *Behavior Research Methods, 45*(3), 765–771. https://doi.org/10.3758/s13428-012-0296-8

Gutiérrez, E., Müller, O., Baus, C., & Carreiras, M. (2012). Electrophysiological evidence for phonological priming in Spanish Sign Language lexical access. *Neuropsychologia, 50*, 1335–1346. https://doi.org/10.1016/j.neuropsychologia.2012.02.018

Gutierrez, E., Williams, D., Grosvald, M., & Corina, D. (2012). Lexical access in American Sign Language: An ERP investigation of effects of semantics and phonology. *Brain Research, 1468*, 63–83. https://doi.org/10.1016/j.brainres.2012.04.029

Hahne, A., & Friederici, A. D. (2001). Processing a second language: Late learners' comprehension mechanisms as revealed by event-related brain potentials. *Bilingualism: Language and Cognition, 4*(2), 123–141. https://doi.org/10.1017/S1366728901000232

Heil, M., Rolke, B., & Pecchinenda, A. (2004). Automatic semantic activation is no myth: Semantic context effects on the N400 in the letter-search task in the absence of response time effects. *Psychological Science, 15*(12), 852–857. https://doi.org/10.1111/J.0956-7976.2004.00766.X

Holcomb, P. J. (1993). Semantic priming and stimulus degradation: Implications for the role of the N400 in language processing. *Psychophysiology, 30*(1), 47–61. https://doi.org/10.1111/j.1469-8986.1993.tb03204.x

Holcomb, P. J., & Neville, H. J. (1990). Auditory and Visual Semantic Priming in Lexical Decision: A Comparison Using Event-related Brain Potentials. *Language and Cognitive Processes, 5*(4), 281–312. https://doi.org/10.1080/01690969008407065

Hosemann, J., Mani, N., Herrmann, A., Steinbach, M., & Altvater-Mackensen, N. (2020). Signs activate their written word translation in deaf adults: An ERP study on cross-modal co-activation in German Sign Language. *Glossa: A Journal of General. Linguistics, 5*(1), 57. https://doi.org/10.5334/gjgl.1014

Karadöller, D. Z., Peeters, D., Manhardt, F., Özyürek, A., & Ortega, G. (2024). Iconicity and gesture jointly facilitate learning of second language signs at first exposure in hearing nonsigners. *Language Learning.* https://doi.org/10.1111/LANG.12636

Kroll, J. F., & Ma, F. (2017). The Bilingual Lexicon. In *The Handbook of Psycholinguistics* (pp. 294–319). Wiley. doi: 10.1002/9781118829516.ch2.

Kubus, O., Villwock, A., Morford, J. P., & Rathmann, C. (2015). Word recognition in deaf readers: Cross-language activation of German Sign Language and German. *Applied Psycholinguistics, 36*(4), 831–854. https://doi.org/10.1017/S0142716413000520

Küper, K., & Heil, M. (2009). Electrophysiology reveals semantic priming at a short SOA irrespective of depth of prime processing. *Neuroscience Letters, 453*(2), 107–111. https://doi.org/10.1016/j.neulet.2009.02.013

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: Finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology, 62*(1), 621–647. https://doi.org/10.1146/annurev.psych.093008.131123

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2014). *LmerTest: Tests for random and fixed effects for linear mixed effect models. R package, version 2.0-3.*.

Lee, B., Meade, G., Midgley, K. J., Holcomb, P. J., & Emmorey, K. (2019). ERP evidence for co-activation of English words during recognition of American Sign Language signs. *Brain Sciences, 9*(6), 148. https://doi.org/10.3390/brainsci9060148

Liu, Y., & van Hell, J. G. (2020). Learning novel word meanings: An ERP study on lexical consolidation in monolingual, inexperienced foreign language learners. *Language Learning, 70*, 45–74. https://doi.org/10.1111/lang.12403

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: An open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience, 8*(1 APR). https://doi.org/10.3389/fnhum.2014.00213

Luchkina, T., Koulidobrova, E., & Palmer, J. (2020). When You CAN See the Difference: The Phonetic Basis of Sonority in American Sign Language. *Proceedings of the Annual Meetings on Phonology, 8*, 1–10. https://doi.org/10.3765/amp.v8i0.4686

Luke, S. G. (2017). Evaluating significance in linear mixed-effects models in R. *Behavior Research Methods, 49*(4), 1494–1502. https://doi.org/10.3758/s13428-016-0809-y

Marshall, C., Bel, A., Gulamani, S., & Morgan, G. (2021). How are signed languages learned as second languages? *Language and Linguistics Compass, 15*(1), 1–17. https://doi.org/10.1111/lnc3.12403

McGarry, M. E., Massa, N., Mott, M., Midgley, K. J., Holcomb, P. J., & Emmorey, K. (2021). Matching pictures and signs: An ERP study of the effects of iconic structural alignment in American sign language. *Neuropsychologia, 162*. https://doi.org/10.1016/j.neuropsychologia.2021.108051

McLaughlin, J., Osterhout, L., & Kim, A. (2004). Neural correlates of second-language word learning: Minimal instruction produces rapid change. *Nature Neuroscience, 7* (7), 703–704. https://doi.org/10.1038/nn1264

Meade, G., Midgley, K. J., Sehyr, Z. S., Holcomb, P. J., & Emmorey, K. (2017). Implicit co-activation of American Sign Language in deaf readers: An ERP study. *Brain and Language, 170*, 50–61. https://doi.org/10.1016/j.bandl.2017.03.004

Mendoza, E., & Jackson-Maldonado, D. (2020). Lectura de palabras por personas sordas usuarias de lengua de señas mexicana. *Revista de Logopedia, Foniatria y Audiologia, 40* (1), 4–11. https://doi.org/10.1016/j.rlfa.2019.05.003

Mestres-Missé, A., Rodriguez-Fornells, A., & Münte, T. F. (2007). Watching the Brain during Meaning Acquisition. *Cerebral Cortex, 17*(8), 1858–1866. https://doi.org/10.1093/cercor/bhl094

Morford, J. P., Kroll, J. F., Piñar, P., & Wilkinson, E. (2014). Bilingual word recognition in deaf and hearing signers: Effects of proficiency and language dominance on cross-language activation. *Second Language Research, 30*(2), 251–271. https://doi.org/10.1177/0267658313503467

Morford, J. P., Occhino, C., Zirnstein, M., Kroll, J. F., Wilkinson, E., & Piñar, P. (2019). What is the source of bilingual cross-language activation in deaf bilinguals? *The Journal of Deaf Studies and Deaf Education, 1–10*. https://doi.org/10.1093/deafed/enz024

Morford, J. P., Occhino-Kehoe, C., Piñar, P., Wilkinson, E., & Kroll, J. F. (2017). The time course of cross-language activation in deaf ASL-English bilinguals. *Bilingualism: Language and Cognition, 20*(2), 337–350. https://doi.org/10.1017/S136672891500067X

Morford, J. P., Wilkinson, E., Villwock, A., Piñar, P., & Kroll, J. F. (2011). When deaf signers read English: Do written words activate their sign translations? *Cognition, 118*(2), 286–292. https://doi.org/10.1016/j.cognition.2010.11.006

Mott, M., Midgley, K. J., Holcomb, P. J., & Emmorey, K. (2020). Cross-modal translation priming and iconicity effects in deaf signers and hearing learners of American Sign Language. *Bilingualism: Language and Cognition, 23*(5), 1032–1044. https://doi.org/10.1017/S1366728919000889

Nation, I. S., & Nation, I. S. P. (2001). *Learning Vocabulary in Another Language* (Vol. 10). https://doi.org/10.1017/9781009093873

Ormel, E., Hermans, D., Knoors, H., & Verhoeven, L. (2012). Cross-language effects in written word recognition: The case of bilingual deaf children. *Bilingualism, 15*(2), 288–303. https://doi.org/10.1017/S1366728911000319

Ortega, G., Özyürek, A., & Peeters, D. (2020). Iconic gestures serve as manual cognates in hearing second language learners of a sign language: An ERP study. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 46*(3), 403–415. https://doi.org/10.1037/xlm0000729

Ortega, G., Schiefner, A., & Özyürek, A. (2019). Hearing non-signers use their gestures to predict iconic form-meaning mappings at first exposure to signs. *Cognition, 191*. https://doi.org/10.1016/j.cognition.2019.06.008

Palma, P., & Titone, D. (2021). Something old, something new: A review of the literature on sleep-related lexicalization of novel words in adults. *Psychonomic Bulletin & Review, 28*(1), 96–121. https://doi.org/10.3758/s13423-020-01809-5/Published

Pichler, D. C., & Koulidobrova, H. (2016). Acquisition of sign language as a second language (L2). In U. O. U. P. Oxford (Ed.), *The Oxford Handbook of Deaf Studies in Language: Research, Policy, and Practice* (pp. 218–230). doi: 10.1093/oxfordhb/9780190241414.013.14.

Pu, H., Holcomb, P. J., & Midgley, K. J. (2016). Neural changes underlying early stages of L2 vocabulary acquisition. *Journal of Neurolinguistics, 40*, 55–65. https://doi.org/10.1016/j.jneuroling.2016.05.002

Qian, D. D., & Lin, L. H. F. (2020). The relationship between vocabulary knowledge and language proficiency. *The Routledge Handbook of Vocabulary Studies*, 66–80.

R Core Team. (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.r-project.org/.

Shook, A., & Marian, V. (2012). Bimodal bilinguals co-activate both languages during spoken comprehension. *Cognition, 124*(3), 314–324. https://doi.org/10.1016/j.cognition.2012.05.014

Soskey, L., Holcomb, P. J., & Midgley, K. J. (2016). Language effects in second-language learners: A longitudinal electrophysiological study of Spanish classroom learning. *Brain Research, 1646*, 44–52. https://doi.org/10.1016/j.brainres.2016.05.028

Stickgold, R., & Walker, M. P. (2007). Sleep-dependent memory consolidation and reconsolidation. *Sleep Medicine, 8*(4), 331–343. https://doi.org/10.1016/j.sleep.2007.03.011

Tamminen, J., & Gaskell, M. G. (2013). Novel word integration in the mental lexicon: Evidence from unmasked and masked semantic priming. *Quarterly Journal of Experimental Psychology, 66*(5), 1001–1025. https://doi.org/10.1080/17470218.2012.724694

Thierry, G., & Wu, Y. J. (2007). Brain potentials reveal unconscious translation during foreign-language comprehension. *Proceedings of the National Academy of Sciences of the United States of America, 104*(30), 12530–12535. https://doi.org/10.1073/pnas.0609927104

Villameriel, S., Dias, P., Costello, B., & Carreiras, M. (2016). Cross-language and cross-modal activation in hearing bimodal bilinguals. *Journal of Memory and Language, 87*, 59–70. https://doi.org/10.1016/j.jml.2015.11.005

Williams, J., & Newman, S. (2016). Interlanguage dynamics and lexical networks in nonnative L2 signers of ASL: Cross-modal rhyme priming. *Bilingualism: Language and Cognition, 19*(3), 453–470. https://doi.org/10.1017/S136672891500019X

Yum, Y. N., Midgley, K. J., Holcomb, P. J., & Grainger, J. (2014). An ERP study on initial second language vocabulary learning. *Psychophysiology, 51*(4), 364–373. https://doi.org/10.1111/psyp.12183

Zwitserlood, I., van der Kooij, E., & Crasborn, O. (2023). Units of sub-sign meaning in NGT. *Sign Language & Linguistics, 26*(2), 276–322. https://doi.org/10.1075/sll.20009.van