Tracking Lexical Processing in Bimodal Bilingualism

Evidence from Catalan Sign Language

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TESI DOCTORAL UPF / 2022

Directora de la tesi

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Mans que volen com una papallona
mans que volen aprendre a comptar,
mans que parlen i a vegades s'amaguen,
mans que fan petons, abans d'anar a dormir.

Mans que busquen un vaixell pirata,
mans que mosseguen com un cocodril,
mans que parlen i a vegades s'amaguen,
mans que fan petons, abans d'anar a dormir.

Mans que fan una forta abraçada,
mans que diuen adeu, adeu, adeu,
mans que parlen i a vegades s'amaguen,
mans que fan petons, abans d'anar a dormir.

Cançó popular infantil

Agraïments

Tot el que hi ha escrit a continuació només és el cim. El que els lectors no podreu percebre és la immensa part que no es veu, i que és precisament aquella que ho ha fet possible. No avanceu cap als capítols sense arribar al final d'aquesta secció. De fet, és la més important. És la via que tinc per transmetre la meva profunda gratitud a totes les persones que han estat els fonaments d'aquesta tesi. Sense elles, no tindríeu res a llegir. En consideració a elles, us les anomeno.

El primer reconeixement necessàriament ha de ser per la meva família, per la que m'ha vist créixer i per la que em veu les ulleres cada matí. Als meus pares, Ascen i Manel, pel seu amor i etern recolzament i respecte a les meves decisions. A l'Emma i a en Gael, per regalar-me dia a dia els somriures, abraçades i petons més honestos que poden existir.

Gràcies també a tota la gent del món científic que l'ha fet possible. Primerament, als meus tutors de tesi. A l'Albert Costa, que em va obrir les portes del seu grup i la mirada a la ciència. A la Cristina Baus, que va haver d'entomar el rol en solitari d'educar aquesta mirada i sempre hi ha estat per fer-ho. Per centrar-me en els objectius, polir dissenys i comentar la poesia dels escrits. I, sobretot, pel seu suport que any rere any m'ha permès seguir amb la tesi, facilitant sempre que em pogués adaptar a les circumstàncies que he anat passant. Aquesta tesi va néixer amb un projecte que tant l'Albert com la Cristina van recolzar i em van ajudar a desenvolupar. Tant de bo haguéssim pogut discutir-lo plegats fins a avui.

També voldria agrair a en Luca Bonatti el tracte rebut a la reunió que vam fer per resoldre els meus dubtes del que suposava fer un màster d'investigació. Vaig entrar amb una desena de pors i en vaig sortir amb energia per intentar superar-les. No totes estan resoltes (encara), però aquella xerrada distesa em va donar l'empenta que necessitava per començar.

Gràcies als que m'heu ajudat a tirar endavant experiments, articles i projectes. A la Ivette, Ferran i a tots els que m'heu ajudat fent de models signants i orals. A l'Andreas Mädebach i a l'Eva Gutiérrez-Sigut per les seves valuoses col·laboracions. He après molt amb i de vosaltres. A la Rebeca Sánchez i a la Marta López per l'assistència en els experiments. El meu agraïment als que amb la seva dedicació m'han facilitat enormement l'estada al laboratori: Xavi, Sílvia, Cristina, Pam, Bea, Florencia, Joana, Núria. I a totes les persones que han participat com a subjectes experimentals i sense les quals la recerca no hauria estat possible.

A tota la gent del Center for Brain and Cognition, que han participat d'una forma o una altra en el meu creixement com a investigador. Als integrants del grup de l'Albert, Speech Production and Bilingualism: Marco, Kalinka, Alice, Gabrielle, Elisa, Joana i Carlos. Per compartir la seva recerca i el feedback sobre la meva. Presentar al seminari sovint feia mandra, però participar-ne és de les activitats més enriquidores que he fet durant la tesi. Me'n vaig adonar tard. A la Camille, la Chiara, en Colomer, l'Iris, l'Andrea, en Jesús, la Katia, la Carlota i la Isabel; per tots els dinars, cafès i riures compartits. Només ho llegireu aquí, però éreu aquell aire fresc que necessites cada dia. També als que m'heu regalat moments indescriptibles al despatx: Ane, Konstantina, Manel, David, Ludo, Federico. No sempre m'he pogut implicar en tot allò que em proposàveu, però us agraeixo molt que ho féssiu. A en Gonzalo, per estar sempre disposat a mirar un codi d'R i comentar dubtes d'anàlisi de dades. A l'Ege, perquè tot i que tinc la sensació que no ens acabem d'entendre, és d'aquelles persones que transmeten una energia especial. I a tota aquella gent que durant aquests anys m'ha enriquit amb una conversa, una salutació, o un somriure.

A en Marc Lluís, que em portava on serveixen els cafès més lents de la ciutat per poder estar més estona xerrant, de la vida, de ciència, i de la vida altra vegada. Per preocupar-se per mi i per oferir-me una amistat sincera i sorollosa, basada en que qualsevol cosa que es digui - menys les referències a persones gegants i capgrosses o petites i maquiavèl·liques - no es fa per molestar a l'altre. Per no donar-me quasi mai la raó, tot i tenir-la sovint (but see, Vives, M. LL.; 2020. Doctoral dissertation. Agraïments, pàg. 6).

Gràcies a tots aquells que, més per amistat que per interès científic, en algun moment m'heu preguntat allò de: - com va la tesi? Especialment als de la colla de Sgt102, pel vostre suport, comentaris i consells. Escoltar coses que han passat a gent que ha caminat pel camí per on va un mateix, sempre enriqueix. Sovint un pensa que ell és diferent i que les experiències d'altres no apliquen. Però igual de sovint te n'adones que si. A en Ferran, perquè xerrar mentre corres per Montjuic et dona una perspectiva diferent de les coses, i sempre ha trobat moments per fer-ho.

I a la Marta, que durant tots aquests anys sempre m'ha recolzat quan ho he necessitat i sempre m'ha animat i facilitat seguir endavant. Tant a nivell laboral com, sobretot, a nivell personal. Com diu una de les seves cançons de capçalera, la vida és bonica però complicada. Quan es complica, comptar amb algú que et fa veure que si fas allò que et fa feliç tot s'anirà posant bé, és indispensable. I quan te n'adones que no t'ho diu per un desig sinó per una ferma convicció que passarà, no pots fer res més que agrair-li i tirar endavant. Per a ella, el pilar moral d'aquesta tesi.

Abstract

A central topic in understanding how the brain processes language is to characterise the dynamics underlying lexical access. In bimodal bilinguals, individuals who use sign languages and oral languages, lexical processing entails handling information in two different language modalities. This dissertation focuses on the study of bimodal bilingual lexical processing in two different populations, deaf signers and hearing early sign language learners. We report evidence that iconicity influences sign retrieval when deaf signers produce signs. In addition, our results show that the effects of iconicity were not pervasive but modulated by the task at hand. We also present results showing that sign production is influenced by word processing. This effect was observed both when the oral language was explicit in the task and when it was not included. Covert language activation is also reported in the early stages of sign learning. More specifically, we show that word processing in hearing learners is influenced by covert activation of the corresponding sign translations. Furthermore, we report evidence of how novel sign lexical entries are integrated in the mental lexicon in this population. Altogether, these results extend previous knowledge on the nature of lexical access in bimodal bilingualism and on general bilingual language processing.

Resum

Un tema central per entendre com el cervell processa el llenguatge és caracteritzar les dinàmiques subjacents a l'accés al lèxic. En bilingües bimodals, individus que utilitzen llengües de signes i llengües orals, el processament lèxic comporta el tractament de la informació en dues modalitats lingüístiques diferents. Aquesta tesi se centra en l'estudi del processament lèxic bilingüe bimodal en dues poblacions diferents, sords signants i oïdors aprenents d'una llengua de signes. Presentem evidències que la iconicitat influeix en la recuperació lèxica de signes quan sords signants produeixen signes. Addicionalment, els nostres resultats mostren que els efectes d'iconicitat no es donen de forma generalitzada, sinó modulats per la tasca en qüestió. També exposem resultats que mostren que la producció de signes està influenciada pel processament de paraules. Aquest efecte es va observar tan quan la llengua oral era explícita a la tasca com quan no estava inclosa. Mostrem també l'activació encoberta de la llengua en els primers estadis de l'aprenentatge de signes. Més concretament, mostrem que el processament de paraules en aprenents oïdors està influenciat per l'activació encoberta de les corresponents traduccions signades. A més, reportem com s'integren noves formes lèxiques signades en el lexicó mental d'aquesta població. En conjunt, aquests resultats amplien els coneixements previs sobre la naturalesa de l'accés lèxic en el bilingüisme bimodal i sobre el processament del llenguatge bilingüe en general.

Preface

Suppose we are good tennis players and want to learn to play ping-pong. Does the way we play tennis affect how we play ping-pong? Would we play ping-pong in the same way if we were not tennis experts? This metaphor is intended to illustrate a line of thought about language interactions in bilingual language processing for non-experts in the matter. The argument behind the metaphor refers to the extent to which the sustained interaction between bilingual people's two languages results in structural changes within the language network. This dissertation aims to push the tennis metaphor one step further by exploring whether playing tennis affects how we play football, a sport involving very different skills. Applying the sports metaphor to language, this dissertation explores interactions occurring between bilinguals' two languages involving different articulatory and perceptual mechanisms, such as sign and oral languages.

There are several things that I should admit. Firstly, the tennis metaphor is not mine but Albert's. I just tweaked the idea to fit my interest, sign language processing. Secondly, this paragraph was not meant to be here, but somewhere in the introduction section. At least, that was the intention when I started the PhD, but now it will also end up appearing in a chapter of a book in tribute to his memory. Life takes many turns, and this dissertation has also evolved with it.

It all started a few years ago, after having worked for more than ten years –and still working– as a speech therapist for deaf children in educational centres with a bimodal bilingual educational approach. In these schools and secondary schools in Barcelona, deaf students are educated in a sign language (Catalan Sign Language) and in oral languages. As the years go by, you realise that you know a few more things and, above all, that many unanswered questions remain. This is where my research stage began, with the aim of deepening our knowledge of lexical access in sign and oral languages and how they interact in the brain of a bilingual. After studying a Master's Degree in the Brain and Cognition, we obtained a grant to carry out a project focusing on these cross-language interactions. Afterwards, we obtained grants for two more projects on bimodal lexical access. Some experiments were successful, others not so much. Among the latter, there are still a few in the pipeline that I hope will come to fruition. Now, after a few twists and turns on both a personal and social level, this dissertation lies before you.

This is an original work that aims to contribute to our knowledge of lexical processing of bimodal bilinguals and the interactions between their signed and oral languages. It is not targeted just at the community of psycholinguistics and cognitive neuroscientists specialised in sign language research. The dissertation strives to ensure that anyone interested in sign languages –whether for work or personal reasons– will find theoretical frameworks and experimental data to gain a more in-depth understanding of the field. Moreover, hopefully, it will also spark curiosity for new questions.

As a reader, you will find novel studies in this dissertation that address bimodal lexical processing and its electrophysiological correlates in deaf bimodal bilinguals and hearing L2 sign learners. In the first study, we focus on the influence of iconicity and lexical frequency in sign lexical retrieval during sign production. In addition, it also compares how the effects are modulated by the type of task. At both a behavioural and electrophysiological level, we report data that iconicity effects when deaf bimodal bilinguals produce signs are influenced by the processes induced by the task at hand (i.e., naming pictures or translating words). Then, in the next chapter, we elaborate on cross-language effects of the oral language when deaf bimodal bilinguals produce signs. We report evidence that the oral (non-dominant) language influences lexical retrieval of signs (dominant language). Interestingly, effects are observed in a picture-word interference task, but also in a picture-picture interference task, without the explicit presence of the oral language. As discussed, these results offer new insights into covert language activation in bimodal bilingualism and into the general non-selective nature of bilingual lexical access. In the last experimental chapter, we address the neural changes that occur when hearing non-signers learn signs. In a longitudinal study over the course of a week, we explore the stages of sign vocabulary learning by tracking lexical and semantic consolidation. We report data on both effects very early in learning. Moreover, we observe covert activation of recently learned signs during word processing, that is, in line with cross-language effects in the first study, covert activation of the non-dominant language during lexical processing of the dominant language. Obviously, all the activities conducted as side projects could not be captured in this dissertation. However, as a bonus, in the appendix, you will find a study in which we investigated whether, when teaching signs to non-signing adults, it is better to offer different signer models or just one. To put it in more scientific terms, the study examines whether indexical variability benefits sign learning.

This dissertation does not represent an end, but a beginning. For now, I hope you enjoy reading.

Marc Gimeno Martínez
Barcelona, December 2022

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INTRODUCTION

Chapter 1

A central issue in the study of language processing is how lexical forms are retrieved from the mental lexicon. This process is known as lexical access and involves entering the mental lexicon –the dictionary where lexical forms of a language user are stored– and retrieving information about a specific lexical form. This information can be, for instance, the meaning associated to the lexical form (i.e., semantics) or the sublexical units that constitute it (i.e., phonology). Characterising how the mental lexicon is organised and what principles govern retrieval of lexical information have been the main research concerns of experimental psycholinguistics and neurolinguistics over the past half-century. One of the first questions addressed by scholars, which constitutes the starting point of this dissertation, was: which aspects of lexical access can be considered as universal principles and which are modality-specific? In answering this question, research on sign languages has been one of the richest sources to understand how lexical access unfolds through different language modalities (i.e., languages that differ in the means by which language is produced and perceived).

Sign languages are natural languages that, unlike oral languages, are processed through visual-gestural channels. From the seminal studies by William Stokoe (1960) and Klima and Bellugi (1979) onwards, research on sign languages has contributed toward identifying the principles of a modality independent language network. For example, very similar neural systems have been identified for sign and oral language (MacSweeney et al., 2008). Likewise, linguistic information flows across the same levels of language processing in both language modalities (Sandler & Lillo-Martin, 2006). Demonstrating that sign languages follow the same linguistic principles as oral languages contributed to the acceptance of sign languages as natural languages and not mere pantomime or ‘second-class’ linguistic systems.

The initial research interest in describing the modality-general aspects of language has more recently turned to a growing interest in defining specific principles of the signed modality and how this specificity may impact sign language processing (e.g., Meier et al., 2002). For instance, there have been studies exploring the role of the articulators in information transfer capacity (Malaia et al., 2018), the particularities of the visual-gestural perceptual system in viewpoint spatial relations (Pyers et al., 2015), and the greater potential of sign languages for iconic representations (Perlman et al., 2018).

Turning to lexical access, modality-general and modality-specific principles have mainly been described by exploring which variables modulate the retrieval of lexical forms. Studies usually analyse how experimental manipulations of psycholinguistic variables modulate behavioural or neurobiological responses in tasks involving comprehension or production. For instance, studies on sign lexical processing have explored the extent to which well-established psycholinguistic variables that modulate word retrieval (e.g., lexical frequency) and other prominent variables of the signed modality (e.g., iconicity) modulate sign lexical access. As a general observation, sign retrieval is similarly sensitive to effects observed in word retrieval (e.g., neighbourhood density, Caselli et al., 2021; lexical frequency, Emmorey, Winsler, et al., 2020), as well as modality-specific effects (e.g., iconicity, Baus & Costa, 2015; code-blending, Emmorey et al., 2012).

In addition to the study of how the sign mental lexicon is organised, the last decade has seen a flourishing body of studies focusing on understanding how words and signs stored in the mental lexicon interact during lexical access. This is the case of bimodal bilinguals, individuals who use a sign language and an oral language, either in its spoken or in its written version. With respect to bilinguals that use two oral languages (hereafter, unimodal bilinguals), the current dominant view is that language is non-selective. In other words, language processing involves interaction between the two languages at all levels of processing. Remarkably, this cross-language interaction occurs even when the context is restricted to one language. In the field of research on bimodal bilingualism, a fundamental theoretical question was (and still is) how sign and oral languages interact at different levels of processing. Notably, the phonological systems of sign and oral languages do not overlap (see section 1.2.b). Hence, no direct relations can be established across sublexical levels, which indicates that interaction must occur via lexical links (e.g., Ormel et al., 2012). To characterise how cross-language interaction unfolds through lexical links it becomes particularly interesting to explore how experimental manipulations of specific variables of one modality influence lexical processing of the other modality, and to what extent those effects (if any) can be observed when the context is restricted to one language (i.e., one language modality).

The present dissertation approaches the study of sign lexical access by tracking behavioural and neural correlates of (i) modality-general and modality-specific psycholinguistic variables in sign production (Chapter 2), (ii) cross-language effects in sign production (Chapter 3) and (iii) sign lexical processing in hearing novel L2 learners (Chapter 4). The following sections of the introduction offer the most prominent theoretical aspects behind these topics. Firstly, we address how lexical frequency and iconicity modulate sign production. Next, we describe evidence on cross-language interactions in bimodal bilingualism. Finally, we discuss neural changes associated to lexical consolidation during sign learning.

1.1. Tracking lexical retrieval in sign production

In sign production, information flows through semantic, lexical and sublexical (i.e., phonological) levels before a sign is articulated. Evidence for this claim comes from studies reporting effects on mental chronometry (Corina & Hildebrandt, 2002; Navarrete et al., 2015), slips of the hands (Hohenberger et al., 2002; Newkirk et al., 1980), “tip of the fingers” (Thompson et al., 2005), or phonological priming (Baus et al., 2008; Carreiras et al., 2008). Effects occurring at different language levels have been observed to take place with different chronometry, which indicates a certain sequentiality in the subjacent processes of lexical access (Corina & Knapp, 2006). As in word production, concepts are retrieved earlier than their corresponding lexical representations, and lexical representations are retrieved before sublexical forms. Given this sequentiality, a central question in sign production has been how lexical information flows between these language processing levels. To explore this question, researchers employ tasks (e.g., picture-naming task), in which psycholinguistic variables are experimentally manipulated, and observe how these manipulations influence sign retrieval. Next, we focus on how lexical retrieval during sign production is influenced by two psycholinguistic variables, one modality-general –lexical frequency– and the other characteristic of the signed modality –iconicity–.

a) Lexical frequency

Crucial for tracking lexical access, lexical frequency has been the most explored psycholinguistic variable across language modalities. The term refers to how common a given lexical entry –sign or word– is in daily life and has been taken as a reliable index of lexical processing. The experimental manipulation of lexical frequency results in the frequency effect, which refers to high-frequency lexical entries being produced faster and more accurately than low-frequency ones. For instance, words such *house* are produced faster and more accurately than *stool*. In oral language databases, lexical frequency counts are based on large corpora studies. In contrast, there are currently no sign language databases based on a large number of sign entries, and there are no normative frequency counts available.

As a result, to date, studies have used subjective measures of familiarity (i.e., how familiar a sign is) or frequency counts from oral language databases as a proxy for sign lexical frequency (Baus & Costa, 2015; Carreiras et al., 2008; Emmorey, Winsler, et al., 2020). Importantly, experimental manipulations of sign lexical frequency based on these approximate measures have yielded the same effects as experimental manipulations of lexical frequency in oral languages. In other words, high-frequency signs, such as HOUSE, are produced faster and more accurately than low-frequency signs, such as STOOL (Baus & Costa, 2015; Emmorey et al., 2012, 2013).

At the neural level, the time-course of frequency effects has been taken across language modalities as an index of when the brain engages in lexical access (Baus & Costa, 2015; Emmorey, Winsler, et al., 2020; Strijkers et al., 2010). For example, Baus and Costa (2015) observed delayed frequency effects when hearing bimodal bilinguals name pictures in Catalan Sign Language (*Llengua de Signes Catalana*, LSC) relative to when the same participants named the pictures in the oral language. This result was interpreted as suggesting that the speed with which the lexicon is accessed might be modulated by the output modality (manual or spoken; see also Baus et al., 2013). As such, the neural chronometry of frequency effects provides a benchmark to investigate how other psycholinguistic variables influence lexical access.

b) Iconicity

With respect to modality-specific variables of sign languages, iconicity has been by far the most explored. Iconicity is understood as the perceptual or sensorimotor resemblance between the linguistic forms and the meaning they express. Although it is a general property of sign and oral languages, sign languages stand out for a high prevalence of iconic lexical representations (Perlman et al., 2018). Iconicity in sign languages can be characterised by the different ways in which the sign form depicts features of a concept. For instance, among iconic signs we can find signs depicting actions, signs resembling perceptual features of the referent or signs representing a concept associated with an object. For example, in LSC, the sign TO-BRUSH-YOUR-TEETH resembles the action of brushing your teeth, the sign RABBIT is an abstract representation of a rabbit's ears, and the sign TIME is performed by tapping on an imaginary wristwatch. Given that iconicity is based on the mapping between form and meaning, it depends on the subjective evaluation an individual makes when knowing the sign's meaning (Occhino et al., 2017).

Importantly, iconicity in sign languages is not just a descriptive variable but a psycholinguistic variable that modulates sign processing. Accumulated evidence has shown that iconicity modulates lexical access in sign production (Baus & Costa, 2015; Navarrete et al., 2017; Pretato et al., 2018; Vinson et al., 2015), sign comprehension (Grote & Linz, 2003; Thompson et al., 2009, 2010; Vinson et al., 2015), and sign learning (see Ortega, 2017, for a review). In sign production, results from deaf (Vinson et al., 2015) and hearing bimodal bilinguals (Baus & Costa, 2015; Pretato et al., 2018) indicate that pictures corresponding to iconic signs are named faster and more accurately than pictures corresponding to non-iconic signs. Baus and Costa (2015) reported that the onset of iconicity effects occurs very early in processing. In a picture-naming task in LSC, ERPs showed that hearing signers were sensitive to iconicity effects 100 ms after the onset of picture presentation. Given the early time-course of the effect, iconicity effects were interpreted as indexing an early engagement of the semantic system in which semantic features of iconic signs would be more activated than those of non-iconic signs (see also Bosworth & Emmorey, 2010). In addition, iconicity effects were also observed later in processing coinciding with the time-course of frequency effects. This result suggests that, beyond the semantic system, iconicity effects seem to percolate to other levels of language processing (Bosworth & Emmorey, 2010; Thompson et al., 2010). When considering the generalisation of iconicity effects in sign processing, it is worth noting that many studies on sign production exploring the effects of iconicity have primarily used tasks involving picture stimuli (Navarrete et al., 2017; Pretato et al., 2018). Pictures are a type of stimuli that easily trigger semantic representations, providing fast and automatic access to meaning (Carr et al., 1982). In that sense, it is unknown whether the influence of iconicity in sign production is a pervasive phenomenon of sign lexical access, or the result of the direct activation of the semantic system by using pictures as stimuli in the tasks.

Chapter 2 examines this question in greater depth by tracking the neurophysiological correlates of iconicity and lexical frequency effects during sign production. To that end, deaf bimodal bilinguals performed two tasks that differ in how they induce semantic processing, a picture-naming and a word-to-sign translation.

1.2. Lexical access in bimodal bilingualism

When a bilingual listens, reads or speaks, the language that is not used cannot be turned off. Large corpora of studies provide evidence of sensitivity to lexical forms of bilinguals' two languages, even when the context requires lexicalisation to be restricted to one language (e.g., Thierry & Wu, 2007). Furthermore, this phenomenon is not determined by the modality of the two languages. Activation of bilinguals' two lexicons also occurs in bimodal bilinguals, individuals that use a sign language and an oral language (in its spoken and/or written form). Notably, sign-oral bilingualism is coined 'bimodal' because the use of a sign language and an oral language entails the use of two languages that differ in the modality –the means– in which the language is produced and perceived, namely the visual-gestural modality of sign languages and the auditory-vocal modality of spoken languages. Importantly, although both language modalities can be characterised according to the same linguistic levels –lexical, semantic, syntactic, morphological and phonological–, inherent specific features of the sign language modality lead to unique ways through which bimodal cross-language interaction can take place.

This section focuses on the interplay between sign and oral lexical representations in bimodal bilingual language processing. Firstly, we describe cross-language interactions in unimodal bilinguals. As will be appreciated, phonological relations play an important role in the characterisation of cross-language effects. Given that sign and oral languages have very different phonological systems, the next section makes some brief considerations about the phonology of sign languages. Next, to contextualise cross-language effects in relation to language dominance, we elaborate on the diversity of linguistic profiles taking into account linguistic variables such as the number of interlocutors or the number of contexts in which sign and oral languages are used by deaf and hearing individuals. Finally, we describe the most important cross-linguistic effects in bimodal bilinguals.

a) Lexical access in unimodal bilingualism

Consider that you are experimentally confronted with a picture-naming task in which you are asked to name the picture of a pan in English , while you must ignore an overlapping distractor picture of either bread or cheese. If you are an English monolingual, you will take a similar amount of time to name *pan* regardless of the distractor picture. However, if you were an English-Catalan bilingual, you would be faster naming the word *pan* if it is presented with the overlapping picture of bread compared to the overlapping picture of cheese. This facilitation effect is described as a result of activation of the Catalan translation of *bread* (*pa* in Catalan), providing additional activation to those phonemes shared with the English target word *pan*. Although the task is restricted to the English language, the additional activation that the English phonemes of the target word receive through the phonemes shared with the Catalan translation speeds up production. Evidence in this regard favours the idea that processing of the intended language (i.e., English) is influenced by covert activation of the corresponding lexical representations of the language not in use (i.e., mental representations of Catalan words) or, in other words, that lexicalisation cannot be restricted to one language by deactivating the language not in use, which illustrates the non-selective nature of bilingual lexical access.

One of the most cited works showing that both languages are active even if lexicalisation is restricted to one language is that of Thierry and Wu (2007). The authors reported electrophysiological evidence of covert activation of the non-intended language (L1-Chinese) while completing a task entirely in English (L2). In a semantic similarity judgement task, participants were asked to decide whether or not English word pairs were semantically related. The hidden experimental manipulation was that some of the English pairs were form-related in Chinese (e.g., post – mail share a character when translated into Chinese). Electrophysiological modulations of the N400 event-related potential (ERP) component revealed that Chinese translations were covertly activated during processing of English words. Generally, the N400 is characterised by reduced negativities of the electrophysiological brain activity around 400 ms after stimulus presentation, and it has been extensively defined as reflecting associative priming, among many other lexico-semantic effects (see Kutas & Federmeier, 2011; for a review). Differences in the N400 component comparing processing of English word pairs that were form-related or form-unrelated in Chinese were taken as evidence in favour of language non-selective accounts. In a further experiment, Wu and Thierry (2010) determined that covert phonological activation of Chinese modulated electrophysiological responses while processing English words. Notably, phonemes in both English and Chinese are processed through auditory-vocal channels, raising the question of whether covert language activation occurs whenever bilinguals' two languages share the phonological system. The emergence of sign language studies thus offered a step forward in terms of exploring whether cross-linguistic effects driven by phonological activation apply to languages involving a different phonological system (i.e., through visual-gestural channels).

b) Brief notes on the phonology of sign languages

One of the common debates at a linguistic level surrounding sign language linguistics is whether to use terminology from oral languages to define sign languages. The term 'phonology' is a good example. Phonology is commonly understood as the branch of linguistics that studies how speech sounds are systematically organised in a language. As such, considering levels of language processing, the phonological level refers to where the set of sounds used in a given human language are processed. From this definition, it seems obvious that this terminology does not apply to sign languages. However, research on sign languages shows that, although they are not based on speech sounds, the structure of sign languages at the sublexical level resembles that of oral languages (Brentari, 2019). Hence, sign language studies has adopted the term ‘phonology’ to emphasise the similarity in structure at this level and, nowadays, the term ‘phonology’ is used generally to refer to how the sublexical units of a language (oral or signed) are organised.

With respect to sign language phonology, signs consist of a set of components that, when combined, produce meaningful manual forms. These constituents are termed ‘parameters’ and are used to describe how a given sign behaves within the signer’s space. Lexical signs are mainly composed of four manual parameters: handshape, movement, location and palm orientation (Brentari, 1998), as well as non-manual markers (e.g., mouth patterns, facial expressions; Pfau & Quer, 2010). Comparable to phonemes in oral languages, different combinations of parameters result in different lexical signs. Also comparable is the existence of phonological relations between lexical representations. Just as one word can be obtained from another word by changing just one phoneme and this change results in a change of meaning (e.g., glass – grass), changes in one parameter can result in a different sign with a different meaning. For example, the signs TO TEACH and TO TAKE CARE OF in LSC only differ in the movement of the dominant hand. In the sign TO TEACH, the movement consists of two short linear movements whereas, in TO TAKE CARE OF, the movement is circular. All the other parameters remain the same. In both signs the handshape corresponds to the letter ‘q’ in the LSC fingerspelling system, they are performed in a neutral space in front of the torso and the palm is facing the conversational partner (see Figure 1.1).

Figure 1.1 Example of signs phonologically related in LSC. Adapted from ioc.xtec.cat (Jarque Moyano & Vega Llobera, 2017).

Importantly when considering cross-language interactions, since the phonological systems of sign and oral languages do not overlap, no direct relations can be established between the sublexical units of sign languages (visual-gestural phonemes) and oral languages (auditory-vocal phonemes). Thus, in the absence of direct sublexical links, bimodal cross-language effects cannot be accommodated within theoretical models based on the spread of activation across sublexical levels between languages (orthography/phonology, e.g., BIA+ model by Dijkstra & van Heuven, 2002). Consequently, in general terms, theoretical bimodal bilingual models have been constructed based on assumptions of top-down feedback from the semantic system and/or lateral connections between the two lexicons (Morford et al., 2017; Ormel et al., 2012).

c) On the variety of linguistic profiles in bimodal bilingual populations

The term *bimodal bilingualism* refers to bilinguals managing a sign language and an oral language (either in its written or spoken form). Even if taken as a uniform group, bimodal bilinguals include a variety of populations with different sociolinguistic profiles. Examples of bimodal bilingualism can be found in deaf signers born to deaf signer parents, hearing signers born to deaf parents (Children of Deaf Adult, CODA), or deaf or hearing individuals that learn a sign language later in life. Importantly, each bimodal bilingual population encompasses their particular linguistic idiosyncrasy that can be described in terms of language dominance.

Language dominance is a construct that can be operationalised according to two main dimensions: language use and language proficiency (Treffers-Daller, 2019). In this dissertation, unless otherwise specified, we will use the term language dominance to refer to the language most frequently used. Notably, the language most frequently used does not necessarily coincide with the language acquired first chronologically.

In general terms, it seems quite straightforward that sign languages are the dominant languages among adult deaf bimodal bilinguals and oral languages the dominant languages among adult hearing bimodal bilinguals. But this assumption regarding adults is not as reliable among children. Due to family or educational factors, for many children who begin to acquire a sign or an oral language, the chronological first language gradually becomes the least used (non-dominant) over time. Many deaf infants who have an initial contact with one oral language and, as they grow up, they prefer a sign language as the main language to communicate with their peers. Likewise, CODAs have an initial contact with the sign language of their parents and, later in life, switch dominance to the oral language of the community.

Another factor to consider is that, in most communities, the dominant language is an oral language. This means that, in most cases, children who use a sign language have fewer opportunities to develop it. In this respect, bimodal bilingual children have been compared to heritage language users (Lillo-Martin et al., 2022). Heritage language users are users of a minority language –mainly learned at home– that have difficulty to achieve full development due to insufficient social input. As a consequence, their language acquisition patterns differ either from L1 users whose L1 is the dominant language of the community or L2 learners of that language. Similarly, children who use a sign language have few interlocutors to interact with and little variety of contexts in which to use the sign language. Thus, their sign language development will be greatly influenced by these factors and will result in a wide variety of linguistic profiles.

In summary, factors such as age of exposure, the number of interlocutors, and the number of contexts in which sign and oral languages are used may influence lexical access processes. Thus, studies of bimodal bilingual populations must take into consideration the great diversity of individual experiences across bimodal bilingual children and adults (Quer & Steinbach, 2019).

d) Cross-language interactions in bimodal bilingualism

As mentioned, the term bimodal bilingualism includes populations that have different linguistic profiles of language dominance. In view of such language dominance patterns, cross-language effects can be characterised as effects of the dominant language on the non-dominant language, and vice versa. With respect to deaf bimodal bilinguals, studies have focused almost exclusively on the effects of covert activation of sign lexical forms during oral language processing or, in terms of language dominance, the effects of the dominant language during processing of the non-dominant language.

The initial evidence in this area suggested activation of signs while reading words. Treiman and Hirsh-Pasek (1983) asked American Sign Language (ASL)-English bilinguals to make grammaticality judgements of English written sentences. Of those English sentences, half of the ASL translations contained at least three similar signs. For example, the sentence “I ate the apples at home yesterday” was considered a similar sign sentence because of the similarity between the ASL signs for “eat”, “apples”, “home”, and “yesterday”. Results showed that participants had difficulty in making grammaticality judgements when the signed translation of the sentence contained several similar signs, thus suggesting the language non-selective nature of lexical processing in bimodal bilinguals.

Some decades later, Morford and colleagues (2011) reported evidence of covert activation of ASL when performing a task in an English monolingual context, which motivated the last ten years of research on bimodal bilingual cross-linguistic effects. Adapting the paradigm from Thierry and Wu (2007) to sign languages, deaf ASL-English bilinguals were asked to judge the semantic relation between pairs of printed word pairs. Among the prime-target pairs in both semantic conditions (related and unrelated), some pairs had phonologically related translations in ASL. For example, the semantically related word pair *bird-duck* was considered as phonologically related in ASL because their corresponding sign translations overlapped in movement and location. Importantly, the task was in a monolingual English context, so ASL was not required to make semantic judgements, and ASL could not be directly induced by the phonology/orthography of the English printed words. Despite that, ASL phonological relations influenced response times of both semantic conditions. When responding to semantically unrelated word pairs, participants were slower when the ASL translations were phonologically related compared to non-related ASL translations. In contrast, when the pairs were semantically related, phonologically related ASL translations induced faster responses. In other words, when judging the semantic similarity of word pairs, phonological relations through sign translations hindered semantically unrelated judgements but facilitated semantically related responses. These results demonstrate that non-selective lexical access is a general property of bilingual language processing that occurs even when the intended and non-intended language involve different phonological systems. Further studies replicated and expanded these findings to other experimental paradigms and languages, which provides a robust corpus of evidence of sign lexical activation during oral language processing (Chiu et al., 2016; Chiu & Wu, 2016; Kubus et al., 2015; Meade et al., 2017; Mendoza & Jackson-Maldonado, 2020; Morford et al., 2011, 2014, 2017, 2019; Ormel et al., 2012; Pan et al., 2015; Thierfelder et al., 2020; Villwock et al., 2021).

In contrast, cross-language effects of a (non-dominant) oral language during processing of a (dominant) sign language are still scarce. Moreover, as with sign-to-oral cross-language effects, to the best of our knowledge, these have only been reported in language comprehension (Hosemann et al., 2020; Lee et al., 2019). These studies proposed different links between lexical and sublexical levels by which covert activation of the oral language would take place. Lee et al. (2019) adapted the semantic similarity judgement task by presenting pairs of signs instead of written words. In the task, deaf and hearing ASL-English bilinguals were asked to judge whether pairs of signs were semantically related or not. Half of the semantically unrelated sign pairs had form-related (i.e., orthography/phonology rhymes) English translations (e.g., BAR - STAR). Results showed that both deaf and hearing signers were sensitive to English rhymes during sign processing. Unexpectedly, while hearing participants showed the typical N400 priming effect (reduced negativities elicited by form-related pairs; Meade et al., 2017; Thierry & Wu, 2007), N400 polarities among deaf participants showed a reversed N400 effect, with greater negativities elicited by form-related pairs. These differences in polarity were interpreted as reflecting facilitation/competition at the lexical level driven by differences in the links between lexical and sublexical levels in hearing and deaf signers. Hearing signers relied mainly on phonological English rhymes leading to the typical priming effect related to covert phonological activation (Wu & Thierry, 2010). Conversely, since deaf readers mainly acquire English vocabulary through orthography and fingerspelling, this would have led to rely mainly on English orthographic overlap (e.g., Bélanger & Rayner, 2015). Thus, it was argued that the typical priming effect indexed facilitation at the phonological level while the reverse priming effect indexed competition between orthographically similar English words. Interestingly, deaf participants who reported being aware of the English rhyme manipulation showed the typical ERP-priming pattern of polarities starting in the N400 time-window over right sites and continuing in a later time window. This later effect was taken as later activation of the English phonology once lexical access occurred and participants became aware of the manipulation (see also Cripps et al., 2005, for an interpretation of late priming effects as phonological post-access). Somewhat in contrast to this result in terms of polarity of the priming effect, Hosemann et al. (2020) reported the more typical N400 priming effect when deaf German Sign Language (*Deutsche Gebärdensprache*, DGS) - German bilinguals processed sign sentences. In the study, participants were asked to watch videos of DGS sentences and answer yes/no questions about their content. Within some sign sentences, two of the signs were form related –orthographic/phonologically– in German (unrelated in DGS), differing only in the onset grapheme/phoneme. For example, in the DGS sentence for *My mother takes out the butter from the refrigerator*, the signs MUTTER - BUTTER (mother-butter, in English) are form-related in German. The results revealed that participants were sensitive to German-form during DGS processing, as indexed by reduced negativity in the N400 component elicited by form-related primes compared to form-unrelated primes. In addition, N400 deflections were also observed in sign sentences containing two phonologically-related DGS signs (i.e., sentences with explicit sign-phonological overlap). Considering results from both covert English and overt DGS primes, the authors concluded that N400 effects were indexing sign primes leading to pre-activation of both German and DGS forms of target signs.

As mentioned, the pattern of polarities in the N400 component observed in Hosemann et al. (2020) contrasts with the reverse priming effect observed in Lee et al. (2019). Therefore, it is not possible to strongly sustain an interpretation of the polarity of the priming effect in terms or facilitation or interference driven by the covert activation of the lexical form of the oral language.

Chapter 3 examines the characterisation of oral-to-sign cross-language effects in greater depth by exploring for the first time whether the oral language influences sign production in deaf bimodal bilinguals. To that end, deaf bimodal bilinguals performed a picture-word and a picture-picture interference task in which we experimentally manipulated the phonological relations within the oral language. Behavioural and electrophysiological measures are compared to assess whether oral-to-sign cross-language effects can be observed in sign production and whether these effects (if any) can be observed without the explicit presence of the oral language in the task. The results are discussed in relation to models of bimodal language processing.

1.3. Building up a sign language lexicon

As adults, we are able to learn a second language and reach a fairly good command of that language. To that end, one of the essential requirements is to build up a new lexicon by incorporating lexical forms of the second language into the existing lexicon. In general, this is not a burdensome task and a few exposures are enough to assimilate new lexical forms in memory. With the integration of each novel lexical form the mental lexicon changes, which implies continuous modifications throughout life. To understand how the mental lexicon is organised and what linguistic properties govern this organisation has been a crucial issue for psycholinguistic theories in the last few decades. In the case of bimodal bilinguals, this means how to integrate and organise lexical forms of a different language modality to the one already existing in the lexicon.

In particular, for a non-signer, learning signs involves encoding the meaning associated with novel sublexical 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., face, body) that are performed along with the sign. As such, how do hearing adult learners of a sign language integrate novel signs into the existing mental lexicon? This section aims to characterise the neural changes occurring during early stages of L2 sign vocabulary learning. Firstly, we elaborate on the neural changes related to lexical processing in novice L2 learners. Secondly, we consider the nature of connections at the lexical level between new (L2) and old (L1) lexical entries.

a) Lexical integration of novel L2 signs

Acquisition of new vocabulary is a fast and efficient process that, put simply, involves establishing knowledge about the lexical form and the meaning. Previous studies in L2 word acquisition suggest that a certain level of knowledge of word forms is required as a prerequisite for semantic access. In a longitudinal study by McLaughlin et al. (2004), English learners of French judged whether the second of a pair of letter strings was a real French word or a pseudoword. In addition to lexicality, the semantic relationship between prime and target words was experimentally manipulated so that some pairs were semantically related and some were not. After fourteen hours of formal instruction, a lexicality effect was observed at the electrophysiological level, indexed by a reduced N400 for French words compared to pseudowords. It was not until a later testing session (after sixty-three hours of instruction) that semantic effects were observed, with reduced N400 for semantically related pairs in comparison to semantically unrelated pairs. These results seem to suggest that it takes some time before new words become fully integrated within the mental lexicon and interact with other existing words (Leach & Samuel, 2007).

When considering the learning processes underlying the lexical integration of new L2 signs in hearing non-signers, distinctive features between language modalities should be taken into account. With respect to lexical forms, a sign language learner has to deal with information that is not processed through the usual channel of communication (auditory-vocal) but rather through the visual-gestural channel. As stated earlier, encoding a sign lexical form involves, among other features, establishing knowledge about how the sign is performed considering the handshape, its location in relation to the body and its movement over time. The four-dimensional nature of the visual-gestural channel is regarded as the foundation for close relations between form and meaning (e.g., iconicity) in sign languages (Fusellier-Souza, 2006). Of interest here, lexical and grammatical form-meaning mappings have been reported to influence sign processing, especially in hearing non-signers (Marshall et al., 2021; Pichler & Koulidobrova, 2016). In this context, it is possible that close form-meaning relations lead to hearing non-signers relying more on meaning over form when learning signs (Ortega & Morgan, 2015). Under this hypothesis, it is possible that form-meaning relations in sign languages could potentially influence how L2 signs are integrated in the mental lexicon.

b) Cross-language interactions during L2 language learning

As seen in the previous sections, lexical access in bilinguals is largely non-selective. In other words, both languages are active even if lexicalisation is restricted to one language. This effect appears to originate very early when learning a new language, after very few meaningful exposures to novel L2 lexical forms and a period of offline consolidation (e.g., overnight sleep). For example, Pu et al. (2016) observed that, after only two days of two-hour laboratory training, L1 word lexical access was modulated by prior presentation of novel L2 words. In a backward translation recognition task, participants were required to indicate whether a given L1 word was the correct translation for the preceding L2 word. At the electrophysiological level, attenuated N400 modulations for correct L1 translations compared to unrelated L1 translations were interpreted as an index of semantic priming due to pre-activation of L1 words by their L2 counterparts. These results illustrate the rapid plasticity that occurs in the early stages of learning a new language or, in other words, neural changes in the existing L1 lexical network as a consequence of L2 lexical consolidation (see also Bice & Kroll, 2015, for cognate effects in beginning learners).

Theoretically, effects of L2 words on the lexical retrieval of L1 words have been associated to lexical connections from L2 to L1 lexical representations (BIA-d, Grainger et al., 2010; Revised Hierarchical Model, Kroll & Stewart, 1994). Importantly, it has been suggested that these effects are modulated by the degree of similarity between languages. Greater similarity at lexico-phonological levels would result in greater influence of the L2 on the L1 (e.g., Kartushina et al., 2016). In this sense, while the study by Pu et al. (2016) provides evidence of cross-language interaction during the first stages of vocabulary training, it is not known whether (and how) similar language processes can be applied to bimodal bilinguals. As stated in previous sections, cross-language interaction cannot occur at phonological levels given that signed and spoken phonological repertoires are dramatically different. Hence, in hearing sign language learners, the influence of newly learned L2 signs during lexical retrieval of L1 word forms could potentially be reduced. Hearing non-signers who learn a sign language are a valuable population group for exploring experimentally how novel L2 lexical forms are integrated into the mental lexicon. Firstly, the absence of direct links between sublexical levels between languages offers a valuable opportunity to explore how cross-language effects originate in lexical processing. Secondly, overall, hearing non-signers reach high accuracy levels of sign learning after intensive laboratory training with a large number of items (Mott et al., 2020). Thirdly, sign language proficiency is not a determinant factor in showing sensitivity to sign phonology during oral language processing (Morford et al., 2014). Thus, experimental manipulations of sign phonology can be used to explore its influence on lexical retrieval.

In Chapter 4, we characterise the neural signatures underlying the early stages of L2 sign vocabulary learning in hearing non-signers. The aim is twofold: (i) to explore the neural signatures associated with lexical processing of recently learned L2 signs and (ii) to explore the neural signatures (if any) of early L2-to-L1 bimodal cross-language interaction in lexical retrieval. Characterising early L2 sign lexical processing and early cross-language effects will not only be informative for models of bimodal language processing, but also relevant for general models of bilingual language processing.

The following chapters develop the experimental part of the dissertation, focusing on sign lexical access and its underlying neural correlates. Chapter 2 explores the brain responses to iconicity and lexical frequency in sign production, a modality-specific and a modality-general psycholinguistic variable, respectively. Specifically, we examine whether these brain responses are modulated by the processes elicited by the task at hand. Next, Chapter 3 focuses on cross-language effects in bimodal bilingualism. Effects of the oral language during sign production are investigated within the context of direct and covert activation of the oral language. Lastly, Chapter 4 characterises the neural changes associated with L2 vocabulary learning. Neural traces of lexical consolidation and L2 covert activation effects are examined in hearing non-signers learning vocabulary from a sign language.

ICONICITY IN SIGN LANGUAGE PRODUCTION: TASK MATTERS

Chapter 2

Gimeno-Martínez, M., & Baus, C. Iconicity in sign language production: Task matters. Neuropsychologia. 2022; 167:108166.

DOI: 10.1016/j.neuropsychologia.2022.108166

Iconicity in Sign Language Production: Task Matters

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Keywords: iconicity, lexical frequency, sign languages, bimodal bilingualism.

Abstract

The present study explored the influence of iconicity on sign lexical retrieval and whether it is modulated by the task at hand. Lexical frequency was also manipulated to have an index of lexical processing during sign production. Behavioural and electrophysiological measures (ERPs) were collected from 22 Deaf bimodal bilinguals while performing a picture naming task in Catalan Sign Language (Llengua de Signes Catalana, LSC) and a word-to-sign translation task (Spanish written-words to LSC). Iconicity effects were observed in the picture naming task, but not in the word-to-sign translation task, both behaviourally and at the ERP level. In contrast, frequency effects were observed in the two tasks, with ERP effects appearing earlier in the word-to-sign translation than in the picture naming task. These results support the idea that iconicity in sign language is not pervasive but modulated by task demands. As discussed, iconicity effects in sign language would be emphasised when naming pictures because sign lexical representations in this task are retrieved via semantic-to-phonological links. Conversely, attenuated iconicity effects when translating words might result from sign lexical representations being directly accessed from the lexical representations of the word.

2.1. Introduction

It is broadly agreed that iconicity, understood as the non-arbitrary resemblance between the linguistic form and its meaning, is a general property of languages, hence including oral and sign languages (e.g., Dingemanse, 2018; Perniss et al., 2010). Both modalities include iconic examples in their linguistic repertoires (e.g., onomatopoeias), although they differ in the prevalence of this language feature. Sign languages stand out for a high incidence of iconicity. Relative to the aural-oral modality, the visual-manual modality provides a rich medium to express sign forms that mimic perceptuomotor properties of their referents (e.g., in Italian Sign Language, *Lingua dei Segni Italiana*, LIS, 50% of the handshapes are considered to have an iconic motivation, Perlman et al., 2018; Pietrandrea, 2002). For instance, the sign TEAR in many sign languages is represented with the index finger moving down from the eye towards the cheek, resembling the path of a falling tear.

The singularity of sign languages regarding iconicity has stimulated an increasing interest of scholars on language processing to determine the role of iconicity in fundamental language processes such as sign comprehension, production or learning (see Ortega, 2017; Thompson, 2011, for a review). Iconicity appears crucial during L2 adult sign learning, with numerous studies revealing that iconicity benefits sign learning. Iconic signs are more accurately learned and memorized than non-iconic signs (Baus, Carreiras, & Emmorey, 2013; Campbell, Martin, & White, 1992; Lieberth &

Gamble, 1991; Ortega & Morgan, 2015b, 2015a; Poizner, Bellugi, & Tweney, 1981; see Ortega, 2017, for a review). These results have been interpreted as iconicity helping sign learning and processing because of a strengthened link between semantics and the form (manual representation) of iconic signs relative to non-iconic signs. In contrast to the generalised effect of iconicity on sign learning, its impact during sign language processing remains disputable, with some studies showing iconicity effects but not others.

In sign comprehension, accumulated evidence shows that iconicity influences sign recognition. Differences between iconic and non-iconic signs in picture-sign matching tasks (Grote & Linz, 2003; Thompson et al., 2009; Vinson et al., 2015), or phoneme monitoring tasks (Thompson et al., 2010; Vinson et al., 2015), have been taken as evidence that phonological forms of iconic signs automatically activate the corresponding semantic representations. Thompson et al. (2010) showed that Deaf signers were slower making phonological decisions about signs (whether handshapes involved straight or curved fingers) when those signs were iconic. The presence of iconicity effects in a task in which semantic activation was not necessarily required, was taken as evidence that iconicity effects are not limited to tasks tapping into semantic representations. Notwithstanding, these results contrast with others in sign comprehension using tasks tapping into semantics that did not obtain priming effects related to iconicity (e.g., Bosworth & Emmorey, 2010; Mott, Midgley, Holcomb, & Emmorey, 2020).

In sign production, the same mixture of results has been obtained. For instance, Baus et al. (2013) showed no effect of iconicity when hearing L2 signers were translating words into signs. In contrast, Baus and Costa (2015) showed that iconic signs were produced faster than non-iconic signs when hearing L2 signers named pictures in Catalan Sign Language (*Llengua de Signes Catalana*, LSC; see also Pretato et al. 2018, Experiment 1 for the same effect testing Deaf signers). Importantly here, Pretato et al. (2018) showed that iconicity effects in sign production relied on the semantic access required by the task. In a picture naming task, the authors showed that the effect of iconicity disappeared when semantic-to-phonology mappings were bypassed by the task requirements (but see Thompson et al., 2010). Iconicity effects revealed when naming pictures in Italian Sign Language (*Lingua dei Segni Italiana*, LIS), were not observed when for the same pictures, signers were asked to use a marked demonstrative pronoun (referring to the previous location of the object) plus the colour of the object, hence avoiding the picture's corresponding name. As these results showed, iconicity effects were only observed when the link between the picture concept and its corresponding phonological form was emphasised by the task demands.

These contrastive results on iconicity, both in sign comprehension and production, suggest that the influence of iconicity during online processing is not pervasive, but rather induced by different factors, including the type of materials (Grote & Linz, 2003; Thompson et al., 2009; Vinson et al., 2015), type of task (Navarrete et al., 2015;

Pretato et al., 2018), sign language competence (Baus et al., 2013; Thompson et al., 2009), or the interaction of iconicity with other psycholinguistic variables (e.g., frequency, Baus & Costa, 2015; age of acquisition, Vinson et al., 2015). The present study aims to shed light on the functional role of iconicity during sign language production by exploring iconicity effects in two tasks differing in how they prompt semantic-to-phonology mappings, a picture naming and a word-to-sign translation. The use of these tasks was motivated by the observation that words do not tap into semantic representations as pictures do. Different studies, both in signed and oral languages, reveal that lexical retrieval is not mediated by semantics or at least not to the same extent when stimuli are words and the tasks involved word processing (Damian et al., 2001; Navarrete et al., 2015; Vigliocco et al., 2005). Of relevance, in sign language processing Navarrete et al. (2015) showed that Deaf signers showed a cumulative semantic cost effect when naming pictures in LIS, but the effect was not observed when naming Italian written words in LIS (i.e., word-to-sign translation task). That is, when naming pictures in a sequence, picture-naming latencies increased for every successive exemplar within the same semantic category. Crucially, no increase in naming latencies was observed with printed word stimuli. The authors argued that in the word-to-sign translation task, Deaf bimodal bilinguals can directly access the sign language lexicon, without semantic mediation. In this sense, lexical access would rely on the direct mapping between the lexical representations of the spoken language and the production of lexical representations of the sign.

Following the same rationale in our study, we can articulate the following hypothesis: if iconicity effects stem from semantic activation (Pretato et al., 2018) and this is modulated by the task requirements (Navarrete et al., 2015), differences are expected depending on how semantic-to-phonology mappings are prompted by the task. To explore this issue, Deaf bimodal bilinguals performed two tasks while event-related potentials (ERPs) were recorded. Importantly, the experimental design was maintained in both tasks except for the input that triggered lexical processing: naming pictures in LSC (picture naming task) or signing the corresponding Spanish written words (word-to-sign translation task). If the influence of iconicity is automatic in nature and does not depend on induced semantic activation by the task (Thompson et al., 2010), iconicity effects should be found in both tasks. In contrast, if iconicity is modulated by semantic activation and this is modulated by the task requirements, iconicity effects are expected to be reduced or even cancelled out when signing written words compared to pictures (Navarrete et al., 2015; Pretato et al., 2018).

Electrophysiological measures are especially relevant to explore the influence of iconicity throughout the time-course of sign production. Baus and Costa (2015) observed an early effect of iconicity (P100) when hearing L2 signers named pictures in LSC. Also in a picture naming task, McGarry et al. (2020) reported iconicity modulations associated to the N400 component. Despite some differences between studies, the same interpretation of the results was provided: iconicity effects resulted from the engagement of the conceptual system when signing, with greater activation of semantic features for iconic compared to non-iconic signs (Baus & Costa, 2015; McGarry et al., 2020; Navarrete et al., 2017). From these results, we can predict iconicity effects both at the behavioural and ERP level in the picture naming task. Importantly, by comparing iconicity effects in the two tasks, we would be able to determine whether the influence of iconicity in sign processing is a general property in sign lexicalization or determined by the characteristics of the task at hand. We hypothesised that, if iconicity is mainly driven by pictures inducing the activation of semantic representations, we should observe ERP modulations associated to iconicity in the picture naming task but not in the word-to-sign translation task.

While the main interest was on iconicity, lexical frequency was also manipulated in our study. Lexical frequency effects, taken as an index of lexical processing, have been observed in both sign and oral languages and in both word and picture naming tasks. High-frequency words and signs are produced faster than low-frequency ones (Emmorey et al., 2013; Jescheniak & Levelt, 1994). Similarly, ERP modulations in sign processing have also showed differences between high and low-frequency signs (Baus & Costa, 2015; Emmorey et al., 2020). Baus and Costa (2015) and Emmorey et al. (2020) reported ERP lexical frequency effects while hearing signers named pictures in LSC or performed a go/no-go semantic categorization task to videoclips of American Sign Language (ASL) signs. Thus, in the present study we expected to find lexical frequency effects both when naming pictures or translating written words. Moreover, frequency effects at the ERP level will offer a benchmark to evaluate the time course of iconicity effects in relation to when lexical processing takes place.

In sum, the purpose of the present study was to explore iconicity effects on sign lexical retrieval, and how it varies depending on the task demands. To that end, we compared behavioural and electrophysiological measures from Deaf bimodal bilinguals while signing picture names or written words. Lexical frequency effects were taken as an index of lexical processing, and their timing was compared to that obtained for iconicity.

2.2. Methods

a) Participants

Twenty-two Deaf LSC-Spanish bilinguals participated in the present study (M_{age} = 35.3 years, *SD* = 14.5 years). Participants reported normal or corrected-to-normal vision and completed an informed consent form before the experiment and a language background questionnaire (Table 2.1). In this questionnaire, similar age of exposure to LSC and Spanish ($t(21) = 0.77$, $p = 0.45$) were reported. Self-ratings of proficiency on a 10-point scale showed that LSC was rated higher than Spanish ($t(21)= 4.4$, $p < 0.001$). All participants received monetary compensation for their participation in the experiment according with the standards of the Center for Brain and Cognition (Universitat Pompeu Fabra). Three additional participants were run but excluded from the analyses due to excessive number of artefacts.

Table 2.1 Demographic information of the participants. Mean ratings (M) and standard deviation (SD).

	M (SD)
Age (years)	35.3 (14.5)
Age of exposure to LSC (years)	2.8 (4.1)
Age of exposure to Spanish (years)	3.6 (2.8)
Age of exposure to Catalan (years)	9.9 (8.3)
LSC comprehension proficiency *	9.9 (0.4)
Spanish reading proficiency *	8.5 (1.5)
Spanish spoken comprehension proficiency *	6.8 (2.1)
Catalan reading proficiency *	7.4 (2.0)
Catalan spoken comprehension proficiency *	4.9 (2.8)

* Self-ratings from a language questionnaire; proficiency was rated on a 10-point scale ranging from 'almost none' to 'very proficient'.

b) Materials

The items employed, iconicity ratings, and lexical frequency values were obtained from the study of Baus and Costa (2015), which comprised two hundred forty pictures from different databases (Bates et al., 2003; Snodgrass & Vanderwart, 1980). Within this set, half of the items were categorised as corresponding to iconic signs and the other half corresponding to non-iconic signs. Iconic signs included two types of iconicity: signs resembling perceptual features of the referent (e.g., shape; the sign BALL represents the shape of the ball) and signs depicting pantomimic elements of the referent (e.g., how the referent is used or how an animated referent moves; the sign KEY is performed by moving the hand as if turning a key inside a door lock)[1]. To ensure that the choice of iconic and non-iconic signs was properly made, Baus and Costa (2015) obtained iconicity ratings from two different groups of participants. First, iconicity ratings were obtained from a group of hearing speakers (n = 12) with no knowledge of sign language. Raters were asked to evaluate the iconic relation between pictures and their corresponding signs. For each sign, raters were asked to evaluate how well the sign resembled the picture presented on a scale from 1 (no iconic) to 5 (very iconic). Iconicity ratings from this group were also compared with ratings provided by a second group of four Deaf signers. Iconicity ratings in both groups were highly correlated ($r = 0.81$, $p < 0.001$). Thus, one hundred twenty stimuli were considered as having iconic sign translations ($M = 3.8$, $SD = 0.9$) and the remaining one hundred twenty stimuli as having non-iconic sign translations ($M = 2.2$, $SD = 1$), ($t(238) = 12.3$, $p < 0.001$). To ensure that iconicity ratings based on picture items did not bias results in the word-to-sign translation task, a new group of twelve hearing non-signers rated iconicity with written words instead of pictures. Iconicity ratings from written Spanish words (iconic: $M = 3.7$, $SD = 1$; non-iconic: $M = 2.4$, $SD = 1.2$; $t(232) = 9.3$, $p < 0.001$) were compared with iconicity ratings from pictures in Baus and Costa (2015). Both ratings were significantly correlated ($r = 0.71$, $p < 0.001$). Thus, it can be excluded

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[1] Despite exploring type of iconicity was out the scope of the present study, a post-hoc analysis considering the influence of type of iconicity on performance was carried out. No differences were obtained between those signs resembling objects forms and those resembling object actions, both at the behavioural and ERP levels

that iconicity ratings in Baus and Costa (2015) were biased because picture stimuli were used in the rating task.

Considering lexical frequency, word frequency values were taken from the Spanish corpus B-Pal (Davis & Perea, 2005). Unfortunately, unlike oral languages, there are no sign language databases available for psycholinguistic variables of signs based on millions of sign-tokens. As a consequence, frequency values are usually taken either from subjective measures of sign familiarity or from spoken language databases (Baus & Costa, 2015; Carreiras et al., 2008; Emmorey et al., 2020). In Baus and Costa (2015), there was no LSC corpus available to assess whether the lexical frequency for the Spanish translation of the pictures was similar to the LSC translation, so the group of four Deaf signers also rated familiarity of the signs. Frequency values from the Spanish corpus B-Pal (Davis & Perea, 2005) correlated with familiarity ratings from the group of Deaf signers ($r = 0.17$, $p < 0.01$). Thus, half of the stimuli ($n = 120$) were considered of high-frequency (*mean frequency per millions of occurrences*: 49.9; *SD* = 76.04) and half of the stimuli were considered of low-frequency (*mean frequency per millions of occurrences*: 4.04, *SD* = 2.5). Stimuli orthogonally varied in iconicity and lexical frequency. Importantly, the degree of iconicity was similar between high and low-frequency sets ($t(238) < 1$) and frequency values were similarly distributed between iconic and non-iconic sets ($t(238) < 1$; high-frequency iconic: $M = 54.8$, $SD = 93$; high-frequency non-iconic: $M = 45$, $SD = 53$; low-frequency iconic: $M = 4.5$, $SD = 2$; low-frequency non-iconic: $M = 3.5$, $SD = 2$).

c) Procedure

Participants were tested individually in a sound attenuating dimly lit room while engaging in two tasks: a picture naming task and a word-to-sign translation task. The order of the tasks was counterbalanced across participants. Before the experiment, participants were familiarized with the pictures and words selected. In this familiarization phase, the experimenter showed the participants each of the pictures and its related word, and asked them to perform the corresponding sign. If the participant knew more than one sign for the object or she/he did not know the sign, the experimenter showed the appropriate sign and asked the participant to repeat it.

The following procedure was the same in the two tasks, with the exception that participants were presented with either pictures (picture naming task in LSC) or words (Spanish written-words to LSC translation task). In both tasks, participants were asked to perform the picture/word corresponding sign while ERPs were continuously recorded. E-Prime 2.0® was used to present the stimuli and record signing latencies. In both tasks, stimuli were presented randomly in three blocks with eighty trials in each block, and each task began with a practice block of eight warm-up trials. At the beginning of each trial, an instruction message on the screen asked participants to press and hold the spacebar of the keyboard. Once the spacebar was pressed, a 500 ms central fixation point was presented followed by a blank of 300 ms. Stimulus was displayed and maintained for 3000 ms or until participants released the spacebar to perform the sign. Signing latencies were measured from the onset of the stimulus display until the moment that participants released their hands from the space bar. Participants' responses were recorded on video and checked for accuracy after the experiment ended.

d) Behavioural analysis

Signing latencies were analysed for each task in a 2 x 2 ANOVA (R Core Team, 2019; package ez, Lawrence & Lawrence, 2016). The factors included in the analysis were iconicity (iconic vs non-iconic) and lexical frequency (high-frequency vs low-frequency) as independent measures, and participants (*F1*) and items (*F2*) as random factors. Tukey's range test was applied for pairwise comparisons and corrected values are reported. Responses were considered as errors and were excluded from the analyses when the elicited sign was not correct or when participants released their hands from the keyboard but hesitated before performing the sign (picture naming task = 7.8 %; word-to-sign translation task = 9.6 %).

In addition, correlation analyses were conducted considering iconicity and lexical frequency as continuous variables. Signing latencies of items were correlated with lexical frequency (B-Pal; Davis & Perea, 2005) and iconicity ratings (a composite of iconicity ratings from pictures in Baus & Costa; 2015,and from the written words obtained here).

e) EEG recording and analysis

EEG activity was continuously recorded from 30 Ag-AgCl electrodes, mounted on an elastic cap (ActiCap, Munich, Germany) and positioned according to the international 10-20 system. EEG was recorded online to a common reference located at electrode site FCz. Eye movements and blinks were monitored with two electrodes placed below the right eye and at the outer canthus of the left eye. EEG data was sampled at 500 Hz with a bandpass of the hardware filter of 0.1–125 Hz. Offline EEG data pre-processing and processing were carried out using the Brain Analyzer 2.1 (Brain Products, Munich, Germany), EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes. Signals were filtered offline with a bandpass filter of 0.03-20 Hz and re-referenced to the average activity of the two mastoids. Eye blinks and motor or low band-pass artefacts 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). ERPs were computed offline for each participant in each condition, time-locked to the onset of the target stimuli presentation, relative to a 100 ms pre-stimulus baseline and until 750 ms post-stimulus onset. Epochs with incorrect responses, amplitudes above or below 100μV or with a difference between the maximum and the minimum amplitude larger than 75μV were discarded from the analysis. ERP values were computed for the two factors of interest, iconicity, and lexical frequency. An average of 53 trials per condition in the picture naming task (89% of the total number of epochs) and 49 trials in the word-to-sign translation task (82% of the epochs) were considered in the final analysis. Mean amplitudes for six stimulus-locked latency windows were submitted to repeated-measures ANOVAs: P1 (70-140 ms), N1 (140-210 ms), P2 (210-280 ms), N3 (280-350 ms), and 350-550 ms.

Factors included in the analysis were: iconicity (iconic vs non-iconic), lexical frequency (high vs low-frequency), task (picture naming and translation), and electrode cluster (Anterior Left: FC5, F3, FC1; Anterior Right: FC6, F4, FC2; Centro-Posterior: CP1, Cz, CP2; Posterior Left: CP5, P7, P3; Posterior Right: CP6, P8, P4; Occipital: O1, Oz, O2; see Figure 2.1). Greenhouse–Geisser correction was applied when necessary and adjusted p-values are reported.

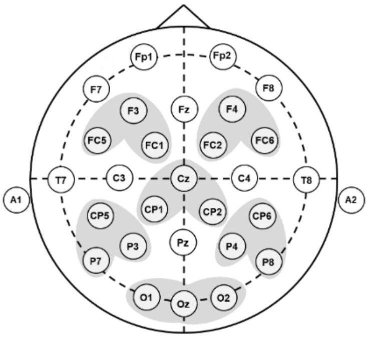

Figure 2.1 Electrode montage used in the present study. Highlighted sites and regions were included in the analysis.

2.3. Results

a) Behavioural analysis

Picture naming task

The analysis of signing latencies (Table 2.2) revealed both significant effects of iconicity ($F1(1,21) = 127.75$, $p < 0.001$, $\eta^2_p = 0.86$; $F2(1,236) = 21.79$, $p < 0.001$, $\eta^2_p = 0.85$) and frequency ($F1(1,21) = 12.18$, $p<0.01$, $\eta^2_p = 0.37$; $F2(1,236) = 0.96$, $p = 0.33$, $\eta^2_p = 0.04$).

Table 2.2 Signing latencies (in ms) and errors by iconicity and frequency across tasks. Values for mean, standard errors, confidence intervals, and percentage of errors are reported. Values in the iconic/non-iconic and high/low-frequency conditions were computed for half of the items in each factor sorted by its estimate values

		Picture Naming			
		Mean	*SE*	Confidence Intervals	% Err
Iconicity	Iconic	774	20.9	[730, 817]	6.1
	Non-ico	828	20.9	[785, 871]	8.2
Frequency	High	794	20.8	[751, 837]	7.3
	Low	808	20.8	[764, 851]	7

		Translation			
		Mean	*SE*	Confidence Intervals	% Err
Iconicity	Iconic	684	21.8	[639, 729]	10.6
	Non-ico	678	21.5	[634, 723]	8
Frequency	High	655	20.0	[614, 697]	7.6
	Low	707	23.5	[659, 756]	11

Deaf bimodal bilinguals signed faster those pictures related to iconic signs compared to those pictures related to non-iconic signs. Considering lexical frequency, pictures of high-frequency signs were signed faster than pictures of low-frequency signs. The interaction between these two factors resulted significant ($F1(1,21) = 16.55$, $p < 0.001$, $\eta^2_p = 0.44$; $F2(1,236) = 1.69$, $p = 0.19$, $\eta^2_p = 0.07$), revealing that the iconicity effect was larger for low-frequency signs (67 ms; $t(35.7) = 11.71$; $p < 0.001$, $\eta^2_p = 0.8$) when compared to high-frequency signs (42 ms; $t(35.7) = 7.33$; $p < 0.001$, $\eta^2_p = 0.6$). Furthermore, the frequency effect was significant for non-iconic signs (26 ms; $t(39.6) = 5.253$; $p < 0.001$, $\eta^2_p = 0.41$) but not for iconic signs (1.25 ms; $t(39.6) = 0.25$; $p = 0.99$).

In addition, a significant correlation between iconicity ratings and signing latencies was observed, $T = -0.19$, $p < 0.001$, but not between lexical frequency and signing latencies, $T = -0.08$, $p = 0.08$, (Figure 2.2, left panels).

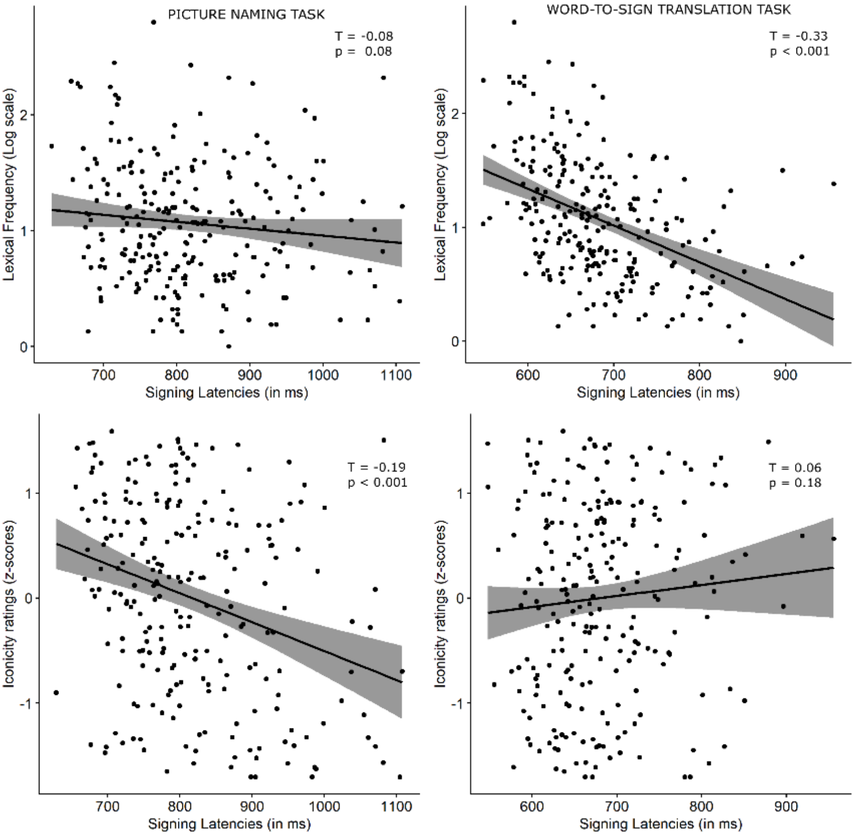

Figure 2.2 Kendall’s correlation analyses across tasks between signing latencies (in ms), ratings of iconicity (z-scores) and lexical frequency (log scale).

Word-to-sign translation task

Signing latencies in this task (Table 2.2) showed no iconicity effect in the word-to-sign translation task ($F1(1,21) = 1.92$, $p = 0.18$, $\eta^2_p = 0.08$; $F2(1,236) = 0.34$, $p = 0.56$, $\eta^2_p = 0.001$). Considering lexical frequency, a significant main effect was observed. High-frequency words were signed faster than low-frequency words ($F1(1,21) = 52.41$, $p < 0.001$, $\eta^2_p = 0.71$, $F2(1,236) = 26.62$, $p < 0.001$, $\eta^2_p = 0.10$). The interaction between iconicity and lexical frequency was not significant ($F1(1,21) = 1.96$; $p = 0.18$, $\eta^2_p = 0.09$; $F2(1,236) = 0.77$; $p = 0.38$, $\eta^2_p = 0.003$).

In addition, the correlation analysis of the two factors of interest with signing latencies revealed a significant correlation for lexical frequency, $T = -0.33$, $p < 0.001$, but not for iconicity, $T = 0.06$, $p = 0.18$, (Figure 2.2, right panels).

b) ERP results

Picture naming task

Only significant results related to our factors of interest are discussed below (see Figs. 3 and 4).

	time window (in ms)				
	70-140	**140-210**	**210-280**	**280-350**	**350-550**
FR	p=0.08	p=0.31	p=0.55	p=0.09	**F(1 ,21)=7.83** **p=0.01**
ICO	p=0.96	p=0.23	p=0.34	p=0.77	p=0.21
FR*EC	p=0.95	p=0.48	p=0.49	p=0.5	p=0.18
ICO*EC	p=0.56	**F(2.98, 62.48)=2.73** **p=0.05**	**F(3.02, 63.33)=4.46** **p<0.01**	**F(3.12, 65.62)=4.46** **p=0.04**	p=0.16
FR*ICO	p=0.65	p=0.99	p=0.25	p=0.58	p=0.69
FR*ICO*EC	p=0.85	p=0.72	p=0.4	**F(3.18, 66.81)=3.00** **p=0.03**	p=0.15

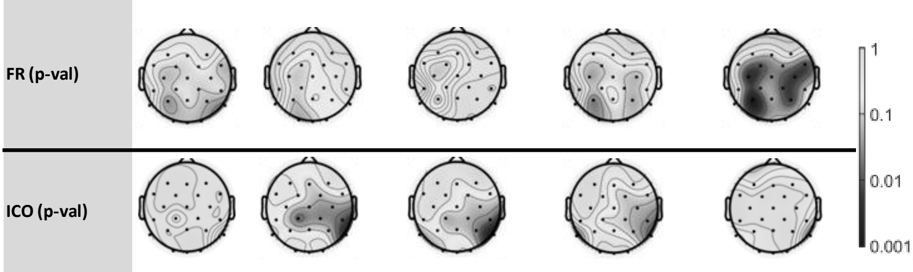

Figure 2.3 Picture Naming Task. Main effects and interactions in the five analyses epochs. Significant results are highlighted in bold. Topographical p-values maps for lexical frequency effects (High-frequency – Low-frequency) and iconicity effects (Iconic – No iconic).

The ERP analysis for the picture naming task at the 140-210 ms time window revealed a significant interaction between iconicity and electrode cluster ($F(2.98, 62.48) = 2.73$; $p = 0.05$, $\eta^2_p = 0.11$). Follow-up comparisons revealed that the iconicity effect was significant at the Centro-Posterior Central region ($t(47.9) = 2.19$; $p = 0.03$, $\eta^2_p = 0.09$). In this region, pictures whose corresponding signs were non-iconic elicited more positive-going waves compared to those pictures corresponding to iconic signs.

At the 210-280 ms time window, there was a significant interaction between iconicity and electrode cluster ($F(3.02, 63.33) = 4.46$; $p < 0.01$, $\eta^2_p = 0.17$). Follow-up comparisons showed that the effect of iconicity was significant at the Posterior Right region ($t(30.2) = 2.32$; $p = 0.03$, $\eta^2_p = 0.15$), following the same pattern of positivity as in the previous time window.

At the 280-350 ms time window, a significant interaction between iconicity and electrode cluster ($F(3.12, 65.62) = 2.91$; $p = 0.04$, $\eta^2_p = 0.12$) was observed, as well as a triple interaction between lexical frequency, iconicity and electrode cluster ($F(3.18, 66.81) = 3.00$; $p = 0.03$, $\eta^2_p = 0.12$). None of the subsequent follow-up comparisons revealed significant effects (all Fs<1).

Finally, at the 350-500 ms time window, the analysis revealed a main effect of frequency ($F(1,21) = 7.83$; $p = 0.01$, $\eta^2_p = 0.27$). In this late time window, pictures related to low lexical frequency elicited more positive waves compared to pictures related to high lexical frequency.

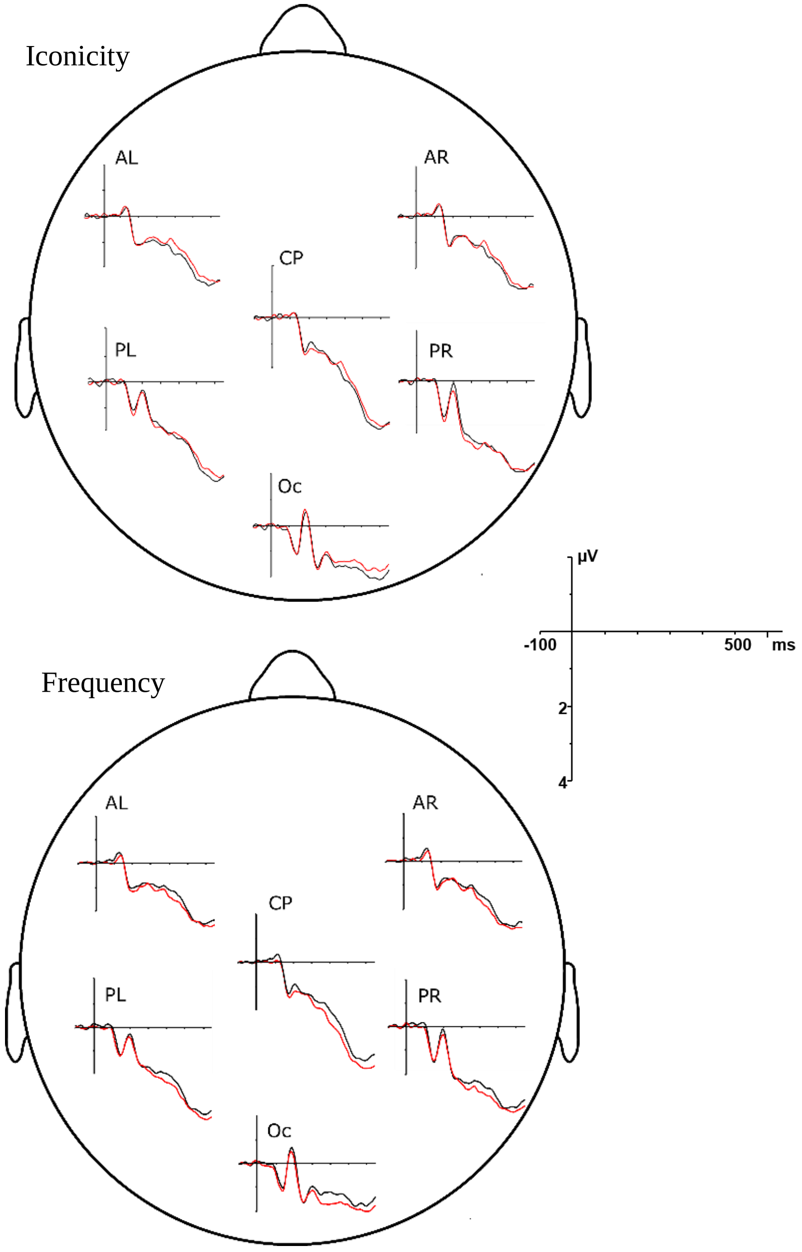

Figure 2.4 Picture Naming Task. ERP amplitudes for the main effects of iconicity (left panel) and lexical frequency (right panel). Seven regions of interest are represented for the ERP amplitudes. Positive amplitudes are plotted down. For the iconicity effect panel, black lines represent iconic words and red lines represent non-iconic words. For the lexical frequency effect panel, black lines represent high-frequency words and red lines represent low-frequency words.

Word-to-sign Translation Task

Only significant results related to our factors of interest are discussed below (see Figs. 5 and 6).

	time window (in ms)				
	70-140	**140-210**	**210-280**	**280-350**	**350-550**
FR	p=0.95	**F(1 ,21)=4.41** **p=0.05**	p=0.06	**F(1 ,21)=4.34** **p=0.05**	**F(1 ,21)=5.91** **p=0.02**
ICO	p=0.93	p=0.06	p=0.12	p=0.14	p=0.68
FR*EC	p=0.41	p=0.19	p=0.07	p=0.13	p=0.16
ICO*EC	p=0.34	p=0.31	p=0.17	p=0.47	p=0.64
FR*ICO	p=0.85	p=0.93	p=0.35	p=0.81	p=0.75
FR*ICO*EC	p=0.67	p=0.53	p=0.65	p=0.79	p=0.33

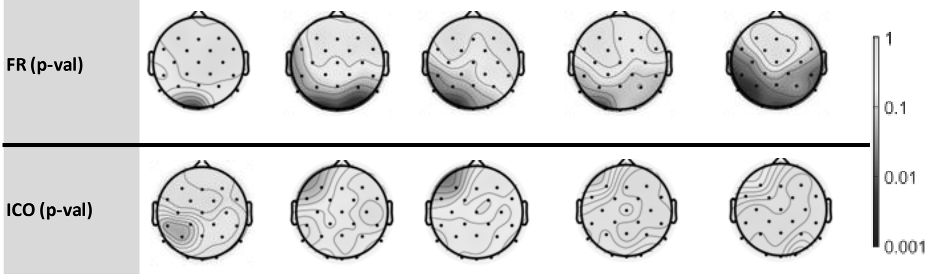

Figure 2.5 Word-to-sign translation task. Main effects and interactions in the five analyses epochs. Significant results are highlighted in bold. Topographical p-values maps for lexical frequency effects (High-frequency – Low-frequency) and iconicity effects (Iconic – No iconic).

The analysis of the word-to-sign translation task revealed a significant effect of lexical frequency at the 140-210 ms time window ($F(1,21) = 4.41$; $p = 0.05$, $\eta^2_p = 0.17$). High-frequency words elicited greater positivity compared to low-frequency ones.

At the 280-350 ms time window, there was observed a main effect of lexical frequency ($F(1,21) = 4.34$; $p = 0.05$, $\eta^2_p = 0.17$), following the same pattern of positivity observed in the early 140-210 ms time window.

Finally, at the 350-550 ms time window, the effect of lexical frequency remained significant ($F(1,21) = 5.91$; $p = 0.02$, $\eta^2_p = 0.22$), also with high-frequency words eliciting greater positivity compared to low-frequency words.

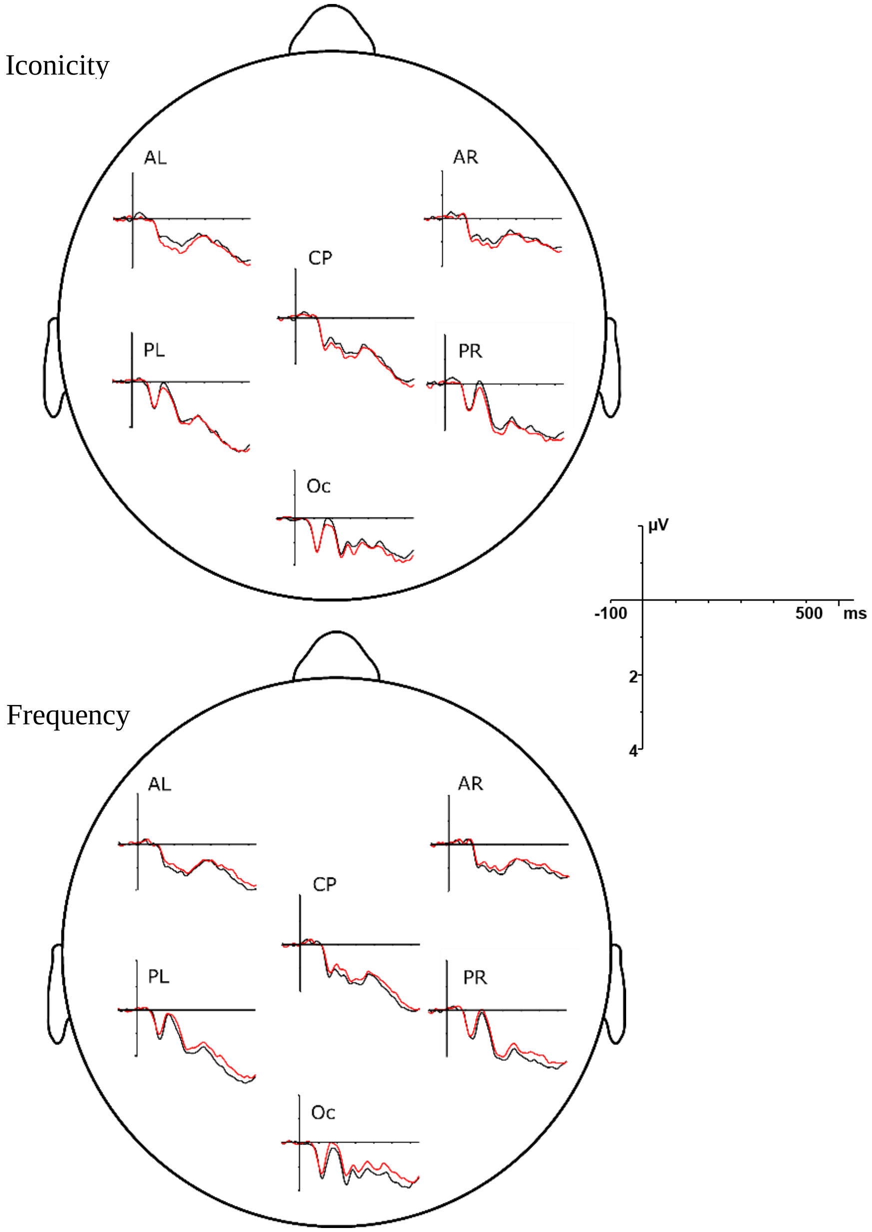

Figure 2.6 Word-to-sign translation task. ERP amplitudes for the main effects of iconicity (left panel) and lexical frequency (right panel). Seven regions of interest are represented for the ERP amplitudes. Positive amplitudes are plotted down. For the iconicity effect panel, black lines represent iconic words and red lines represent non-iconic words. For the lexical frequency effect panel, black lines represent high-frequency words and red lines represent low-frequency words.

2.4. Discussion

The present study explored the influence of iconicity and lexical frequency in sign lexical retrieval and how this is modulated by the type of task employed. Our working hypothesis was that if pictures and words differed in the extent to which semantic representations are activated, then iconicity, a semantic-related variable, but not frequency, a lexical-related variable, should be affected by the characteristics of the task. A group of Deaf bimodal bilinguals performed a picture naming task and a word-to-sign translation task while behavioural and electrophysiological measures were recorded. Both tasks required production of the same signs but differed in the stimuli triggering the sign response: pictures or Spanish written words. The results confirmed our hypothesis: iconicity effects in sign production were modulated by the processes induced by the task at hand.

Both at the behavioural and ERP levels, iconicity effects were observed in the picture naming task but not in the word-to-sign translation task. Participants were faster naming pictures related to iconic signs than pictures related to non-iconic signs. The effect of iconicity was greater for low-frequency signs compared to high-frequency ones, in line with previous findings showing a greater impact of iconicity when lexical retrieval entails some level of difficulty, such as naming low-frequency signs (Baus & Costa, 2015) or late-acquired signs (Vinson et al., 2015). Such interaction was not observed at the ERP level, where only a main effect of iconicity was found around 200 ms after stimulus onset presentation. Importantly, the iconicity ERP effect was only observed in the picture naming task but not in the word-to-sign translation. At the 140-210 ms and 210-280 ms time windows, pictures related to non-iconic signs elicited more positive amplitudes than pictures related to iconic signs. Although the iconicity ERP effect appeared earlier in our study than in McGarry et al. (2020), the same polarity was obtained in both studies, with iconic signs eliciting a reduced positivity compared to non-iconic signs (see Baus & Costa, 2015, for a different polarity of the iconicity effect). In the realm of the polarity and timing (N400 time-range) obtained, McGarry et al. (2020) interpreted the effect of iconicity as having a semantic origin. In particular, differences between iconic and non-iconic signs were described to arise from a greater activation of semantic and sensory-motoric features (e.g., the physical properties of an object or how an object is used) denoted by iconic signs relative to non-iconic signs. Our results here, expanded McGarry et al. (2020) and other studies on iconicity (Baus & Costa, 2015; Bosworth & Emmorey, 2010) by showing that iconicity, as other semantic manipulations (cumulative semantic effect; Navarrete et al., 2015), only facilitates lexical retrieval when semantic representations are sufficiently activated by the task, as in the picture naming task.

In contrast with the results observed in the picture naming task, results in the word-to-sign translation task showed that participants were unaffected by iconicity. The absence of significant effects replicates previous evidence testing semantically-related manipulations (iconicity: Baus et al., 2013; cumulative semantic effect: Navarrete et al., 2015) and supports the idea that translating words into signs could be accomplished lexically, without semantic mediation. Navarrete et al. (2015) interpreted the lack of semantic effects in the word-to-sign translation as consistent with Kroll and Steward's (1994) proposal that links between bilinguals' two languages are semantically driven from the L1 to the L2, and lexically driven from the L2 to the L1. As in Navarrete et al. (2015), participants in our study were Deaf signers translating printed words (L2) into signs (L1), which would indicate that lexical links between the bilinguals' two lexicons are not determined by the modality of bilingualism, whether unimodal or bimodal. Those proposals though, cannot readily account for the lack of iconicity effects obtained in Baus et al. (2013) when hearing bimodal bilinguals translated printed words, their L1, to sign language, their L2. Considering all those results, a more plausible explanation of the lack of semantic effects in the word-to-sign translation task is that words do not trigger activation of semantic representations as pictures do, thus affecting the impact of semantic-related variables. In line with this view, Vigliocco et al. (2005) showed that words do not automatically activate imagistic conceptual representations unless the task motivates it. In a meaning similarity judgement task, hearing speakers were presented with three words of three semantic classes, and they were asked to group the two more similar in meaning. When English speakers were instructed to make a mental image of the words, their grouping of words was more similar to the grouping of signs (in British Sign Language, BSL) made by Deaf native signers. The authors argued that, while Deaf signers automatically activate imagistic representations related to sign forms (e.g., iconicity), English speakers only activate imagistic representations related to words when the task explicitly motivates it.

Altogether, our results on iconicity do not support the idea that iconicity in sign language is automatic in sign language processing (Thompson et al., 2010). The present behavioural and electrophysiological results are more in line with the idea that iconicity effects arise when the task enhances semantic-to-phonological links (Meteyard et al., 2015; Pretato et al., 2018). As such, differences between the two tasks in the present study would arise because pictures (but not words) lead to greater activation of semantics, thus promoting the engagement of the links between semantic concepts and sign phonological representations. Conversely, written words might activate phonological sign representations via a direct lexical route, bypassing semantic activation.

Our results on lexical frequency also emphasised the idea that differences between words and pictures were restricted to semantics and did not expand to other levels of processing. When lexical frequency was manipulated, both tasks revealed an effect: high-frequency items, pictures and words, were signed faster than low-frequency items. These results replicated the well-established phenomenon reported in the signed modality (Baus & Costa, 2015; Emmorey et al., 2012, 2013; 2020) as well as in the oral modality (Oldfield & Wingfield, 1964; see Brysbaert et al., 2018, for a review).

In addition, frequency effects were obtained at the ERP level in the two tasks. While those results clearly reflect sensitivity to frequency during lexical access in sign production, there were some differences worth commenting between the two tasks regarding the polarity and the latency of the frequency effect.

In the picture naming task, pictures related to high-frequency signs elicited a reduced positivity at the 350-550 ms time window, in comparison to pictures related to low-frequency signs. These results replicate the polarity obtained in previous picture naming studies in both sign and oral languages (Baus et al., 2014; Baus & Costa, 2015; Qu et al., 2016; Strijkers et al., 2010; Strijkers & Costa, 2011) and the timing reported in picture naming studies in the signed modality (Baus & Costa, 2015). In contrast, ERP frequency effects in the word-to-sign translation task showed a reverse polarity and an earlier onset of the effect. High-frequency words elicited a greater positivity compared to low-frequency words, an effect starting in the 140-210 ms time window and being maximal at around 400 ms (350-550 ms).

Differences in polarity between pictures and words are not unusual and have previously been found in oral language experiments (e.g., Fairs et al., 2021), which supports the idea that task-related variables regulate not the presence of the effect but how lexical variables, such as lexical frequency, modulate the pattern of ERP components (e.g., Fischer-Baum et al., 2014; Strijkers et al., 2015).

Differences between the two tasks were also observed in the latency of the ERP frequency effects. Both tasks revealed a prominent effect of lexical frequency in the N400 time-range (although opposite polarity), thus replicating previous findings both in the oral, written and spoken (Fischer-Baum et al., 2014; Winsler et al., 2018), and signed literature (Baus & Costa, 2015; Emmorey et al., 2020; Osmond et al., 2018). Frequency effects in this time-range have been univocally attributed to lexical processing, with the N400 indexing changes in the level of activation of lexical representations depending on their frequency. In the picture naming task, such ERP modulations most likely reflected the greater activation of high-frequency signs compared to low-frequency ones. Contrastingly, in the word-to-sign translation task, because both language modalities are involved in the task (one in the input and the other in the output), the N400 ERP frequency effect could be reflecting the impact of word frequency, sign frequency or the parallel activation of both modalities (Gimeno-Martínez et al., 2021; Lee et al., 2019). Although the present data do not allow determining the modality of processing reflected in the N400 time-range, two data points appear to suggest that effects in the word-to-sign translation are reflecting the processing of words. First, the early effect of frequency obtained in the word-to-sign translation resembled that reported in the oral modality, using words or pictures as stimuli in the task (Baus & Costa, 2015; Dambacher et al., 2006; Fairs et al., 2021; Hauk & Pulvermüller, 2004; Strijkers et al., 2010; Strijkers et al., 2015; Winsler et al., 2018). Many of those studies interpreted the early effect of frequency as the impact of frequency on sublexical processing during word recognition. Importantly, characteristics of the task influence participant’s attention to those sublexical properties (Strijkers et al., 2015; Winsler et al., 2018). Considering those results, written words in our study might have influenced sensitivity of our participants to the sublexical properties of the oral modality. Second, the polarity of the frequency effect in the word-to-sign translation task was the same in the early and the late portion of the effect (but reversed to that obtained in the picture naming task). Thus, taking into account the polarity and latency of the frequency effect, a more parsimonious explanation of the frequency effects in the word-to-sign translation is that frequency effects might occur at multiples levels during word processing, including sublexical and lexical processing (e.g., Emmorey et al., 2020; Knobel et al., 2008; Winsler et al., 2018).

Note that, although the main interest of our study was on iconicity, the results on lexical frequency across tasks revealed a very interesting pattern, worth further exploring in the future. Importantly, finding differences in latency and polarity of the frequency effect across tasks does not preclude our conclusion that iconicity effects but not frequency effects are modulated by the characteristics of the task.

To summarize, the present study explored the influence of iconicity on lexical access during sign language production. By means of a picture naming task in LSC and a Spanish written-word to LSC translation task, we investigated iconicity as a constituent index of the sign language modality, and lexical frequency as a general index of lexical access across language modalities. Both behavioural and electrophysiological results reported here showed that the impact of iconicity on sign language production is dependent on the processes induced by the task at hand.

Acknowledgements

This work was supported by the Ministry of Science and Innovation of Spain (RTI2018-096238-A-I00) and by the BIAL Foundation (Grant Number 2026/2016). Cristina Baus was supported by the Ramon y Cajal research program (RYC2018-026174-I). We would like to thank Gemma Barberà for making the participants pool available to us, Iris Milán-Maillo for her assistance during the testing sessions, and all the participants for taking part in the study.

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CROSS-LINGUISTIC INTERACTIONS ACROSS MODALITIES: EFFECTS OF THE ORAL LANGUAGE ON SIGN PRODUCTION

Chapter 3

Gimeno-Martínez, M., Mädebach, A., & Baus, C. Cross-linguistic interactions across modalities: Effects of the oral language on sign production. Bilingualism: Language and Cognition. 2021; 24(4):779-790.
DOI: 10.1017/S1366728921000171

Cross-linguistic Interactions Across Modalities: Effects of the Oral Language on Sign Production

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Keywords: cross-linguistic interactions, sign languages, bimodal bilingualism, phonology, semantics.

Author note: Data and analyses scripts are stored and publicly available at the Open Science Framework under https://osf.io/ymz9q/.

Abstract

To investigate cross-linguistic interactions in bimodal bilingual production, behavioural and electrophysiological measures (ERPs) were recorded from 24 Deaf bimodal bilinguals while naming pictures in Catalan Sign Language (LSC). Two tasks were employed, a picture-word interference and a picture-picture interference task. Cross-linguistic effects were explored via distractors that were either semantically related to the target picture, to the phonology/orthography of the Spanish name of the target picture, or were unrelated. No semantic effects were observed in sign latencies, but ERPs differed between semantically related and unrelated distractors. For the form-related manipulation, a facilitation effect was observed both behaviourally and at the ERP level. Importantly, these effects were not influenced by the type of distractor (word/picture) presented providing the first piece of evidence that Deaf bimodal bilinguals are sensitive to oral language in sign production. Implications for models of cross-linguistic interactions in bimodal bilinguals are discussed.

3.1. Introduction

A well-established phenomenon in the literature is that bilinguals cannot restrict lexicalization to one of their languages. While speaking, listening, or reading, bilinguals’ two languages are simultaneously and automatically activated, revealing that lexical access in bilinguals is largely language non-selective (for discussion see, e.g., Kroll, Bogulski, & McClain, 2012). Evidence of cross-linguistic interactions comes from studies on word comprehension (Marian & Spivey, 2003b, 2003a; Wu & Thierry, 2010) and word production (Colomé & Miozzo, 2010; Hermans, Bongaerts, De Bot, & Schreuder, 1998), showing that activation of the non-intended language influences processing in bilingual’s intended language.

Critically, the non-selective nature of bilingual lexical activation has also been shown in bilinguals with two languages of different modality (oral and signed), termed “bimodal bilinguals”. A number of experiments have showed that Deaf and hearing bimodal bilinguals activate sign properties when processing words (Kubus, Villwock, Morford, & Rathmann, 2015; Morford, Kroll, Piñar, & Wilkinson, 2014; Morford, Occhino-Kehoe, Piñar, Wilkinson, & Kroll, 2017; Morford, Wilkinson, Villwock, Piñar, & Kroll, 2011; Shook & Marian, 2012; Villameriel, Dias, Costello, & Carreiras, 2016).

For example, Morford et al. (2011) showed that phonological relationships in American Sign Language[2] (ASL) influenced semantic similarity judgements of written word pairs in English (see also Villameriel et al., 2016, for similar results with hearing bimodal bilinguals and Morford et al., 2014, for a different result with hearing bimodal bilinguals).

Much scarcer is the evidence showing cross-linguistic influences of words on sign processing (Emmorey, Mott, Meade, Holcomb, & Midgley, 2020; Giezen & Emmorey, 2016; Hosemann, Mani, Herrmann, Steinbach, & Altvater-Mackensen, 2020; Lee, Meade, Midgley, Holcomb, & Emmorey, 2019). Using the same paradigm as Morford et al. (2011), Lee et al. (2019) showed that hearing bimodal bilinguals were sensitive to the phonological relationship of the English-translations (i.e., rhymed) while judging the semantic relationship of ASL sign pairs. Relevant here, results were not replicated in the Deaf group, unless Deaf individuals were aware of the English phonological manipulation.

While those results help demonstrate that cross-linguistic interactions in bilinguals are not modality-specific, they are also suggestive that, as in unimodal bilingualism, cross-linguistic interactions are not a

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[2] Different than phonemes in oral languages, phonemes in sign languages are defined by structural units based on manual parameters such as handshape, place of articulation, movement, palm orientation (Brentari et al., 2018) and non-manual behaviours of the face and the body (Pfau & Quer, 2010). Therefore, signs and words do not share any of its core components and the aforementioned parameters are not the translation of spoken phonemes, and vice versa.

ubiquitous phenomenon. At least two factors should be considered when exploring cross-linguistic interactions in bilinguals. The first relates to language dominance and proficiency. Cross-linguistic influences from L2 to L1 are weaker than the reverse and they only occur when sufficient proficiency in L2 has been attained (Van Hell & Tanner, 2012). Because most Deaf signers are more dominant and proficient in sign language than in the oral language, this unbalance between languages could explain the lack of L2 (spoken) influence on L1 sign comprehension for Deaf bilinguals in Lee et al. (2019). The second factor, and more specific to bimodal bilingualism, relates to the mechanisms of phonological activation of the oral language, which might be different between hearing and Deaf bilinguals. Because Deaf bimodal bilinguals acquire the oral (L2) language via the written form (e.g., also referred as sign-print bilinguals; Piñar, Dussias, & Morford, 2011), phonological effects could be enlarged when spoken phonology is directly induced by the written language or, as showed in Lee et al. (2019), in those Deaf bilinguals with higher phonological awareness of the oral language.

Keeping these factors in mind, in the present study we tested Deaf bimodal bilinguals during sign language production to further characterize cross-linguistic effects of the oral L2 on the sign L1 language. Before describing our study, cross-linguistic effects in language production and theoretical models of bilingual lexical selection are described.

a) Cross-linguistic effects in language production

In language production, most of the evidence on cross-linguistic interactions comes from studies using interference tasks. In these tasks, both a picture and a distractor are presented; participants are then asked to name the picture while ignoring the distractor. Experimental manipulations of the relationship between the distractor and the picture have been studied to inform models of bilingual language production (for a review see Hall, 2011). In particular, semantic and phonological effects[3] in picture-interference tasks have produced a fruitful debate concerning the role of competition in bilingual lexical selection.

Considering semantic effects, semantically related distractor words in the non-intended language (e.g., distractor: gato (*cat*) – target: DOG) elicit semantic interference (slower naming latencies and more errors in the semantically related condition than in the unrelated condition; Costa & Caramazza, 1999; Costa, Colomé, Gómez, & Sebastián-Gallés, 2003; Hermans et al., 1998). Models of bilingual language production have explained these semantic interference effects as a result of lexical competition between the two languages (Hermans, 2004; Hermans et al., 1998) or within the intended language (Costa et al., 2003; Roelofs, Piai, Garrido Rodriguez, & Chwilla, 2016). Even though both views propose that interference is based on conflict at the lexical level, between-language competition

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[3] Along the present manuscript we use the terms *semantic and phonological effects* referring to the semantic and phonological experimental manipulations, but it does not imply a semantic or a phonological locus of the effects.

assumes that lexical selection is accomplished through competition of all activated candidates regardless of language, and within-language competition assumes that distractors are automatically translated and then competition only occurs among lexical candidates in the target language. Alternatively, models assuming non-competitive lexical selection (Response Exclusion Hypothesis; Mahon, Costa, Peterson, Vargas, & Caramazza, 2007) explain semantic interference effects as arising post-lexically, from control processes operating just prior to articulation.

At the ERP level, most of the picture-word interference studies have reported N400-like modulations of the semantic effect. Less negative ERP for pictures presented with semantically-related words (relative to semantically-unrelated words) have been taken as an index of semantic priming in competitive and non-competitive accounts of speech production alike (Blackford, Holcomb, Grainger, & Kuperberg, 2012; Dell'Acqua et al., 2010; Koester & Schiller, 2008; Piai, Roelofs, Jensen, Schoffelen, & Bonnefond, 2014; Roelofs et al., 2016; Zhu, Damian, & Zhang, 2015). Importantly here, differences between models arise in the predicted timing of the semantic interference effects. While lexical competition models predict a semantic effect during lexical selection, the response exclusion account predicts a later effect, much closer to the speech onset. Considering the time estimates of lexical selection in simple picture naming, which occurs at around 200 ms (e.g., Costa, Strijkers, Martin, & Thierry, 2009), ERP modulations occurring at ~200 ms have been taken as competition occurring at the lexical level, therefore supporting lexical-competition models. Conversely, semantic effects starting at ∼400 ms may imply a post-lexical locus, supporting non-competitive lexical selection models. However, it is not trivial to map time course estimates from simple picture naming to the picture-word interference task (in which naming latencies are prolonged). In addition, the electrophysiological literature does not show a consistent picture regarding the time course of semantic distractor effects, with studies showing earlier (200–500 ms; Aristei, Melinger, & Rahman, 2011; Hoshino & Thierry, 2011) and later effects (325–600 ms; Blackford et al., 2012), making it difficult to localize the origin of semantic effects during speech production.

Relative to unimodal bilingualism, studies with bimodal bilinguals seem to favour predictions of the response exclusion hypothesis. Giezen and Emmorey (2016) and Emmorey et al. (2020) found no behavioural semantic interference effects in the picture-word interference task when hearing or deaf bimodal bilinguals were signing pictures in the presence of auditory or written distractors. According to the response exclusion account, semantic interference effects are not predicted in sign language (Emmorey et al., 2020; Giezen & Emmorey, 2016) because there should be no post-lexical conflict between signs and word responses. Conversely, a semantic facilitatory effect is predicted as a result of activation of the semantic properties of the picture caused by a semantically related word prime. Indeed, Emmorey et al. (2020), obtained a semantic facilitation effect supporting this prediction (cf. Giezen & Emmorey, 2016). In addition, consistent with a semantic priming effect, they observed an

ERP modulation starting around 300 ms, with pictures paired with semantically related words showing an early N400-like attenuation. Interestingly, semantic effects in Emmorey et al. (2020) matched the timing obtained in Baus and Costa (2015) when lexical variables were manipulated (i.e., lexical frequency, iconicity) in a picture signing task, which reinforces the idea that language interactivity is modality invariant and has a lexical origin (Shook & Marian, 2012).

Here we further explored behavioural and ERP correlates of semantic processing in deaf bimodal bilinguals. If as described by the response exclusion account there is no competition at the articulatory buffer between signs and words (Emmorey et al., 2020; Giezen & Emmorey, 2016), then we should obtain a facilitatory effect of semantic relatedness behaviourally and a semantic priming effect at the ERP level. Note however that even if signs and words do not compete (at lexical or articulatory levels) semantic effects could be also expected as a result of within-(oral) language competition. Unlike unimodal bilinguals, bimodal bilinguals can produce signs and words at the same time (i.e., code-blending) because signed and spoken languages use different motor systems. In this context, lexical competition might occur among candidates of the non-intended language (oral modality), which might end up affecting how words and signs are synchronized to produce a code-blend sign (Hosemann et al., 2020; Vinson, Thompson, Skinner, Fox, & Vigliocco, 2010). We return to this issue in the discussion.

Experiments with phonological distractor manipulations have broadly shown that distractors in the non-intended language which are phonologically related to the target facilitate picture naming (e.g., distractor: dos *(two)* – target: DOG; Colomé & Miozzo, 2010; Costa et al., 2003; Costa, Miozzo, & Caramazza, 1999; Hermans et al., 1998). Conversely, distractors in the non-intended language which are phonologically related to the target's translation slow down picture naming (e.g., distractor: pera (*pear*) - target: DOG (perro in Spanish); Boukadi, Davies, & Wilson, 2015; Costa et al., 2003; Hermans et al., 1998; Hoshino & Thierry, 2011; Knupsky & Amrhein, 2007; but see Costa, Albareda, & Santesteban, 2008). Similar to semantic effects, phonological interference effects have been attributed to competition at the lexical level in models assuming between-language competition (Hermans, 2004) and to competition at the phonological level by models assuming within-language lexical competition (Costa et al., 2003; Roelofs et al., 2016).

At the ERP level, Hoshino & Thierry (2011) showed similar semantic and phono-translation effects in a picture-word interference task. The behavioural interference occurred in the presence of reduced negativities for the semantic and phono-translation conditions relative to the unrelated condition. Both semantic and phono-translation effects elicited ERP modulations in two time windows (at around 200 ms and 350 ms respectively), which were interpreted as evidence of cross-language competition at the lexical level and beyond.

To the best of our knowledge, cross-modal phonological effects through the oral language in picture-word interference have not been tested in bimodal bilinguals. Different directions of the phonological effect could be expected depending on within or between-language competition views. Following within-language competition views (Roelofs et al., 2016) interference could only occur at the phonological level which is shared across oral languages. Because conflict at the phonological level should not exist between sign and oral languages, facilitation should be observed due to priming of the translation-equivalent in the non-intended language. Note that the same result would be predicted in code-blending production, when mouthing is activated and articulated together with the sign. In contrast, if phonological interference effects are observed, as have been found in unimodal picture-word interference studies, this finding would support between-language competition views, where interference occurs at the lexical level (Hall, 2011). It should be noted that the response exclusion account has not been described to account for phonological effects in bilingual production. One tentative prediction for bimodal production could be that, since language membership is a response-relevant feature and no competition needs to be solved at the articulatory level, the phonology of the oral language is irrelevant and easily disregarded. In consequence, there should not be phonological influence from the oral language while signing.

b) The present study

In the present study, we explored cross-linguistic interactions in sign production by testing Deaf bimodal bilinguals in two tasks, a picture-word and a picture-picture interference task. Comparing performance in two different interference tasks allowed us to examine whether cross-linguistic effects require the oral language to be directly activated by the (written) distractors in the task.

Semantic and phono-translation effects and their locus during sign production were evaluated, allowing us to test behavioural and electrophysiological traces of lexical selection processes in bimodal sign production. For example, the picture of a DOG (perro in Spanish) was presented with the distractor word or the distractor picture “gato” (*cat* in English; semantic condition), the word/picture “pera” (*pear* in English*;* phonological condition), or the word/picture “casa” (*house* in English; unrelated condition) superimposed on the target picture.

To explore cross-linguistic semantic effects (the contrast between the semantic and the unrelated condition) predictions necessarily must be put forward in the context of the picture-word inference task, given that results in the picture-picture interference task would not be informative regarding the involvement of the oral language in the task. A semantic effect in the picture-word interference task would demonstrate that activation of the oral lexicon (induced by the distractor word) influences sign production. If our results support the non-competitive nature of lexical selection, cross-modal co-activation should result in facilitation due to semantic priming because there should be no post-lexical conflict between sign and oral language (for discussion see Emmorey et al., 2020; Giezen & Emmorey, 2016; Mahon et al., 2007).

The contrast between the form-related and the unrelated condition has the potential to reveal more about cross-linguistic interactions across modalities. Any differential effect of a distractor that is form-related to the Spanish name of the target picture would imply that Spanish was activated during LSC sign production and that the Spanish lexicon influenced sign production. In addition, if the phonological effects do not differ between tasks, it would suggest that these effects are not driven by the explicit presence of the Spanish language in the task.

3.2. Methods

a) Participants

Twenty-four Deaf LSC-Spanish bilinguals (12 females, M_{age} = 34.5 years, *SD* = 14.2 years) participated in the study. Twenty-two participants had profound hearing loss (91-120 dB), one participant had a severe hearing loss (71-90 dB), and one participant had a moderately-severe hearing loss (56-70 dB). Four participants reported using hearing aids, one reported the use of cochlear implants and nineteen participants did not use any type of hearing device. One additional participant was run, but excluded due to an excessive number of artefacts. All participants reported normal or corrected vision and no history of neurological problems. Self-ratings of LSC and Spanish proficiency were collected through a language background questionnaire (Table 3.1). All participants completed an informed consent form before the experiment and were paid for their participation.

Table 3.1 Demographic information of the participants. Mean ratings (M) and standard deviation (SD).

	M (SD)
Age (years)	34.5 (14.2)
Age of exposure to LSC (years)	3.4 (5.4)
Age of exposure to Spanish (years)	3.8 (2.7)
LSC comprehension proficiency *	9.9 (0.4)
Spanish reading proficiency *	8.6 (1.5)
Spanish spoken comprehension proficiency *	7.0 (2.1)

* Self-ratings from a language questionnaire; proficiency was rated on a 10-point scale ranging from 'almost none' to 'very proficient'

b) Materials

A set of thirty pictures and a separate set of ninety picturable words were selected as targets and distractors, respectively, from different databases (E. Bates et al., 2003; Snodgrass & Vanderwart, 1980). In the picture-picture interference task, the stimuli consisted of two overlapping pictures, with targets in green and distractors in red. In the picture-word interference task, stimuli consisted of target pictures with a written superimposed word. In both tasks, each picture was paired with three different distractors (see Table S2.1 in Annex II) and these distractor-set pairings were the same in both tasks. In the form-related condition, distractors were phonologically and orthographically similar to the Spanish name of the targets (e.g., *CEREZA-cerebro*; ‘cherry-brain’ in English), with phono-translation distractors and targets overlapping on 3 phonemes/letters on average (*SD* = 0.86; e.g., *PINcel–PINgüino*, ‘brush - penguin’ in English) and, in most cases, corresponding in their first syllables. Due to the nature of the Spanish language as a language with transparent orthography, materials selected based on phonological relations in Spanish were also mainly orthographically related. Thus, we refer to this condition as form-related condition. In the semantically related condition, distractors were from the same semantic field but were not form-related (e.g., *CEREZA-manzana*; ‘cherry-apple’ in English). A set of unrelated distractors were selected as the baseline condition (e.g., *CEREZA-llave*; ‘cherry-key’ in English). Targets and distractors were always phonologically unrelated in LSC and did not have obligatory mouth patterns as an intrinsic component of the sign. Furthermore, Spanish names for the distractor pictures were matched across conditions in number of phonemes/letters, lexical frequency, concreteness, and familiarity from the Spanish corpus B-Pal (Davis & Perea, 2005) (see Table S2.2 in Annex II).

c) Procedure

Participants were tested individually in an electrically shielded and dimly lit room. Instructions and other communication during the experiment were given in LSC by a hearing proficient signer.

The order of the two tasks, picture-picture interference and picture-word interference, was counterbalanced across participants[4]. In each task, stimuli were presented in two blocks of 45 trials, and each task began with a practice block of three warm-up trials. E-Prime 2.0 ® was used to present the stimuli and record signing latencies. At the beginning of each trial, an instructional message asked participants to press and hold the spacebar to start the trial. Then, a 500 ms black screen was followed by a 500 ms central fixation cross and a 300 ms black screen. Target-distractor pairs were then displayed and maintained until participants released the spacebar in order to sign the name of each target picture. A final 500 ms black screen appeared at the end of each trial. Signing latencies were calculated from the onset of the stimuli display until the key release (see Baus & Costa, 2015; Giezen & Emmorey, 2016; for the same method). Participants responses were recorded on video and checked for accuracy after the experiment ended. In addition to the signed responses, possible mouth movements elicited during sign production were checked by a hearing non-signer researcher.

d) Behavioural Analysis

Two target-distractor pairs were removed from all the analyses reported. One because participants reported a sign from the same semantic field instead of the desired sign (‘boat’ instead of

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[4] Balancing was incomplete for the following reason. Three additional participants were scheduled but did ultimately not participate in the experiment. For this reason, fourteen participants performed the picture-picture interference task first and eleven participants performed the picture-word interference task first. It should be noted that we included task-sequence in the analysis and the critical results do not dependent on this factor.

‘sailboat’), and the other because participants used the same signs adding mouthing to disambiguate between them instead of different signs (‘hair comb’ and ‘brush’).

We analysed the data by fitting linear mixed models, treating participants and items as crossed random factors (Baayen, Davidson, & Bates, 2008). Models were fitted in R (R Core Team, 2019) using the package lme4 (D. Bates, Mächler, Bolker, & Walker, 2015). Signing latencies where fitted with linear mixed models and error rates with generalized mixed models (binomial family). Models included fixed effects for task (sum coded), condition (treatment coded, unrelated condition as baseline), and their interaction.
Significance of the fixed effects estimates was determined using the Satterthwaite approximation for degrees of freedom provided by the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2015). Additional analyses on log transformed latencies (to alleviate problems related to non-normality) as well as additional analyses including fixed effects for task sequence, mouthing[5], and its interactions with the other fixed effects lead to the same conclusions as the latency analyses reported here.

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[5] Following a reviewer’s suggestion, we explored the possibility of mouthing patterns accounting for some of the effects observed. During the experimental session, thirteen participants were overtly mouthing during most of the trials, five participants produced mouthing in some trials and six participants were not mouthing while signing. Post-hoc analysis showed no substantial differences between groups, so mouthing was not included as a factor in the final model.

We aimed to fit models with the maximal possible random-effects structure (Barr, Levy, Scheepers, & Tily, 2013). We started out with a maximal model containing random slopes for distractor condition, task, and their interaction for both participants and items. In cases of non-convergence, we step-wise simplified the random structure, by dropping random correlations and the interaction terms before dropping main effect slopes from the model. In case of singular model fits, we first dropped the interaction terms before dropping condition or task slopes with an estimated variance (close to) zero.

e) EEG recording and analysis

EEG activity was continuously recorded from 30 Ag-AgCl electrodes, mounted on an elastic cap (ActiCap, Munich, Germany) and positioned according to the international 10-20 system. EEG data was recorded online to a common reference located at electrode site FCz. Eye movements and blinks were monitored with two electrodes placed below the right eye and at the outer canthus of the left eye. EEG data was sampled at 500 Hz with a bandpass of the hardware filter of 0.1–125 Hz.

Offline EEG data processing was carried out using the EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) MATLAB toolboxes. Signals were filtered offline with a bandpass filter of 0.1-30 Hz and re-referenced to the average activity of the two mastoids. Artefacts were corrected by means of an Independent component analysis (Extended RunICA, 30 components). ERPs were computed offline for each participant in each condition, time-locked to the onset of the target stimuli presentation, relative to a 100 ms pre-stimulus baseline and until 750 ms post-stimulus onset. Epochs with amplitudes above or below 100µV or with a difference between the maximum and the minimum amplitude exceeding 75µV were considered artefacts and discarded from the analysis. One participant with an excessive number of artefacts (36 % of trials) was discarded from the analysis.

Mean amplitudes for seven post-target onset latency windows were submitted to repeated-measures ANOVAs. ERPs analysis were analysed every 100 ms in order to cover early and late components: 50-150 ms, 150-250 ms, 250-350 ms, 350-450 ms, 450-550 ms, 550-650 ms, and 650-750 ms. The factors included in the analysis were: type of distractor (semantically related, form-related, and unrelated), electrode cluster (Anterior Left: F3, FC1; Anterior Right: F4, FC2, Central Left: FC5, C3, CP5; Central Right. FC6, C4, CP6, Centro-Posterior Left: CP1, P3; Centro-Posterior Right: CP2, P4; and Occipital: O1, Oz, O2; see Figure 3.1) and task (picture-picture and picture-word). Follow-up analyses were corrected using the Bonferroni correction and adjusted p-values are reported.

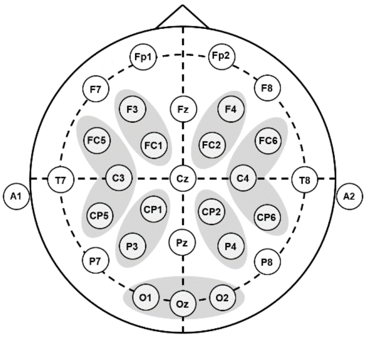


Figure 3.1 Electrode montage used in the present study. Highlighted ROIs were used in the analysis.

3.3. Results

a) Behavioural results

Signing latencies were significantly slower in the picture-picture task than in the picture-word task, $\beta = -110$ ms, $SE = 22.5$, $t(42.8) = 4.88$, $p < .001$. Compared to the unrelated condition, responses were faster in the form-related condition, $\beta = -35$ ms, $SE = 9.9$, $t(29.9) = 3.48$, $p = .002$. This phonological facilitation effect did not change significantly across tasks, $\beta = -1$ ms, $SE = 22.7$, $t(30.1) = 0.06$, $p = .956$. In contrast, there was no significant difference between the unrelated and the semantic condition, $\beta = -4$ ms, $SE = 10.3$, $t(29.5) = 0.36$, $p = .724$ and no significant change of this contrast across tasks, $\beta = 35$ ms, $SE = 19.2$, $t(32.7) = 1.85$, $p = .074$.

Error rates did not differ significantly by task, $\beta = -0.20$, $SE = 0.34$, $z = 0.58$, $p = .563$. There was no significant difference between the unrelated and the form-related condition, $\beta = -0.08$, $SE = 0.17$, $z = 0.49$, $p = .626$, and no significant change of this contrast across tasks, $\beta = 0.11$, $SE = 0.33$, $z = 0.32$, $p = .746$. More errors were made in the semantic compared to the unrelated condition, $\beta = 0.44$, $SE = 0.15$, $z = 2.83$, $p = .005$. This semantic effect differed significantly across tasks, $\beta = 1.32$, $SE = 0.31$, $z = 4.26$, $p < .001$. In the picture-word task the semantic interference effect was significant, $\beta = 1.09$, $SE = 0.21$, $z = 5.18$, $p < .001$, whereas there was no significant semantic effect in the picture-picture task, $\beta = -0.22$, $SE = 0.23$, $z = 0.98$, $p = .327$. Figure 3.2 displays sign latencies and error probabilities as estimated in the model fits.

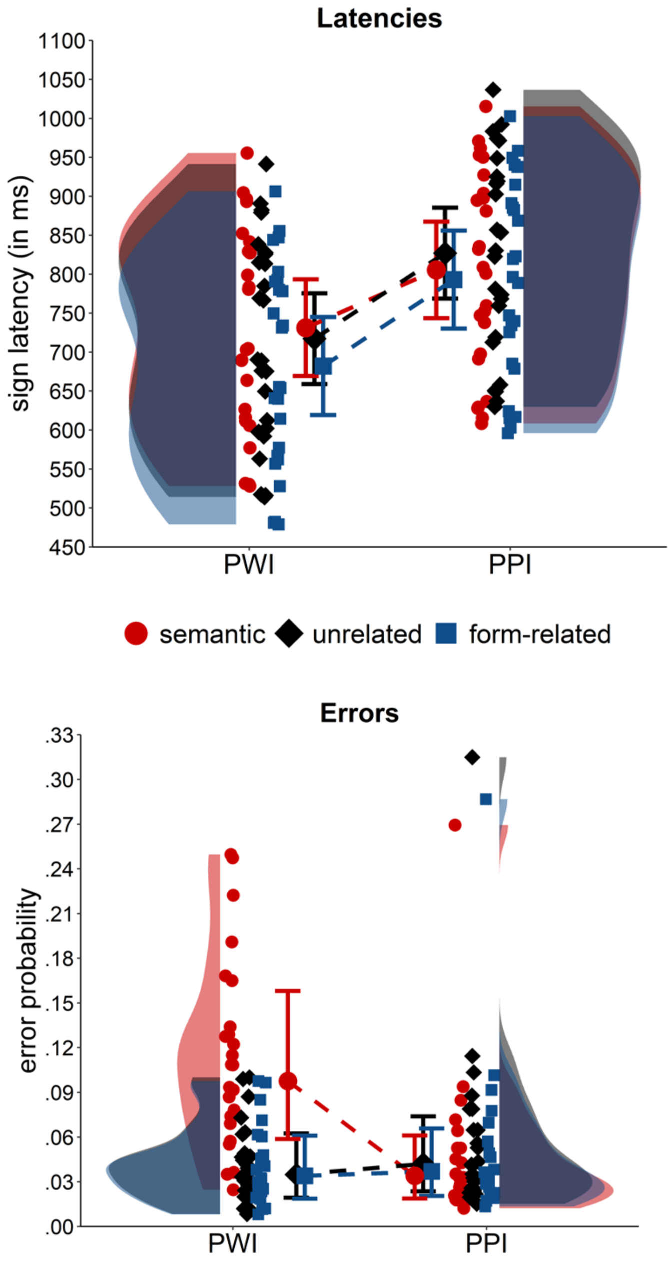


Figure 3.2 Mean naming latencies and error probabilities for the picture-word (PWI) and picture-picture (PPI) interference tasks, as estimated in the model fits. Error bars represent the 95% CI. Small shapes and densities represent the individual means for each participant.

To summarize, behaviourally there was a facilitation effect for form-related distractors which was of similar size across tasks. That is, participants named target pictures faster when distractors (either pictures or words) were related through the Spanish name of the target picture. There was a semantic interference effect in the picture-word interference tasks (on error rates only), whereas there was no semantic effect in the picture-picture interference task.

b) Electrophysiological results

Table 3.2 represents the main effects and interactions throughout the different time-windows. Only significant results are discussed in this section.

In the time window 150-250 ms after the onset of the stimuli presentation, ERP analyses revealed a main effect of type of distractor ($F(1.88,43.13) = 3.31$, $p = 0.05$). Post-hoc comparisons showed that there were significant differences between form-related and unrelated distractors ($t(23) = 2.4$, p = 0.02) and between semantically related and unrelated distractors ($t(23) = 2.36$, $p = 0.03$). Both related conditions elicited a larger positivity than the unrelated condition. In this time-window, there was also a significant interaction between task and electrode cluster ($F(2.14, 49.25) = 4.89$, $p = 0.01$), but post-hoc comparisons did not reveal significant differences.

At 250-350 ms post-onset, there were significant interactions between task and electrode cluster (*F*(1.90, 43.63) = 10.73, *p* < 0.001); however, none of the post-hoc comparisons yielded significant results.

Table 3.2 Significance table displaying the p-values on the repeated measures ANOVAs performed at 7 time-windows. Significant effects are highlighted in bold with the corresponding F-statistics. Corrected values using the Greenhouse-Geisser correction are reported. TW: Time-window (in ms) TD: Type of Distractor, T: Task, EC: Electrode Cluster.

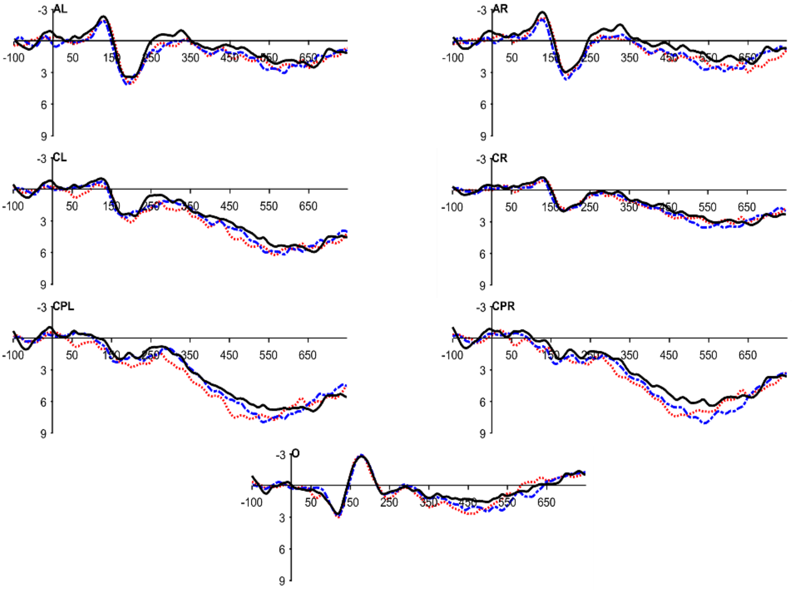
	Time-window (in ms)			
	50-150	**150-250**	**250-350**	**350-450**
TD	p=0.22	**F(1.88, 43.13)=3.31 p=0.05**	p=0.11	**F(1.93, 44.40)=3.38 p=0.04**
T	p=0.62	p=0.64	p=0.52	p=0.39
TD*EC	p=0.17	p=0.07	p=0.09	p=0.4
T*EC	p=0.21	**F(2.14, 49.25)=4.89 p=0.1**	**F(1.90, 43.63)=10.73 p<0.001**	**F(2.68, 61.55)=5.24 p<0.1**
TD*T	p=0.77	p=0.87	p=0.69	p=0.57
TD*T*EC	p=0.26	p=0.42	p=0.68	p=0.85

	Time-window (in ms)		
	450-550	**550-650**	**650-750**
TD	p=0.07	p=0.5	p=0.75
T	p=0.4	p=0.29	p=0.18
TD*EC	p=0.36	p=0.43	p=0.75
T*EC	**F(2.83, 65.03)=3.43 p=0.02**	p=0.46	p=0.35
TD*T	p=0.82	p=0.55	p=0.36
TD*T*EC	p=0.59	p=0.14	p=0.25

At the 450-550 ms time window, there was a significant interaction between task and electrode cluster ($F(2.83, 65.03) = 3.43$, $p = 0.02$). No significant results were obtained in post-hoc comparisons.

To summarize the results reported above, in the early time-window 150-250 ms post-onset and in the late time-window 350-450 ms post-onset, there was a main effect of distractor type, and this factor did not interact with task or electrode cluster. Post-hoc comparisons revealed that form-related and semantically related distractors elicited more positive-going waves compared to unrelated distractors. Figure 3.3 depicts the ERP waves for each type of distractor across tasks, in the seven regions of interest. Figure 3.4 depicts the scalp map for semantic and phonological effects across tasks for the two critical time windows where significant differences were observed.

a) PWI



b) PPI

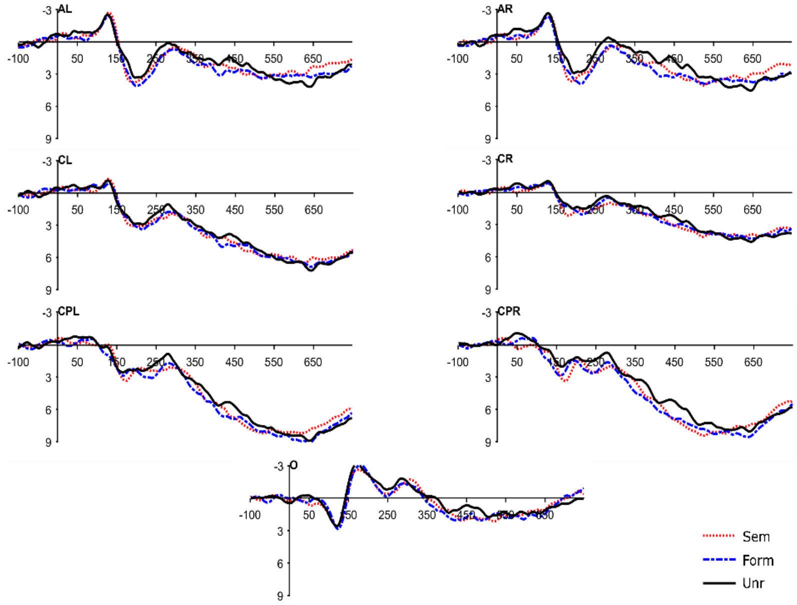


Figure 3.3 Event-related potentials from the semantic (sem), form-related (form) and unrelated (unr) conditions (Y axis: Mean amplitude in μ V) from the stimuli presentation (time 0) to 750 ms. Panel (a) depicts the ERP waves for the picture-word interference task (PWI) and panel (b) depicts the ERP waves for the picture-picture interference task (PPI). Nine regions of interest are represented: anterior left (AL), anterior right (AR), central left (CL), central right (CR), centro-posterior left (CPL), centro-posterior right (CPR) and occipital (O).

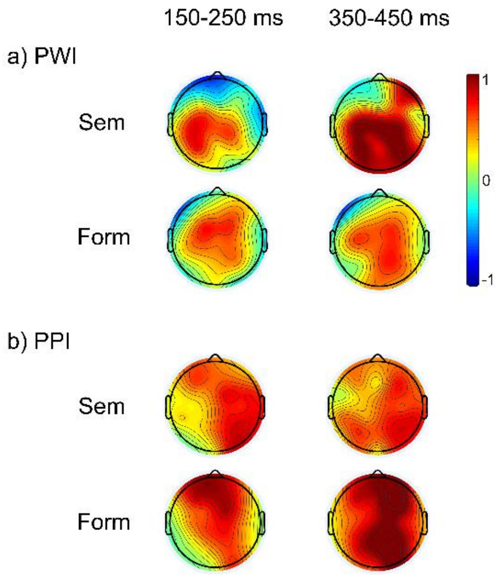


Figure 3.4 Topographic maps depicting semantic (sem) and form-related (form) effects for the critical time-windows. Effects were computed by subtracting the semantic and phonological distractor ERPs from the unrelated distractor ERPs. Voltage scale in microvolts. Panel (a) represents the picture-word interference task (PWI) and panel (b) represents the picture-picture interference task (PPI).

3.4. Discussion

In the present study, we explored cross-language, cross-modal interactions in Deaf LSC-Spanish bilinguals. Participants named pictures in LSC while ignoring visual distractors in the form of Spanish words (picture-word interference task) or pictures (picture-picture interference task). Distractors were either semantically related to the target picture, form-related to the Spanish name of the target picture (phono-translation), or unrelated. For the semantic contrast (vs. unrelated), we observed no significant semantic effect on sign latencies in either task, but participants made more errors in the semantic condition than in the unrelated condition during the picture-word interference task. Electrophysiologically, semantically related distractors elicited less-negative-going waves than unrelated distractors in the time windows 150-250 ms and 350-450 ms post-stimulus onset. For the form-related contrast (vs. unrelated), we observed phonological facilitation across tasks; pictures presented with form-related distractors in Spanish were signed faster than those pictures presented with unrelated distractors. At the ERP level, this relationship elicited a reduced negativity in the same time-windows where semantic effects were reported.

These results provide further evidence of cross-linguistic interactions in deaf bimodal bilinguals, both in language comprehension (Lee et al., 2019; Morford et al., 2011) and language production (Emmorey et al., 2020; Giezen & Emmorey, 2016), and from the weaker L2 oral language onto the more dominant L1 sign language, a pattern seen in other studies within the oral modality (Bobb, Von Holzen, Mayor, Mani, & Carreiras, 2020; Holzen & Mani, 2014). This indicates that Deaf signers had attained sufficient proficiency in their L2 oral language to experience word influences during sign production (Van Hell & Tanner, 2012). Finally, we obtained very similar results in the picture-word interference task and in the picture-picture interference task. Despite differences between the two tasks in the input format of the distractors (written words vs. pictures), the magnitude of the phonological effect was very similar across these tasks. These results suggest that the oral language knowledge of Deaf bilinguals influences sign production even when it is not directly involved in the task.

Regarding the semantic manipulation in our study, we only observed a semantic interference effect on error rates in the picture-word interference task, whereas we did not observe any significant semantic effect on sign latencies. The null result in the picture-picture interference task is in line with previous results in the oral domain. Multiple studies have shown no semantic effects from distractor pictures in picture naming (Damian & Bowers, 2003; Navarrete & Costa, 2005; Roelofs, 2008). Furthermore, there is evidence that semantic interference in this task may only be observed if the task specifically promotes attention to the distractor pictures (Jescheniak, Matushanskaya, Mädebach, & Müller, 2014; Matushanskaya, Mädebach, Müller, & Jescheniak, 2016), which was not the case in the present study.

For the picture-word interference task, the absence of a clear semantic interference on naming latencies is at odds with previous studies in the oral domain (Costa & Caramazza, 1999; Hermans et al., 1998), but corresponds to other results in sign production of bimodal bilinguals. Similar to the present study, Giezen and Emmorey (2016) had reported a null effect on naming latencies, whereas Emmorey et al. (2020) even observed semantic facilitation. This suggests that semantically related distractor words may induce no semantic conflict in sign production in line with predictions of the response exclusion account. However, we believe that this conclusion may be premature for the following reasons. First, we did observe a semantic interference effect on error rates. This was also the case in the study by Emmorey et al. (2020) and suggests that semantically related distractor words induce some level of conflict. Second, the null effect we observed on latencies is not in itself informative because we predicted either semantic interference (lexical competition) or facilitation (non-competitive selection) to occur. It is possible that the null effect in the present study (and in Giezen & Emmorey, 2016) reflects insufficient power of the design to reliably observe semantic interference effects (Brysbaert & Stevens, 2018; Bürki, Elbuy, Madec, & Vasishth, 2020). The result by Emmorey et al. (2020) suggest that the true underlying effect may be one of facilitation. However, we believe that more evidence is needed to evaluate the direction and size of semantic distractor effects in bimodal sign production.

Our ERP results, in particular the observation of less negative ERPs for semantically related distractors in the N400 time-window corresponds to previous results in monolingual and bilingual picture-word interference studies (e.g., Blackford et al., 2012; Dell'Acqua et al., 2010; Roelofs et al., 2016; Rose, Aristei, Melinger, & Rahman, 2019; Zhu et al., 2015). In line with previous studies, we interpret this N400 attenuation to indicate semantic priming between the target picture and a related distractor. Some authors have argued that N400-attenuation reflects facilitatory priming of the target by the distractor and is therefore incompatible with lexical competition (Blackford et al., 2012; Emmorey et al, 2020). However, prominent lexical competition accounts assume that semantic context effects reflect a trade-off between facilitatory priming of the target picture by the distractor and interfering "reverse" priming of the distractor by the target picture. Following this argument, our result is compatible with both competitive and non-competitive production accounts (for discussion see Piai et al., 2014; Roelofs et al., 2016). Interestingly, we found an ERP-modulation not only in the N400 time-window, but also earlier at around 200 ms. As we discuss in the introduction, earlier ERP-correlates of semantic distractor effects have also been found in some previous studies (Aristei et al., 2011; Dell'Acqua et al., 2010; Hoshino & Thierry, 2011; Rose et al., 2019). Such an early modulation fits with common time-course estimates for lexical access in picture naming. A recent study suggested that early ERP-modulations (at around 200 ms) may reflect lexical competition, whereas later modulations (at around 400 ms) may reflect ongoing semantic priming between target picture and distractor word (Rose et al., 2019).

In sum, we conclude that neither the behavioural nor the electrophysiological evidence unequivocally support the competitive or the non-competitive account. The behavioural results are inconclusive in this regard. The ERP-results correspond to similar findings in previous mono- and bilingual studies but appear compatible with both accounts. Moving forward, more evidence is needed to determine whether there is indeed semantic facilitation instead of semantic interference in bimodal picture-word interference tasks (as suggested by the result by Emmorey et al., 2020) and to clarify the functional relevance of the ERP-results for the behavioural effects.

Concerning phonological effects, the observation that picture names were signed faster in the presence of distractor words form-related to the oral name of the picture is, to our knowledge, the first piece of evidence showing that phonological properties of the oral language modulate how Deaf individuals produce signs (see Lee et al., 2019; Hosemann et al., 2020, for similar results in comprehension). This was further validated by the ERPs showing sensitivity to the phonological manipulation. Form-related distractors elicited a reduced negativity compared to unrelated distractors between 150-250 ms, and 350-450 ms post onset. These modulations replicate phono-translation ERP effects reported in the oral modality (Hoshino & Thierry, 2011) and signed modality (e.g., Hosemann et al., 2020). Remarkably, phonological ERP effects were obtained in the same time-windows and with the same direction as those obtained for the semantic contrast, although different results were obtained behaviourally for the two manipulations. This indicates that ERP polarities do not have a direct correspondence with behavioural effects (see also Dell'Acqua et al., 2010). In our study, similar ERP-modulations for the semantic and the phonological contrast might indicate priming between the distractor stimulus and the target picture, while not reflecting the functional consequence of such priming (in terms of facilitation or interference). Note that the polarity and timing (especially the early modulation) of the reported ERPs do not fit with the canonical N400 responses reported in picture-word interference tasks (Chauncey, Holcomb, & Grainger, 2009). Acknowledging the differences, we followed N400 interpretations in picture-word interference studies and interpret our data as evidence of the priming effect for form-related distractors relative to unrelated targets (see also Hosemann et al., 2020 for a similar interpretation of N400-like effects in bimodal bilinguals).

Behaviourally, the phonological effect found here differed from previous studies with unimodal bilinguals using the picture-word interference paradigm (Costa et al., 2003; Hermans et al., 1998). The so-called phono-translation interference effect occurs when distractors are phonologically related to the translation of the target language (saying *perro*, ‘dog’ in English, presented with the distractor *doll*) and it has been interpreted as evidence of lexical competition in bilingual speech production.

Finding phonological facilitation in bimodal bilinguals and phonological interference in unimodal bilinguals could be reconciled by models which posit phonological interference effects arising at the phonological level (within-language competition models). According to this account, in the absence of phonological overlap between language modalities, the activation of the phonological properties of the oral lexicon could not interfere with the activation of the sign language phonology. Thus, these models would account for phonological facilitation effects in sign production arising at the lexical level. In particular, processing of the distractor, word or picture, would lead to lexical activation of the oral phonological neighbours of the distractor. For the form-related distractors this includes activation of the translation equivalents of the target sign. Activation of the target's translation in the oral language (due to phonological priming by the form-related distractor) may then facilitate target retrieval via automatic translation from oral to sign language. Under this assumption, phonological effects would be a consequence from both languages being activated during the task as a result of parallel activation processes.

As mentioned in the introduction, the obtained pattern of semantic and phonological effects, both behavioural and at the ERP level, could be attributed to the “mouthing” of words (or part-words) that co-occurs with sign articulation in code-blending production (Capek et al., 2008; Giustolisi, Mereghetti, & Cecchetto, 2017; Hosemann et al., 2020; Vinson et al., 2010). In this context, it is conceivable that the articulatory buffer is shared for word-distractors and picture mouthings (i.e., the oral language). In this case, the response exclusion hypothesis may predict semantic interference to result from the same post-lexical conflict as for oral production, that is, due to slower exclusion of semantically-related distractor words (relative to an unrelated ones) from the articulatory buffer. This could delay availability of the mouthed phonemes of the picture which would also delay sign onset if mouthings are produced in synchrony with the sign. More importantly, the phonological facilitation effect we observed could be explained by phonemes of the distractor overlapping (fully or partly) with those of the mouthed picture name, thus facilitating mouthing production of phonologically-related words. In other words, the phonological facilitation effect may reflect mouthing preparation rather than genuine cross-linguistic influence of the oral language on sign preparation. Following the suggestion of an anonymous reviewer we conducted a follow-up analysis to explore this possibility. As in previous reports (Vinson et al., 2010), we observed that tendencies to produce mouthing widely varied between participants. In the present study, thirteen out of twenty-four participants were mouthing during most of the trials, and six participants did not produce mouthing while signing, indicating that mouthing and the manual components of signs could dissociate and were not obligatory mouth patterns of the signs selected. Further analysis suggested that mouthing was not a critical factor for the behavioural and the ERP results. That is, there were no substantial differences between those participants who were overtly mouthing and those participants who did not produce mouthing (or produced it only in a few trials). Thus, our results do not seem to be caused by mouthing productions while signing.

From the perspective of the parallel activation account it is surprising that the phonological facilitation effect appeared to be virtually identical with distractor pictures and distractor words. For distractor pictures, parallel activation of the phonological cohort should be much less direct, and thus weaker, than for distractor words, because phonological activation is necessarily mediated by visual and conceptual processing of the picture. In line with this argument, unimodal studies have found phonological facilitation to be more robust with distractor words than with distractor pictures (Bloem & La Heij, 2003; Jescheniak et al., 2009). For this reason, we prefer an alternative account under which the phonological effect is not a direct result of immediate co-activation of the L2 but reflects the reorganisation of the L1 as a result of L2 language learning processes (Costa, Pannunzi, Deco, & Pickering, 2017, 2019). Within this framework, the present results would be reflecting the reorganisation of the sign language lexicon as a consequence of learning an oral language.

Under this account, lexical signs that were a priori not related in the sign language lexicon (e.g., CEREZA and CEREBRO, cherry and brain in English) would become related as a result of the phonological similarity of their corresponding translations in the oral language. It is possible that phonological properties of the oral language are linked to signs via mouthing production, considered to develop with bilingual experience of deaf individuals with the oral modality.

In this line, although not directly proposed for language production, the reading vocabulary acquisition model for Deaf children (Hermans, Knoors, Ormel, & Verhoeven, 2008) could account for the learning hypothesis. The model describes how sign and oral languages interact in three developmental stages. In the first stage, Deaf children only have access to the form of written words and the meaning is necessarily accessed throughout signs. The repeated co-activation of the sign and the written word translation equivalent results in the semantic and syntactic representations of the signs copied into the lexical representation of the written word. Finally, in the last stage, lexical entries contain all the semantic, morphological, and syntactic information. Considering the learning hypothesis, it is also possible that during the second stage, properties of the oral language are linked to sign forms via orthographic/phonological representations and, consequently, relationships in the oral language would ultimately map onto the sign language lexicon.

Either via reading (orthographic links) or mouthing processes (phonological links), or via the two representations combined, the sign lexicon of a native signer would be restructured when learning an oral language, resulting in a lexical network different from that of a Deaf individual without such oral language experience. Thus, when processing a given sign not only the properties of the sign language would be activated, but also properties of the oral language which became linked to the sign. If this is the case, the effects observed in the present study may result from activation flow within the sign language lexicon instead of direct activation flow from the oral language lexicon to the sign lexicon. Note that this account is not arguing against oral language co-activation during sign production itself. The crucial difference is that under this account it is not the immediate co-activation of the oral language that causes the phonological facilitation effect but the reorganization of the sign lexicon following the repeated co-activation of both languages in the process of learning the oral language.

3.5. Summary and conclusion

The present study tested for cross-linguistic effects from an oral language (L2) on sign language production (L1) by Deaf bimodal bilinguals. We found evidence for such cross-linguistic effects, most clearly in form of a phonological facilitation effect of distractors which were form-related to the oral language translation of the target signs. The ERP results suggest a lexical locus of the cross-linguistic interaction between sign and oral language. The critical phonological effect appeared to be similar with distractor pictures and written distractor words. This suggests that cross-linguistic influences of the oral language are not restricted to task contexts involving oral language stimuli (i.e., distractor words). Most importantly, the present results provide the first piece of evidence that Deaf bimodal bilinguals are sensitive to the properties of the oral language in sign production.

Acknowledgements

We would like to thank Gemma Barberà for her help in recruiting participants, Iris Milán for her assistance during the testing sessions, Nicholas Grunden for his suggestions on the present manuscript, and all the participants for taking part in the study. This work was supported by the BIAL Foundation [grant number 226/2016] the Spanish Government (RTI2018-096238-A-I00) and the Catalan government (2017 SGR 268). CB was supported by the Beatriu de Pinòs program [AGAUR grant number 2016 BP 00381]. AM was supported by the Beatriu de Pinòs program [AGAUR grant number 2017 BP 00180].

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RAPID NEURAL CHANGES IN M2L2 SIGN LANGUAGE VOCABULARY LEARNING

Chapter 4

Gimeno-Martínez, M., Gutiérrez-Sigut, E. & Baus, C.
Rapid neural changes in M2L2 sign language vocabulary learning. (in prep).

Rapid Neural Changes in M2L2 Sign Language Vocabulary Learning

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Keywords: Second language acquisition, lexical consolidation, cross-language interaction, sign languages, N400.

Abstract

The number of individuals interested in learning a sign language as a second language has increased considerably in the last decade. Acquisition of vocabulary is one of the essential steps for a good command of the language. The present study explored neural changes related to the early stages of signed vocabulary learning. In three laboratory learning-sessions (24-48 hours apart), thirty-two hearing non-signers were exposed to 150 Catalan Sign Language (LSC) signs. LSC learning-related changes to the N400 ERP component were explored in two priming tasks. First, a sign lexical decision task included a semantic priming manipulation (prime and target being semantically related or unrelated). Second, a written semantic decision task (in Catalan) included a manipulation of the LSC phonology of the signs corresponding to the presented words (overlap of sign parameters). Results from the LSC lexical decision task revealed N400 semantic priming effects in the second session, after one training procedure. In addition, results from both tasks revealed language effects in the third session. In the LSC lexical decision task, N400 effects were obtained both for lexicality and semantic priming. Learning-related effects were also revealed as covert activation of LSC phonology while processing Catalan words in the semantic decision task. Altogether, these results show fast linguistic effects in the early stages of intensive vocabulary training.

4.1. Introduction

Vocabulary learning is a fast and efficient process, critical to build-up a lexicon and ultimately to master a language. A small number of exposures to a new lexical item seem to be sufficient for new vocabulary to be assimilated in memory, which implies that the mental lexicon is continuously changing to accommodate new lexical entries. This is evident for children acquiring their first language and even more for learners of a second language (L2).

Here, we focused on second language learners to explore the neural changes occurring during vocabulary learning of a sign language. Hearing adults that learn a sign language represent a special case in L2 learning, since acquisition of new vocabulary involves a different language modality (M2L2; Chen Pichler 2011). Perceptual and articulatory channels involved in oral languages (in written or spoken format; auditory-vocal) are different from those involved in sign languages (visual-manual). As such, learning a sign 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., face, body) that are performed along with the sign. How hearing adult learners of a sign language integrate novel signs into the existing (oral) lexicon? In two EEG experiments, we sought to characterize the neural dynamics underlying the early stages of sign vocabulary learning.

Acquisition of novel vocabulary (as other types of memories) is described to be a two-stage process (e.g., lexical configuration and lexical engagement; Leach & Samuel, 2007). In an early stage of word learning (*lexical configuration*), word-form features (orthography, phonology and meaning) of the new words are acquired. Those are assumed to be encoded as episodic memory traces and supported by the hippocampal system (complementary learning systems, *CLS*, Davis & Gaskell, 2009), but not yet fully integrated into the lexicon. Accordingly, these words are not yet expected to behave as existing words or to interact with existing words in the learners' mental lexical network. It is not until a post-acquisition stage is reached, including a period of consolidation (e.g., sleep), that words become integrated into the lexicon (and mediated by neocortical structures; Davis & Gaskell, 2009). In the *lexical engagement* stage, orthographically, phonologically and semantically connections are established between the newly integrated words and those already existing in the mental lexicon.

Experimentally, words are considered to be integrated into the lexicon when reveal word-like patterns and influence lexical processing of related words in the language network (Bakker et al., 2015, Batterink & Neville, 2011, Clay et al., 2007, Davis et al., 2009, Dumay & Gaskell, 2007, Gaskell & Dumay, 2003, James et al., 2017, 2019, McLaughlin et al., 2004, Takashima et al., 2017). The N400, an ERP component largely associated to automatic lexico-semantic processing (Kutas & Federmeier, 2011) has been taken as a reliable measure of lexical integration, since it reflexes integration of L2 words into the current semantic context (Holcomb, 1993). In particular, brainwave modulations related to N400 lexicality and semantic effects, obtained for instance in priming lexical decision tasks, have been taken to characterize lexical consolidation. In a longitudinal study, McLaughlin et al. (2004) reported neural changes - indexed by the N400 - associated to L2 instruction. In a primed lexical decision task, L2 French learners judged whether the second of a pair of letter strings was a real French real word or a pseudoword. Real words could be preceded by a semantically related or an unrelated word. A lexicality effect was observed after fourteen hours of formal instruction, with a reduction of the N400 ERP component for French words in comparison to pseudowords. This result showed that learners seem to be sensitive to plausible form combinations of the language to be learned (i.e., lexical configuration stage) after 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 that 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 words integrated in 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).

Further studies tried to determine in much shorter laboratory-learning periods, how many exposures to a given word are required for this to be integrated in the lexicon. As some studies suggest, only after a number of meaningful exposures to novel words, including at least one period of offline consolidation (e.g., overnight sleep), word memory traces can be integrated in the lexicon (e.g., Bakker et al., 2014; Bakker, Takashima, van Hell, Janzen, & McQueen, 2015; Bakker, Takashima, van Hell, Janzen, & McQueen, 2015; 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). As such, lexical consolidation has been explored in laboratory-training sessions, comparing effects related to lexical processing and semantic priming before and after a consolidation period.

With respect to lexicality effects, neural changes associated to lexicalization processes have been reported after one consolidation period. In Bakker et al. (2015), ERPs associated to novel words, learned in two sessions separated by 24 hours, were compared to existing words (L1 of the participants). As revealed, N400 lexicality effects (difference between novel and existing words) reduced with consolidation. That is, while words learned 24 hours before test revealed an N400 pattern like that elicited by existing words, novel words recently learned (minutes before test and without consolidation) elicited a large N400 relative to existing words. This result was interpreted to reflect that at a first stage novel words are processed similarly to pseudowords (difficult to discard), but after a consolidation period their processing resembles existing words (see Yum et al., 2014, for similar results with English learners acquiring words of a different script).

Likewise, a short period of training (and consolidation) seems to be sufficient to observe N400 modulations as an index of semantic engagement of L2 words. In Pu et al. (2016), English monolingual participants attended the laboratory in four experimental sessions within a week. In the first session, participants completed a Spanish – English (L2 to L1) backward translation recognition task, which served as a baseline. In the task, participants were required to answer whether an English word was the correct translation for a preceding Spanish word (translation condition), or not (unrelated condition). In the fourth session, after two days of one-hour L2 Spanish vocabulary training, it was observed larger amplitude of the N400 for unrelated pairs compared to translation-pairs. Hence, lexicosemantic connections between newly learned vocabulary and existing words were observed after a period of lexical consolidation (Bakker et al., 2014; Bakker, Takashima, van Hell, Janzen, & McQueen, 2015; Davis et al., 2009; Yum et al., 2014).

In the present study, we longitudinally explored behavioral and neural changes underlying M2L2 sign learning in two laboratory-training sessions, including two periods of consolidation (24-48 hours each). In three testing sessions, we evaluated integration of newly acquired signs into the lexicon as well as interactions with existing words in the L1 of learners. More specifically, comparing the results of two priming experiments across sessions, we evaluated the neural changes associated to lexicality and semantic effects as well as cross-language interactions between signs and existing words.

When considering how learning-stages might apply to acquisition of signs, some relevant features of the signed language modality should be considered. Relative to words, sign forms often hold a tighter relationship with their meanings. For example, some sign locations (e.g., around heart or head) are related in meaning (Frishberg, 1975) and some handshapes are associated with particular semantic categories (i.e., classifier systems). Moreover, lexical and iconic form-meaning mappings are much prominent in sign languages than in oral languages, which influences sign processing especially for 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. To investigate the developmental stages underlying M2L2 sign learning, Experiment 1 explored neural signatures of the N400 component as an index of signs' lexical and semantic consolidation.

Taking a different approach, Experiment 2 further explored the integration of M2L2 novel signs into the lexicon by testing whether L2 connections influence processing of the L1. Most studies in 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., 2015). Behavioral and neural effects while processing the L1 target have been taken as evidence that new words are integrated in 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 the 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 produce changes to the existing lexical network (Cook, 2003).

In the present study, to track changes in the L1 lexicosemantic network during M2L2 sign learning, we adapted Thierry and Wu (2007) paradigm to the signed modality. In their study, phonological effects of the bilingual's L1 (Chinese) were obtained when processing their L2 (English). These results were taken as strong evidence that bilingual language processing is non-selective, that is, both languages are activated in parallel during language processing. Importantly, adaptations of Thierry and Wu's (2007) paradigm to the signed modality showed language-co activation in bimodal bilinguals (bilinguals of having an oral and a signed language; Morford et al.

2011). Following studies in the signed modality, we presented participants with a written semantic priming task in their L1 (Catalan) and manipulated the phonological relationship of the prime and target sign's translations, having phonologically related LSC translation pairs and phonologically unrelated translation pairs.

In sum, the present study explored the brain dynamics occurring in early stages of M2L2 sign learning. To characterize sign learning, N400 modulations related to lexico-semantic processing (Experiment 1), and covert sign activation (Experiment 2) were tested in three laboratory sessions within the same week (including two consolidation periods).

Experiment 1. Lexicosemantic Processing in M2L2 Sign Learning

4.2. Methods

a) Participants

Thirty-two hearing Catalan-Spanish bilinguals (twenty-one female, M_{age} = 22 years, range = 18–26 years) were recruited to participate in the study. They reported being Catalan-dominant bilinguals with no previous knowledge of LSC. Participants were recruited from the database from the Center for Brain and Cognition (Universitat Pompeu Fabra). They were informed that to participate in the experiment they would have to attend three experimental sessions in 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 an excessive number of artifacts in one session were excluded from the analysis of that session (one participant in the second session and one participant in the third session). In addition, those participants (*n* = 2) with an excessive number of artifacts in two or more sessions were excluded from the analysis of all sessions.

b) Materials

The complete set of video stimuli consisted of individual 150 LSC lexical signs. 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 take into account 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 in such a way that they started 1000 milliseconds before sign onset (*M* = 1000.3, *SD* = 156.4), and finished two seconds after sign onset. Sign onsets were determined as the first frame in which the fully formed handshape contacted the body or, for non-contact signs, when it reached the target location. ERPs were lock to this sign onset and from this, the N400 time range was calculated.

For the LSC lexical decision task, half of the 150 LSC signs were selected as primes and the remaining half as targets. For each of the 75 target signs there were created two types of non-signs: a pseudosign and a non-sign. In pseudosigns, the handshape of the original sign was replaced by another similar handshape from the LSC phonological repertoire. Non-signs were created replacing the handshape of the original sign by a pronounceable hand configuration that does not belong to the LSC handshape repertoire. In such a way, by employing two types of non-signs we avoided that participants could base their decisions on whether or not the sign involved a known handshape. As an example, for the LSC sign CAMEL a pseudosign was created changing the *flat O*-handshape for the *A*-handshape, that is present in other LSC signs such as PHARMACY. The related non-sign involved a handshape that does not belong to the usual LSC phonological repertoire (see Figure 4.1). In both pseudosigns and non-signs, the other sign parameters (i.e., movement, location, orientation) were maintained as in the original sign. In addition, target signs, pseudosigns and non-signs were similar in sign onset ($F(1.88, 139.11) = 0.04$, $p = 0.95$), and duration ($F(1.64, 121.61) = 0.58$, $p = 0.53$).

Figure 4.1 Still images of the sign onset of the videos corresponding to the three variants of the LSC sign CAMEL.

Primes and targets were selected so that they were not phonologically related in LSC. Two experimental lists were created in such a way that primes appeared twice, one before a target sign and one before a non-sign (either a pseudosign or a non-sign). Across lists, half of the non-signs were pseudosigns and the other half were non-signs. For instance, if the prime ELEPHANT appeared with the sign CAMEL and its pseudosign version one list, it appeared with the sign CAMEL and its non-sign version in the other list, and vice versa. 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. Within lists, trial presentation was pseudorandomised with the constrain that a minimum of five trials separated the two presentations of the same prime.

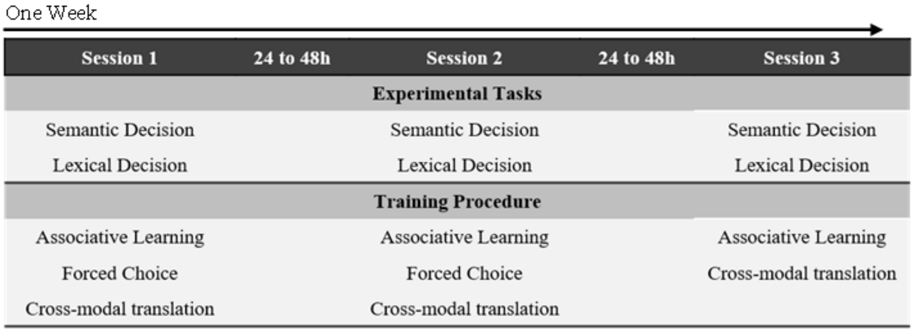
Critical for the task, half of the prime-target signs were semantically related whereas the other half were semantically not related. Semantic ratings for the sign Catalan translations were obtained from twenty-nine participants that did not take part of the experiment. Raters were asked to evaluate the semantic relatedness of each word pair in a scale from 1 (unrelated) to 7 (related). Pairs with semantic ratings below 4 were included in the semantically unrelated condition (*M* = 1.82; *SD* = 1.24), and pairs with mean ratings above 4 were included in the semantically related condition (*M* = 5.68; *SD* = 1.33). Semantically related and unrelated primes and targets 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).

c) Procedure

Participants attended the lab in three sessions within the same week. Each session was 24-48 hours apart and began with two experimental tasks: a semantic decision task (see Experiment 2) and a lexical decision task. This part was followed by the training procedure, similar to Mott's et al. (2020), were participants completed two learning tasks: an associative learning task and then a forced-choice task. Learning outcomes were evaluated through a cross-modal translation task (see annex III for a description of these tasks). All sessions maintained the same structure with the difference that, in the third session, the forced-choice task was not presented (see Table 4.1). In all three sessions, participants were tested individually in a sound attenuated dimly lit room, while behavioural and EEG measurements were recorded. In the following, we describe the procedures for the learning-related tasks (associative learning, forced-choice and cross-modal translation), and the lexical decision task.

Table 4.1 Task structure across the three sessions



One Week

Session 1	24 to 48h	Session 2	24 to 48h	Session 3
Experimental Tasks				
Semantic Decision		Semantic Decision		Semantic Decision
Lexical Decision		Lexical Decision		Lexical Decision
Training Procedure				
Associative Learning		Associative Learning		Associative Learning
Forced Choice		Forced Choice		Cross-modal translation
Cross-modal translation		Cross-modal translation		

In the lexical decision task, participants were presented with 150 trials, in which they saw two videos in succession and had to decide whether or not the second video was an LSC sign or a non-sign. Trials followed a similar design as in the semantic decision task. 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 (until response or a maximum of 8000 ms). Response times were measured from the onset of the target sign until participants responded pressing designated keys on the keyboard. Participants were instructed to blink when the green asterisk was displayed on the screen and/or after response. The task was divided in three blocks of fifty trials, and participants could rest if needed between blocks.

EEG procedure

EEG activity was recorded from 30 Ag-AgCl electrodes (see Figure 4.2), 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 artefacts, respectively. 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.

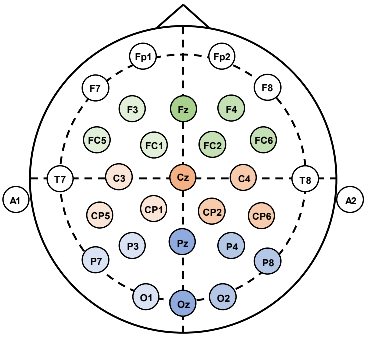


Figure 4.2 Electrode montage with the twenty-two sites (filled circles) used in analyses.

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 0.1-30Hz and re-referenced to the average activity of the two mastoids. Eye blinks and motor artefacts 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 100µV or with a difference between the maximum and the minimum amplitude exceeding 75µV were considered artefacts and discarded from the analysis.

Data analysis

Lexical sensitivity in the behavioural 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 analysed with linear mixed effect models. Models included fixed effects for 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, Mächler, Bolker & Walker, 2015).

ERPs were computed for each participant in each condition (semantically related, semantically unrelated, pseudosigns and non-signs) and session (first, second, third), averaging the activity time-locked to the onset of the target stimuli presentation in twenty-two electrode sites.

In order 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 across conditions and sessions (M = 383 ms after sign onset). 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 studies (e.g., Gutiérrez et al., 2012).

To statistically compare mean amplitudes across conditions, we analysed the data by fitting linear mixed models, treating subjects and electrode site as cross random factors. Models were fitted in R (R Core Team, 2019) using the lme4 package (Bates et al., 2015). Models included fixed effects for condition (semantically related, semantically unrelated, pseudosign, non-sign), session (first, second, third), laterality (left, midline, right), anteriority (anterior, central, posterior), and their interaction. In all analyses, significance of the fixed effects estimates was assessed using the Satterthwaite approximation for degrees of freedom provided by the lmerTest package (Kuznetsova et al., 2015). After significant effects of condition, we conducted follow-up analysis of three contrasts of interest. For lexicality effects, we compared the two conditions with sign targets (semantically related/unrelated) vs the two with non-sign targets (pseudosigns and non-signs). In addition, we also compared the two non-sign targets (pseudosigns vs non-signs). For semantic effects, we compared the two sign targets (semantically related vs semantically unrelated).

4.3. Results

a) Behavioural results

Analysis of d-prime scores (see Figure 4.3) showed significant differences considering sessions (*F*(2,57.9) = 246.57, $p < 0.001$). Comparisons across sessions revealed that d-prime scores significantly improved between first and second sessions (*t*(57.9) = 14.75, $p < 0.001$) and between second and third sessions (*t*(58.2) = 6.58, $p < 0.001$).

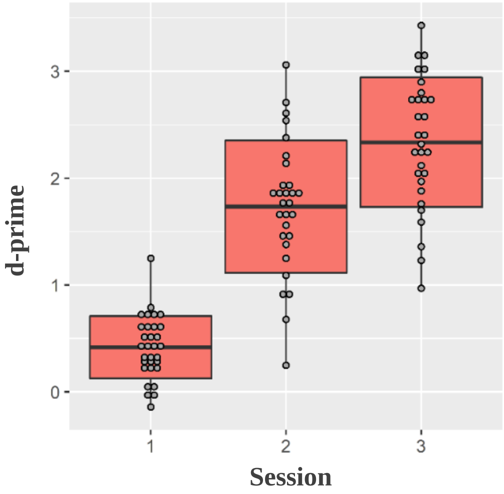


Figure 4.3 D-prime scores across sessions. Boxplots depict means and standard deviations.

b) ERP results

Only significant results related to our factors of interest are commented in this section (see Table S3.1 in Annex III for the complete set of results). The analysis of the difference waves revealed main effects for condition (*F*(3, 7506) = 10.95, *p* < 0.001), session (*F*(2, 7510.6) = 62.53, *p* < 0.001) and its interaction (*F*(6, 7506) = 2.52, *p* = 0.02). No significant interactions were observed between condition and any of the other factors. Follow-up comparisons were conducted for the contrasts of lexicality, semantic relatedness and the two non-sign conditions, across sessions. Results showed no significant effects in the first session. In the second session, only the semantic effect was significant. In this session, semantically unrelated signs elicited more negativities compared to semantically related signs (*t*(7506) = 3.29, *p* = 0.003). In the third session results showed significant effects for the three contrasts of interest. Regarding lexicality effects, non-signs elicited more negativities than signs (*t*(7506) = 2.99, *p* = 0.009). For the semantic contrast, in line with results in the second session, semantically unrelated signs elicited more negativities compared to semantically related signs (*t*(7506) = 3.38, *p* = 0.002). The comparison within the non-sign condition showed that pseudosigns elicited more negativities compared to non-signs (*t*(7506) = 2.9, *p* = 0.01).

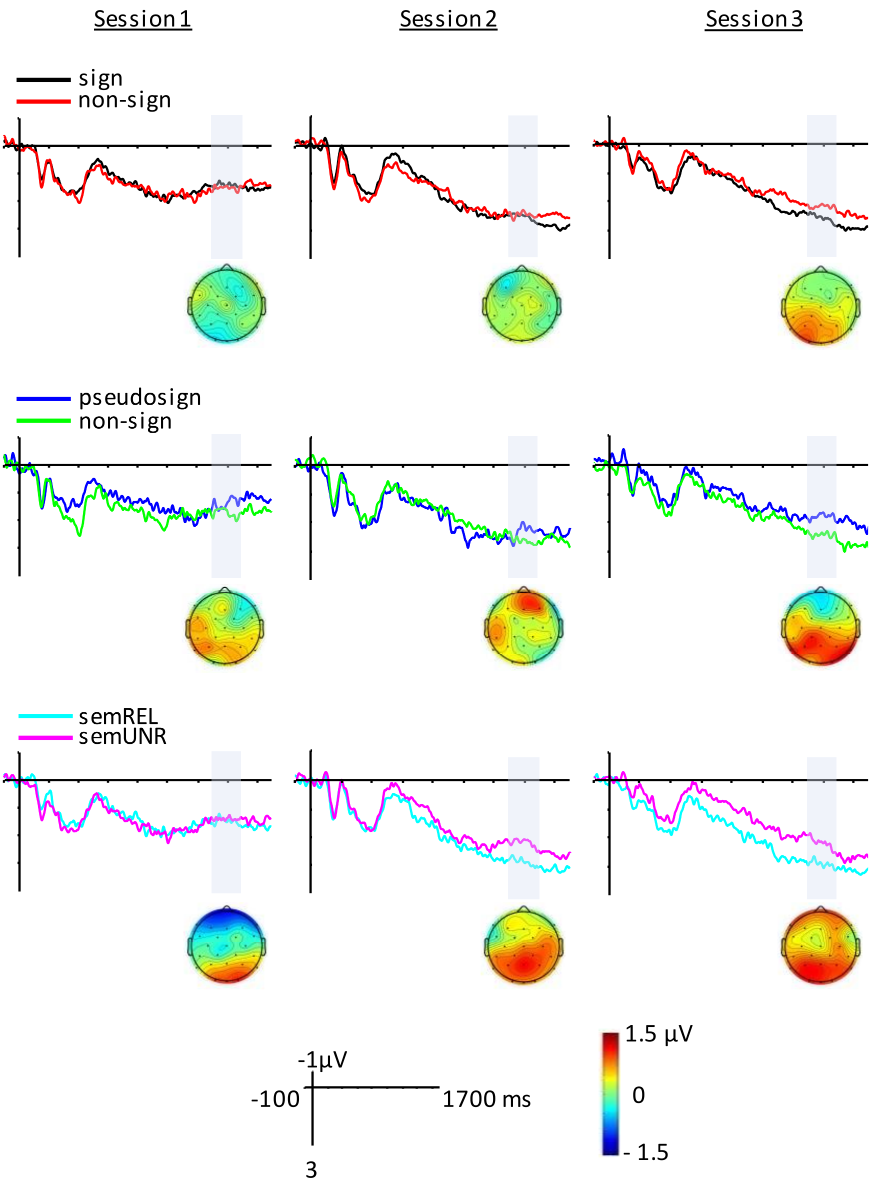


Figure 4.4 Grand average ERPs across sessions for the contrasts of lexicality (sign vs non-sign), non-sign conditions (pseudosign vs non-sign) and semantic relatedness (related vs unrelated), time locked to target video onset. Voltage maps depict the scalp distribution of the effects.

4.4. Interim Discussion

The present experiment aimed to explore the neural changes associated to M2L2 sign learning. More specifically, we explored the neural traces of lexicality and semantic effects in hearing non-signers that underwent to an intensive sign training within a week. In three laboratory sessions, participants completed an LSC lexical decision task before they were presented with 150 LSC signs to memorise.

Electrophysiological measures showed that participants were sensitive to semantics in the second experimental session, after one training procedure. At the N400 time-range, 300-500 ms after sign onset, semantically unrelated sign targets elicited more negativities compared to semantically related sign targets. As expected, this pattern of polarities is in line with results reported for semantic priming effects in both the signed (Meade et al., 2018) and the oral modality (e.g., McLaughlin et al., 2004). That is, as in the present study, semantically unrelated targets typically elicit more negativities compared to semantically related targets in the N400 time range. This semantic priming effect was also observed in the third session, after two training procedures. In addition, in the third session results showed that participants were sensitive to sign form (lexicality effect). Specifically, target non-signs elicited more negativities compared to target signs. This pattern of polarities was in line with McLaughlin’s et al. (2004) study, where pseudowords elicited more negativities compared to target words (see also Chwilla et al., 1995; Hauk et al., 2006). In addition, participants were not only sensitive to the difference between signs and non-signs but also between the two different types of non-signs. In the third session, pseudo-signs elicited more negativities than non-signs (see Holcomb & Neville, 1990, for a similar pattern with pseudowords and non-words). Notably, the chronology of the lexicality and semantic effects observed in the present study contrasts with the one reported in the oral modality by McLaughlin et al. (2004). We defer the discussion on this observation for the general discussion section.

Altogether, data in Experiment 1 showed evidence that hearing non-signers successfully learned LSC signs in a short period of time, and that as a result of this learning there were changes at the neural level indexing lexical and semantic sign processing. To further explore the neural modulations related to M2L2 sign learning processes, the second experimental question concerned whether those recently learned signs modulated the processing of the (L1) oral language.

Experiment 2. Neural changes indexing covert L2 sign activation

4.5. Methods

a) Participants

Participants in this experiment were the same as in Experiment 1.

b) Materials

Stimuli consisted of 150 printed words corresponding to the Catalan translation of the signs described in Experiment 1. Words were grouped in 50 triplets composed by two primes and one target (e.g., *sword – cod – key*). Thus, for a given triplet, two-word pairs were constructed maintaining the same target but with different primes. Thirty-five word triplets were used to form 70 semantically unrelated word pairs (e.g., *sword – key, cod – key*, see Table S3.2 in Annex III). Fifteen triplets were used to form 30 semantically related word pairs (e.g., *airplane – motorbike, car – motorbike*). In addition, to match the number of trials between semantic conditions, 40-word pairs were included as filler trials in the semantically related condition. In such a way, the complete set of stimuli consisted of 70 semantically unrelated pairs and 70 semantically related pairs, for a total of 140 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 of the experiment. Raters were asked to evaluate the semantic relatedness of each word pair in a scale from 1 (unrelated) to 7 (related). Pairs with semantic ratings below 3 were included in the semantically unrelated condition (M = 1.71; SD = 1.19), and pairs with mean ratings above 5 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 70 pairs in each semantic condition, 35 pairs were related via their LSC translation (e.g., *sword – key* share handshape and location) and 35 pairs had unrelated LSC translations (e.g., *cod – key* do not share any parameters). Primes across phonological conditions were controlled by 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 translation (*M* = 6.05; *SD* = 1.13). For each participant, a different list was created in which the trial order was pseudorandomised, including a minimum of five trials between the two presentations of the same target word.

c) Procedure

Participants were asked to decide whether the printed word pairs 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 response. The task was divided in three blocks, and participants could rest if needed between blocks.

EEG procedure

EEG procedure was the same as described in Experiment 1 with the exception that 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, across semantic 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 (e.g., Dell'Acqua et al., 2010). Due to 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 excessive number of artifacts in all sessions. One participant was discarded from the second session due to technical failure.

Data analysis

Response times were analysed by fitting linear mixed models, treating participants and primes nested within target items as crossed random factors. Models were fitted in R (R Core Team, 2019) using the package lme4 (Bates, Mächler, Bolker & Walker, 2015). Semantic and phonological effects were analysed in models including fixed effects for condition (either semantic or phonologically related), number of sessions, and their interaction. We aimed to fit models with the maximal possible random-effects structure (Barr et al., 2013). The maximal model contained random slopes for condition, session, and their interaction for both participants and primes. In cases of non-convergence, we step-wise simplified the random structure, by dropping random correlations and the interaction terms before dropping main effect slopes from the model. In cases of singular model fits, we first dropped the interaction terms before dropping condition or session slopes with an estimated variance close to zero. Significance of the fixed effects estimates was determined using the Satterthwaite approximation for degrees of freedom provided by the lmerTest package (Kuznetsova et al., 2015). Additional analyses on Box-Cox transformed latencies (to alleviate problems related to non-normality and heteroscedasticity, Box & Cox, 1964) lead to the same conclusions as the latency analyses reported here.

Regarding electrophysiological measurements, for the analyses of semantic effects, mean amplitudes were submitted to linear mixed effect models, with subjects and electrode as random effects, and semantic relatedness (related, unrelated), number of session (first, second, third), and their interaction as fixed effects. Covert LSC phonological effects were analysed comparing ERPs for LSC related and unrelated targets within the semantically unrelated condition. Mean amplitudes were submitted to linear mixed effect models, including subjects and electrode as random effects, and phonological relatedness (related, unrelated), session (first, second, third) and their interaction as fixed effects. In all analyses, significance of fixed effects was assessed with the Satterthwaite's degrees of freedom method using the lmerTest package (Kuznetsova et al., 2015) in R.

4.6. Results

a) Behavioural results

Regarding semantic effects (see Figure 4.5), response times were significantly faster for semantically related word pairs compared to unrelated pairs (*F*(1, 109.8) = 67.74; *p* < 0.001), and, overall, participants responded faster across sessions (*F*(2, 7736.3) = 393.67; *p* < 0.001). In addition, it was observed a significant interaction between semantic relatedness and session (*F*(2, 7732.6) = 3.89; *p* = 0.02). Follow-up comparisons revealed significant effects of semantic relatedness across sessions (session 1: *t*(264) = 8.19, *p* < 0.001; session 2: *t*(244) = 6.06, *p* < 0.001; session 3: *t*(245) = 5.66, *p* < 0.001).

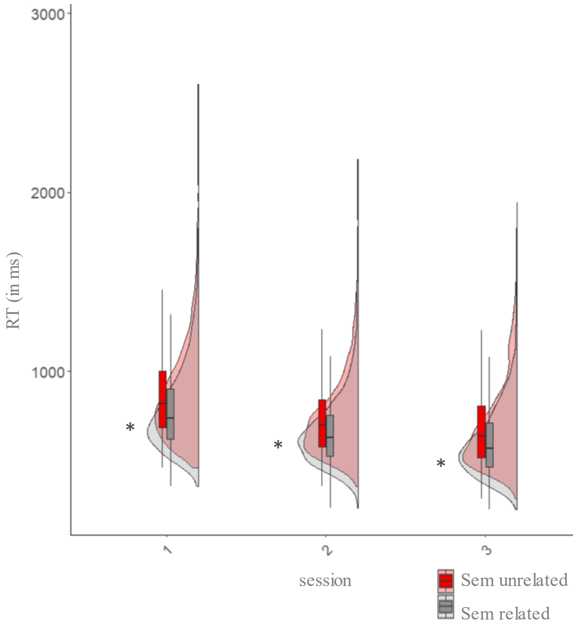


Figure 4.5 Density plots for the semantic relatedness condition across sessions. Boxplots depict means and standard errors.

Regarding LSC phonological effects (semantically unrelated condition, see Figure 4.6), no effect was obtained comparing LSC related and LSC unrelated pairs (*F*(1, 78.1) = 0.92; *p* = 0.34). A main effect of session was observed (*F*(2, 5420.3) = 397.7; *p* < 0.001), but no interaction between phonological condition and session was reported (*F*(2, 5417.2) = 0.46; *p* = 0.63).

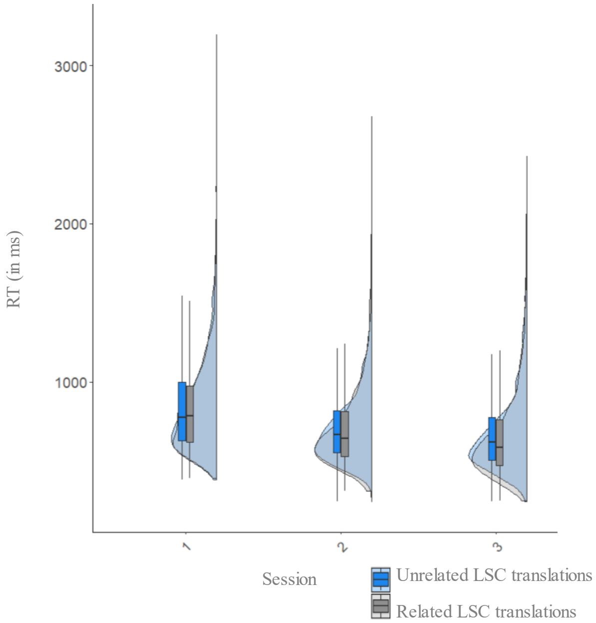


Figure 4.6
Density plots for the phonological relatedness condition across sessions. Boxplots depict means and standard errors.

b) ERP results

Only significant results related to our factors of interest are commented in this section (see Table S3.1 in Annex III for the complete set of results). In the analysis of the difference waves there were significant effects for semantic condition (*F*(1, 3688) = 349.54, *p* < 0.001), session (*F*(2, 3692.4) = 54.39, *p* < 0.001), and their interaction (*F*(2, 3688) = 14.24, *p* < 0.001). Follow up comparisons showed that, across sessions, semantically unrelated pairs elicited greater negativities compared to those pairs semantically unrelated (session 1: $t(3688) = 6.46$, $p < 0.001$; session 2: $t(3688) = 12.11$, $p < 0.001$; session 3: $t(3688) = 13.9$, $p < 0.001$). In addition, significant interactions were found between semantic condition and anteriority ($F(2, 3688) = 17.52$, $p < 0.001$), and between semantic condition and laterality ($F(2, 3688) = 13.54$, $p < 0.001$). Follow-up comparisons showed significant semantic effects across all levels of laterality and anteriority (all $p < 0.001$).

With respect to phonological effects, results showed no significant effects for the phonological condition ($F(1, 3687.9) = 2.1$, $p = 0.15$), but significant effects of session ($F(2, 3692.3) = 19.07$, $p < 0.001$), and the interaction between phonological condition and session ($F(2, 3687.9) = 5.23$, $p = 0.005$). Follow up comparisons revealed that the effect of phonological relatedness was only significant in the third session (session 1: $t(3688) = 1.32$, $p = 0.46$; session 2: $t(3688) = 0.61$, $p = 0.9$; session 3: $t(3688) = 3.25$, $p = 0.003$), in which phonologically LSC-unrelated primes elicited greater negativities compared to LSC-related primes.

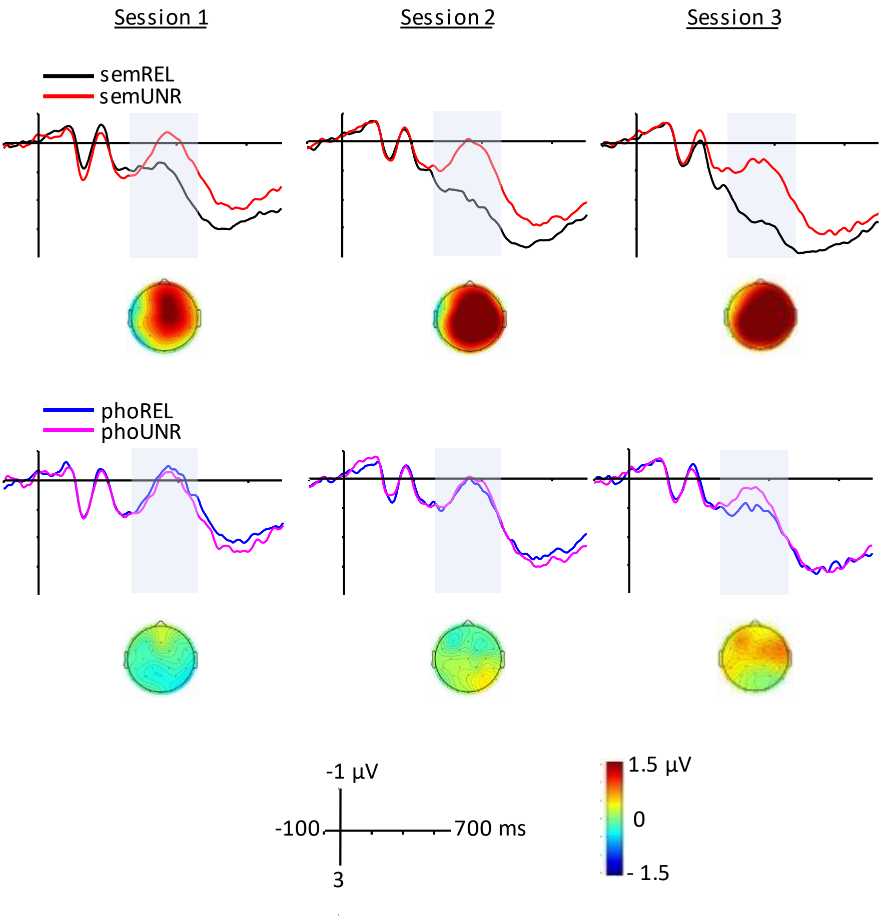


Figure 4.7 Grand average ERPs across sessions for the contrasts of semantic relatedness (related vs unrelated) and phonological relation (related vs unrelated), time locked to target video onset. Voltage maps depict the scalp distribution of the effects.

4.7. Interim Discussion

The present experiment aimed to explore the neural changes associated to covert activation of recently learned M2L2 signs during processing of the oral (L1) language. In a semantic decision task, participants were asked to judge whether pairs of Catalan written words were semantically related. Critically to explore covert sign activation, half of the semantically unrelated word pairs had phonologically similar LSC translations.

Behavioural data showed that response latencies of semantic judgements did not differ between LSC related and LSC unrelated pairs. However, a period of sign exposure was sufficient to observe electrophysiological signatures of covert activation. In the third session, LSC-unrelated primes elicited greater negativities compared to LSC-related primes in the N400 time-window. That is, neural traces of covert sign activation were only observed in the third session, after two training procedures. This cover phonological effect in our study parallels that reported in both bimodal (Meade et al., 2017) and unimodal studies (e.g., Thierry & Wu, 2007) for highly proficient bilinguals. The present data suggest that this phenomenon is not only characteristic of experienced bilinguals, but also occurs with M2L2 sign learners briefly exposed to new lexical entries. We defer the contribution of these results to the general discussion section.

4.8. General discussion

Word learning is considered a two-stage process: a first stage in which word information (i.e., phonology, orthography, meaning) is encoded in memory and a second stage in which learned words are integrated in the already existing lexical network (e.g., Leach and Samuel, 2007). New lexical representations are considered to be fully integrated in the lexicon when can interact with lexical processing of familiar words. In this sense, consolidation has been suggested to strengthen neural representations of newly acquired words in the mental lexicon, making them behave similarly to those existing words established in the lexicon. Evidence of lexical consolidation comes from priming studies in which novel words are interpreted to be lexicalised when eliciting lexical or semantic priming effects (e.g. Bakker et al. 2015; Gaskell and Dumay, 2003; Liu & Van Hell, 2020), generally after a period of consolidation (e.g., sleep; Dumay and Gaskell, 2007). In our study, we sought to broaden current research of how new words are integrated into the mental lexicon by exploring vocabulary acquisition in a different language modality. Specifically, in two studies we explored neural changes associated to M2L2 sign vocabulary learning over three sessions within a week. Data showed semantic effects in the second session (after one period of training and consolidation), and lexicality and cross-language effects in the third session (after two periods of training and consolidation). These results suggest that, after meaningful encounters with new M2L2 signs, more than one period of consolidation is required for these signs to become integrated into the lexicon.

In the primed lexical decision task (Experiment 1), we observed N400 modulations related to lexicality and semantic processing. These results replicate previous studies reporting N400 priming effects after a brief training period (Bakker et al., 2015; Pu et al., 2016), and shows lexicosemantic interaction between new signs and existing words in the early stages of M2L2 vocabulary acquisition. In other words, the results suggest that signs were lexicalised and integrated in the mental lexicon after few meaningful exposures. Remarkably, while N400 semantic effects were present in the second session, N400 lexicality effects appeared in the third session. In relation to two-stage learning accounts, in the initial stage, learners can explicitly recall word information although words are not fully integrated into the lexicon. With respect to our results, absence of lexicality effects in the second session would indicate that information about sign representations could not be fully recalled. However, finding semantic effects in the N400 time range would indicate lexicosemantic retrieval, thus reflecting lexical consolidation. The pattern of results obtained is at odds with results of 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). Differences between language modalities could be based on the closer relation that sign forms have with their meanings and the great potential of the visual-manual modality to suggest meaning. These specific characteristics of the signed modality may influence the early stages of sign learning, thus leading to the observed results.

One possible explanation for the absence of lexicality effects in the presence of semantic effects could be that participants were able to infer meaning following global processing and not relying on the processing of formational parameters as individual units (analytic processing). It has been suggested that bimodal bilinguals process fingerspelled words perceiving the global shape of the word, that is, perceiving the movements of the hand as a whole rather that reading letter-by-letter (Geer & Keane, 2018). Similarly, in word lexical decision tasks, participants rely on the whole word form rather than on analytical processing of each letter (e.g., Valdois et al., 2006). In line with the idea that word forms are perceived in a global manner, it is plausible that sign forms are perceived globally as well. Given that signs are conveyed by the simultaneous presentation of different parameters (i.e. handshape, movement, location, orientation of the palm), it is conceivable that sign parameters are perceived following global processing rather than analytical processing. Thus, it is plausible that in the first stages of sign learning participants derived sign meaning from global processing, without noticing whether or not the combination of parameters conveyed real signs. Furthermore, among the formational parameters of the sign, handshape is the most difficult to perceive (Luchkina et al., 2020), which was the parameter that was manipulated in the present study. Indeed, hearing sign language learners struggle with fingerspelling comprehension as a result of improper weigh cues from handshape transitions because it may be distracting (Geer & Keane, 2018). Hence, in the second session participants could have underweight the cues provided by sub-lexical (handshape) information putting their resources to assess sign lexicality on guessing the signs' meaning. In other words, given that participants in each trial were first exposed to real signs (primes), they would allocate their efforts in inferring the target sign meaning without relying in sub-lexical information. Further support for the idea that sub-lexical information is not readily processed would come from the results of the comparison between the non-sign conditions. In line with lexicality effects, differences between pseudosigns and non-signs were observed in the third session, which would index sublexical processing between those stimuli that required a ‘no’ response in the task.

An alternative consideration (not mutually exclusive) is based on the observation that when signing, two different segments can be perceived in the sign stream: signs and transitional periods (Jantunen, 2013). Transitional movements are hand movements that occur in the transition from the end location of one sign to the start location of the next sign (Blondel & Miller, 2001). By the visual nature of sign languages, these transitional movements are fully visible in sign comprehension. Additionally, these transitional movements carry information that is used for sign language users to generate predictions about the next sign (Hosemann et al., 2013). As an example, in Emmorey et al. (2022), deaf signers underwent a primed go/no-go semantic categorisation task in ASL. Target items were either repeated signs or unrelated signs. Data from N400 modulations showed that repetition priming effects appeared before sign onset, suggesting that participants could extract linguistic information from sign transitional movements to realise whether or not a target sign was a repetition of the prior sign. The authors hypothesised that the repetition priming effect observed before sign onset could be indicative of sub-lexical priming (e.g., priming through handshapes) or indicative of early lexico-semantic priming. The present data seems to support the latter, given that N400 modulations related to semantic effects were observed with prime-target pairs differing in phonological form, thus excluding the possibility of sub-lexical priming. That is, assuming that participants recognised the meaning of the prime sign, they could have used transitional information to generate predictions about the meaning of the next sign, leading to the semantic effects observed.

Data from Experiment 2 seems to support the idea that, in the second experimental session, sub-lexical information was not processed by the participants. It was not until the third session, after two training sessions and two periods of offline consolidation, that we observed cross-language effects based on the phonological relations within signs. Hence, this result would be in line with results in Experiment 1, suggesting that sign forms were not fully lexicalised after one consolidation period.

As in the present study, covert language activation in bilingualism has been typically characterised by form-related trough translation primes eliciting reduced N400 negativities compared to those form-unrelated translation primes (Meade et al., 2017; Thierry & Wu, 2007). Bimodal bilingual studies have vastly reported that sign-phonological relations interfere when making semantically unrelated judgements (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 negativities in form-related primes, combined with behavioural interference, was reflecting pre-activation of the target sign translation and posterior conflict at the response decision level. That is, behavioural interference effects would be reflecting controlled resolution between (implicitly activated) sign and (explicitly activated) word lexical entries, because the sign language may not be robustly suppress in the response decision process. As a consequence of less control demands in their communicative interactions, bimodal bilinguals do not strongly inhibit the non-target language as unimodal bilinguals do (Emmorey et al., 2016). Under this idea, Meade et al. (2017) argued that weaker suppression of signs during word processing would cause the behavioural interference effect. Notably, even though previous studies encompass results from deaf and hearing populations with different levels of sign language proficiency, none of them includes a population of recent learners. Hearing learners in our study had no previous experience using sign languages. In this regard, our results would suggest that some accumulated experience in using a sign language is needed to observe cross-language effects at the behavioural level.

4.9. Conclusion

In two experiments we reported evidence of the rapid neural plasticity that occurs 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 for the first time that few exposures to new M2L2 signs entries are sufficient to stablish lexicosemantic links between signs and words. Concretely, we observed that effects of lexicality and covert language 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, it was necessary more than just one exposure to the new language to occur. Only in the third session, after two training sessions, there was observed sensitivity to the phonological form of signs, either when signs were overtly presented (Experiment 1) or not presented (Experiment 2). Therefore, although minimal, a certain level of exposure to new M2L2 signs along with periods of offline consolidation seems necessary to integrate new signs into the existing mental lexicon.

Acknowledgements

This work was supported by the Ministry of Science and Innovation of Spain (RTI2018-096238-A-I00) and by the BIAL Foundation (Grant Number 2026/2016). Cristina Baus was supported by the Ramon y Cajal research program (RYC2018-026174-I). We would like to thank Rebeca Sánchez and Marta Díaz for their assistance during the testing sessions, and all the participants for taking part in the study.

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GENERAL DISCUSSION

Chapter 5

Models of language production assume that lexical retrieval involves the selection of the target representation among a cohort of related representations (e.g., Costa et al., 1999). What variables influence the selection of the target from the set of activated lexical representations in two different language modalities? This dissertation has taken different experimental approaches to study the neural correlates of lexical access in bimodal bilingualism. We first tracked the neural correlates of iconicity and lexical frequency in sign retrieval when deaf bimodal bilinguals produced signs (Chapter 2). Then, we explored the electrophysiological signatures of oral-to-sign cross-language effects when deaf bimodal bilinguals produced signs (Chapter 3). Finally, we investigated the neural changes indexing sign lexical processing in hearing non-signers during the early stages of sign learning (Chapter 4).

The main experimental findings obtained in this dissertation can be summarised as follows:

(i) In sign production, the influence of iconicity on lexical retrieval is modulated by the linguistic processes elicited by the task at hand.

(ii) Sublexical relations within the oral language influence sign production, even when the oral language is not involved in the task.

(iii) Neural changes indexing lexical integration appear very early during learning.

In the following sections, we discuss the most relevant results and their implications in relation to the literature on bimodal bilingual language processing and bilingual language processing in general.

5.1. The unsolved case of iconicity

In Chapter 2 we observed that iconicity modulates brain responses during sign production, but the effect was mediated by the processes elicited by the task performed. In a picture-naming task, participants were faster naming in LSC pictures that corresponded to iconic signs than pictures that corresponded to non-iconic signs. At the electrophysiological level, pictures corresponding to iconic signs elicited greater negativities than pictures corresponding to non-iconic signs around 200 ms after stimuli presentation. Interestingly, no effects were observed in the word-to-sign translation task.

One explanation for the lack of results in the translation task is related to the idea that words would have not emphasised semantic processing, hence preventing iconicity to modulate behavioural and brain responses. In contrast, because pictures emphasise semantic activation, iconicity effects were observed (see Figure 5.1). This explanation opens up two questions: what is the relationship between semantic processing and iconicity effects, and what is the influence of using pictures/words as experimental stimuli?

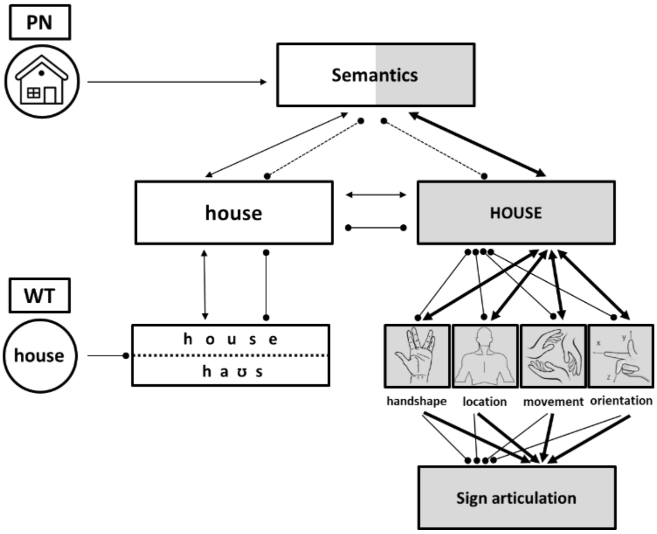

Figure 5.1 Schematic representation of processing streams for iconicity effects during sign production. Lines with arrows represent spread of activation in the picture naming task (PN) and lines with dots represent the word translation task (WT). Thick lines represent iconicity effects.

Generally, two main ideas focus on the special relationship between semantics and iconicity in sign processing. One account argues that iconicity effects arise from sensorimotor semantic features of iconic signs being more robustly encoded at the semantic level (Baus & Costa, 2015; McGarry et al., 2020; Navarrete et al., 2017). McGarry et al. (2020) favoured this idea on the basis of iconicity effects being functionally similar to word concreteness effects, interpreted as the result of activation of the sensorimotor features of concrete words (e.g., the physical properties of an object or how an object is used). They discussed this parallelism by looking at the similarities in the neural responses elicited by pictures related to iconic signs and concrete words. Pictures related to iconic signs in the study by

McGarry et al. (2020) revealed a similar pattern obtained in previous reports for concrete words (e.g., Holcomb et al., 1999), namely, larger N400 mainly in anterior electrode sites. Thus, similarity was based on three main aspects: polarity (large negativity for iconic signs/concrete words), time-course (N400 time-range), and topography of the effects (frontal distribution). With respect to our study on iconicity, we did not fully replicate these three aspects. We observed the same polarity of the iconicity effect, although in early time-windows and with a centro-posterior distribution. Thus, our data do not conform with the idea that iconicity effects are just concreteness effects. However, neither did our results replicate those of Baus and Costa (2015), even though the same materials were used in both studies. Unlike in our and Mc Garry's studies, in Baus and Costa (2015), pictures related to iconic signs elicited reduced negativities in early and late time-windows with a widely distribution of the effect. Considering the three studies, an interesting possibility may be that polarity of the effects indicates language dominance (e.g., Jiang et al., 2009). In our study and in McGarry et al. (2020), the participants were deaf signers for whom sign language was their dominant language. In turn, Baus and Costa's study was conducted with hearing bimodal bilinguals for whom sign language was their non-dominant language. This mixed pattern of EEG deserves further attention in future studies.

A second account argues that iconicity effects are based on the connections between semantic and phonological representations (Pretato et al., 2018; Thompson et al., 2010; Vinson et al., 2015). In line with this idea, Thompson et al. (2010) reported iconicity effects in a phonological decision task (i.e., deciding whether a given sign involved straight or curved fingers). This result was taken as evidence that iconicity effects are automatic and activate meaning-to-form connections, even when the task does not require so. Our results support the special role of meaning-to-form connections in iconicity effects, but differ from Thompson in suggesting that those connections are not automatically activated, but determined by the task involved. Along the same lines, the results presented by Pretato et al. (2018) support the relevance of connections between semantic and phonological levels, and the relevance of the task at hand. In their study, iconicity effects were observed when participants named pictures in LIS (Italian Sign Language) but no effects were observed when pictures were named using a demonstrative pronoun instead of the picture sign. The implications of these results are two-fold. Firstly, it shows that iconicity effects are not just based on the activation of the semantic system and the robust encoding of sensorimotor features because, in that case, effects should be observed in all naming conditions. Secondly, it supports the idea that iconicity effects in sign production do not occur solely because pictures activate conceptual representations (see also Baus et al., 2013), but depend on the characteristics of the task.

Taken together, the studies show that iconicity effects require the involvement of the semantic system, either mediated by the type of task or by the use of pictures that emphasise the structural mapping between the visual features of pictures and sign form representations.

With regard to this last point, it should be noted that, to date, studies have focused on the semantic system but not on properties related to the sign's form that may modulate iconicity effects. To examine this issue in greater depth, one question that requires further exploration is the relationship (if any) between semantic features and the specific sign parameters. Signs are constituted by different parameters performed in synchrony but, to our knowledge, iconicity has only been described as influencing the processing of the whole sign. Given that iconicity refers to the mapping between conceptual representations and sign forms, it is conceivable that iconic features do not apply to the same extent to all parameters (e.g., see Baus et al., 2014; Gutiérrez et al., 2012; for the segmentation of the influence of parameters in phonological priming). To better describe the underpinnings behind iconicity effects in sign production, it would be especially valuable to explore the weight of each individual parameter in iconic representations.

5.2. Word processing in sign production

As argued in the previous section, the lack of iconicity effects in the word-to-sign translation task could be explained due to words not emphasising semantic processing. Under this assumption, the results in the picture-word interference task (Chapter 3) may seem puzzling. We observed an indication of semantic interference effects –only in error rates–, which could demonstrate semantic activation of distractor words. So, what is the relationship between word processing and semantic activation during sign production?

With respect to the word-to-sign translation task in deaf bimodal bilinguals, translating from words to signs can be read as translating from L2 to L1. Typically, in the oral language, this task has been characterised as being accomplished via lexical links, without semantic mediation (Kroll & Stewart, 1994). Of interest here, Baus et al. (2013) reported iconicity effects when hearing bimodal bilinguals translated from signs to words (i.e., from L2 to L1). Thus, this result would not support the view that lack of iconicity effects are based on the direction of the translation in terms of language dominance. It is possible though that, in Baus et al. (2013), the presentation of signs made iconic semantic features salient, thereby forcing automatic semantic mediation.

An alternative explanation for the lack of iconicity effects is that translating words into signs does not directly activate imagistic properties (e.g., iconicity). For instance, Vigliocco et al. (2005) observed that hearing non-signers made semantic groupings of words differently than deaf signers did with signs. Interestingly, when they were asked to form a mental image of the words before responding, their responses resembled those of the deaf participants. This result was taken as evidence that the mere presentation of words does not activate imagistic representations unless the task motivates it. In a similar vein, Baus et al. (2013) did not observe iconicity effects when hearing bimodal bilinguals translated from words to signs. Notably, for hearing bimodal bilinguals, translating words into signs means translating from L1 to L2, a task characterised by being semantically mediated. Thus, these studies seem to favour the idea that, even when the task is semantically mediated, words do not trigger imagistic representations as pictures do.

The lack of iconicity effects in word-to-sign translation tasks could also be explained in line with the idea that the conceptual system is not fully shared between the two languages of bilinguals (e.g., Pavlenko, 2009). In this account, lexical concepts (i.e., concepts that are linked to lexical entries) are multimodal representations that comprehend different types of somatosensory information such as visual, auditory or kinaesthetic input. Of interest here, lexical translation equivalents in different languages do not always rely on equivalent conceptual representations (Malt et al., 2003). Thus, it is possible that word processing only activates word-specific and some word-sign shared representations but does not activate imagistic properties specific to sign representations. In other words, some conceptual features, such as those related to iconicity, would be sign-specific and would not directly transfer to oral representations. In support of this idea, Baus and Costa (2015) observed that neural responses of hearing bimodal bilinguals indicated early iconicity effects when naming pictures in LSC, but this result was not observed when the same participants named pictures in the oral language.

Turning to the picture-word interference task, it seems that any of the abovementioned explanations can fully account for the semantic effects observed. Semantic effects when experimentally manipulating the relation between pictures and words would be indicative that words, either via direct links to semantics or via links through their sign translations, influence semantic processing. Although, overall, this seems to be the case based on the previous literature, results are mixed and rather weak. In our picture-word interference task (Chapter 3), we observed semantic effects in error rates but no effects regarding signing latencies or ERPs. Our lack of chronometric effects replicated those of Giezen and Emmorey (2016) in hearing bimodal bilinguals. In contrast, Emmorey et al. (2020) reported, both in deaf and hearing bimodal bilinguals, more errors for semantically related word distractors, but semantic facilitation in signing latencies. Thus, overall, behavioural results would indicate that words do activate semantics in sign production, although no conclusions can be drawn about the nature of the effects.

In the absence of conclusive behavioural results, electrophysiological results could be more indicative about semantic processing (e.g., Thierry & Wu, 2007). Emmorey et al. (2020) showed identity translation effects between 200-300 ms, which was taken as an indication of pre-activation of imagistic representations by word primes. Weaker effects in the same time-window for semantically-related words was interpreted as reflecting partial activation of conceptual features between words and pictures. In addition, semantic effects were observed related to the N400 component (also observed in our study), which has been argued to index semantic priming effects at a lexical level (Damian & Bowers, 2003).

If ERPs are more sensitive to capturing semantic effects, how do we explain the lack of ERP iconicity effects in the word-to-sign translation task? Perhaps, because relative to the picture-word interference task, in the word-to-sign translation, no semantic conflict needed to be solved before sign articulation and, hence, there is no stimuli that might prime the target representation. Assuming that written words have a direct link to the lexical system, information would flow from word presentation to sign articulation with no need for semantic mediation.

Altogether, results in the picture-word interfere task could be interpreted in line with results of the word-to-sign translation task. In both tasks, we observed evidence supporting the idea that words activate the semantic system, but not fully sign conceptual features. Notably, there is a gap in bimodal bilingualism regarding the extent to which processing stimuli in one language modality influences lexicosemantic processing in the other modality. To explore this question further, the research would benefit from studies using tasks inducing semantic processing from different sources (e.g., employing sentences instead of pictures to elicit conceptual features).

5.3. On the possible role of mouthings behind cross-language effects

In Chapter 3, we reported evidence of the influence of phonological relations within the oral language during sign lexical access. As we have commented several times throughout the dissertation, sublexical representations are not shared across signs and words. However, arguably, there are some situations in which sign languages and oral languages are articulated simultaneously, which could be the origin of phonological (and semantic) effects. We are referring to mouthings, which are mouth actions that co-occur with sign articulation and map phonological representations of one or more syllables of the sign's equivalent word. Significantly, it has been reported that signs and mouthings are retrieved separately and, consequently, they are not bonded in the mental lexicon (Giustolisi et al., 2017; Vinson et al., 2010). As such, mouthings are not considered to be fully integrated into the sign lexicon and are processed via lexical representations of the oral language. Thus, both in sign production (via articulation) and sign comprehension (via visual experience), mouthing involves some degree of activation of the oral language phonology. As such, it is plausible that mouthings might provide specific links of the oral modality mediating oral-to-sign cross-language effects (Hosemann et al., 2020). More specifically, with respect to the form-related effects discussed in Chapter 3, facilitation in the picture interference tasks could be explained by phonemes of the distractor (i.e., picture/word) partly overlapping with those of the mouthing, thus facilitating mouthing production of phonologically related words. In other words, the facilitation effect may reflect mouthing preparation via direct connections between spoken phonological representations rather than connections between sign and word lexical representations. To explore this possibility, we conducted a follow-up analysis on our data. We observed a varied pattern of mouthings across participants, with some participants mouthing during most of the trials and some only mouthing in barely half of the trials or not mouthing at all. In addition, we compared the performance of the subset of participants that were overly mouthing and those participants that did not produce mouthings or did so only in few trials. We did not observe significant differences between groups. This observation is in line with Vinson et al. (2010) and suggests that mouthings are not integrated into the signed lexicon. However, the tasks were not designed to test the influence of mouthings experimentally, so we cannot draw strong conclusions in this regard.

Importantly, although not focused on sign production, a recent study specifically testing the role of mouthings in cross-language effects seems to support our results. In Ormel et al. (2022), participants performed two sign-picture verification tasks in which they were asked to evaluate whether a video of a sign and a picture corresponded to the same concept. The hidden experimental manipulation consisted of some of the sign-picture pairs having similar translations in the oral language. In addition, in one task, videos included signs performed with mouthings and, in the other, the signs were performed without mouthings. In both tasks, there were observed oral-to-sign cross-language effects reflected by slower responses for sign-picture pairs with final rhyme overlap in the oral language. Of interest here, similar results were obtained in both tasks, thus showing that mouthings are not determinant in the activation of representations in the oral language.

To sum up, overall, bimodal cross-language lexical access seems to be modulated by lexico-semantic connections and not by direct activation of oral phonology or connections between sign and oral sublexical representations (see also Morford et al., 2019, for no effects of initialised signs). The validity and generalisation of this argument across deaf and hearing populations and considering sign-to-oral and oral-to-sign cross-language effects in bimodal bilingual language production requires further research along these lines. These results will be particularly valuable for contrasting and completing bimodal bilingual language processing models, which are currently fundamentally based on connections at the semantic and lexical level.

5.4. Modelling cross-language interactions in bimodal bilingualism

In two studies (Chapter 3 and Chapter 4), we have provided evidence of lexical processing of the non-intended language (and modality) in deaf and hearing populations. More specifically, we observed cross-language lexical processing in deaf participants, whose two languages are consolidated, and in hearing non-signers, who needed to incorporate lexical entries from a different modality (i.e., signed) than the one already acquired (i.e., oral). These data expand previous studies (see Ormel & Giezen, 2014, for a review) and support the theory that bimodal bilinguals access lexical representations of their two languages when producing or comprehending in one of them. In this regard, one of the main questions has been what mechanisms are behind the influence that covert activation of the non-intended language exerts on lexical retrieval of the intended language.

One of the ways in which researchers have approached this question is by reformulating models of language processing in unimodal bilinguals to integrate the results obtained with bimodal bilinguals. Broadly speaking, models of bimodal bilingual language processing assert that cross-language activation occurs via lateral connections between sign and oral lexical representations and/or vertical connections between lexical representations and semantics (e.g., Ormel et al., 2012). These connections have been described as dynamic in nature and modulated as a result of the language learning experience (e.g., Hermans et al., 2008). In this sense, in terms of language experience, bimodal bilingual populations in this dissertation may be understood as belonging to two different learning stages. Hearing non-signers could be considered as learners in the first stage of L2 acquisition, and deaf signers as oral language learners who have reached high levels of proficiency.

In the Reading Vocabulary Learning Model, Hermans et al. (2008) described lexical development in deaf children, inspired by Jiang's (2000) developmental model of adult vocabulary learning in a second language. Jiang makes a clear distinction between L1 and L2 vocabulary learning, because L2 vocabulary acquisition generally implies instructional settings in which newly acquired L2 lexical representations become strongly linked to their L1 counterparts. Following Jiang's model, Hermans et al. (2008) described three developmental stages by which sign and oral languages interact in the process of reading vocabulary learning. In the first stage, access to meaning involves the creation of associations between L2 (written) forms and signs. No syntactic or semantic information can be inferred from L2 orthography, so access to meaning necessarily involves sign language translations. In the second stage, the repeated coactivation of the written word and its sign translation results in changes in the representation of the written word that map the semantic and syntactic information of the sign. At this stage, morphological specifications of written words are not present, but words can directly activate their semantic representations. In the third stage, lexical entries contain all the semantic, syntactic and morphological information, and written words have developed strong links with the semantic system.

With respect to cross-language interactions, in line with the stages proposed in the model developed by Hermans et al. (2008), in the first stage of development, interaction between languages occurs through direct connections between word and sign lexical representations. In the second stage, interaction mainly occurs via lexical connections and, to some extent, via the new (but still weak) links between words and the conceptual system. In the third stage, word processing occurs through direct links to the conceptual system and, therefore, sign processing is no longer required. However, as mentioned by Hermans and colleagues, many words will never reach the third stage (see also Jiang, 2000), so lexical links would be the default mode through which information transfers between languages and, by extension, how cross-language interaction occurs. In other words, (L2) word processing is mediated by (L1) sign lexical representations. In Chapter 3, we have observed effects of the oral language during sign production in deaf bimodal bilinguals. Hence, our results show that (L1) sign processing is mediated by (L2) oral lexical processing, supporting that assertion that connections between lexical levels are bidirectional (Morford et al., 2017; Ormel et al., 2012).

In this regard, similar principles have been described as underlying L2 activation during L1 processing in hearing bimodal bilinguals. Activation of L2 sign lexical forms via connections from L1 oral lexical forms and via semantic processing has been described as the basis for cross-language effects in hearing proficient signers (Shook & Marian, 2012) and sign language learners with an intermediate level (Williams & Newman, 2016). Results of beginning learners in Chapter 4 contribute to this body of research by showing that connections between L2 sign and L1 oral languages arise very early during L2 language learning.

All in all, in line with models focusing on hearing bimodal bilinguals in which effects of the L2 on the L1 are depicted through semantic and lexical links, it is plausible to consider that similar dynamics could also explain the effects of the L2 on the L1 in deaf bimodal bilinguals, as reported in Chapter 3. Taking the picture-picture interference task as an example, when seeing pictures, conceptual representations would activate sign and word lexical representations[6]. Once word representations are activated, activation cascades down activating the sublexical representations and feeds back to the lexical level. The following example illustrates this point (see Figure 5.2).

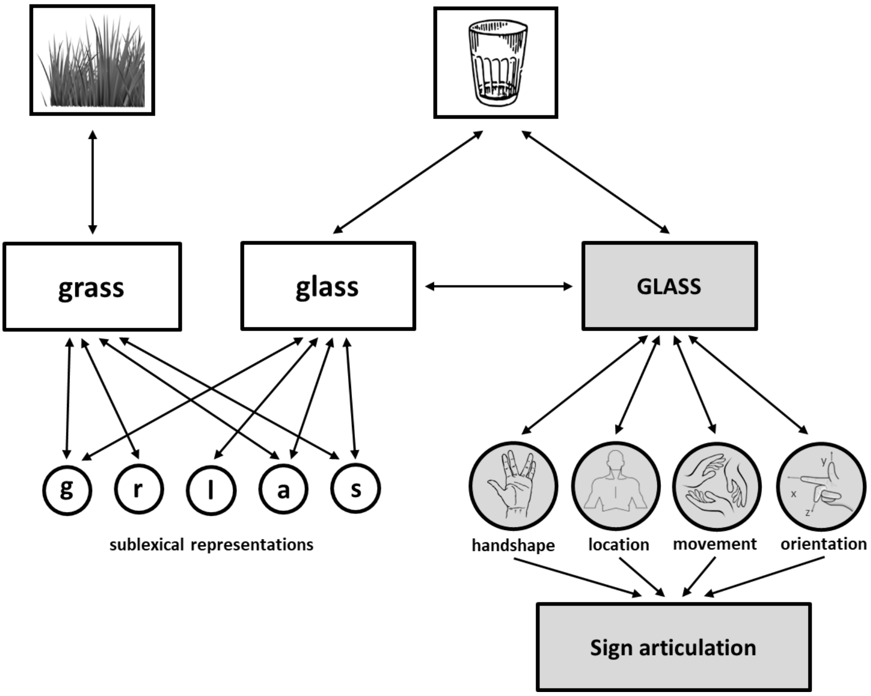

Figure 5.2 Schematic representation of oral language activation during sign production in the picture-picture interference task. For ease of understanding, the images are presented separately, although in the experimental display they overlapped.

Suppose that the target picture *glass* appears alongside the distractor picture *grass*. By assumption, both lexical representations activate their corresponding sub-lexical representations. When selecting the

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[6] Our data is silent about whether the activation of word lexical representations is driven by direct links with the semantic system, if it is mediated by a first activation of the signed lexicon, or is due to a combination of the two.

sublexical representations of the target word *glass*, some have already received activation from the distractor. Priming of sublexical representations of the target would send activation back to their corresponding lexical representation. Then, via spreading activation, activation to the corresponding sign translation equivalent GLASS would ultimately lead to the production of the target sign. Notably, we use the term sublexical representations rather than referring specifically to oral language phonology or orthography, as our experiments were not designed to distinguish between the two. In the absence of direct orthographical input (as in the case of our picture-picture interference task), and considering that the oral languages in our studies are transparent, the relative influence of orthography and phonology in sign production is unknown and merits further research. A plausible proposal given the wide variety of psycholinguistic profiles among bimodal bilinguals is that language expertise plays an important role in the strength of links between oral orthography/phonology and sign lexical representations (Morford et al., 2017, 2019).

Based on the connectionist model Bilingual Language Interaction Network for Comprehension of Speech (BLINCS, Shook & Marian, 2013), Morford et al. (2019) proposed that language learning experience would modulate the connections between orthography and sign/oral phonological representations. In essence, cross-language effects would be the consequence of dynamic mappings between language levels that emerge as a consequence of learning associations, and not the result of default mappings between semantic, lexical and sublexical levels across languages. In this way, the model allows us to consider that processes underlying cross-language effects in lexical access are subject to individual differences as a consequence of the linguistic experience. For instance, deaf signers learning an oral language would rely on different aspects of the oral language input depending on their language exposure. In other words, as exposure to an oral language accumulates, deaf signers gain ability in detecting semantic, lexical and sublexical relations between sign and oral languages. Hence, under the assumption that information flows across levels in both directions (from sign to word representations and vice versa), individual language experience gradually modulates the strength of connections between these levels.

Also using learning-based accounts, in Chapter 3, we proposed that bimodal cross-language effects could also be interpreted as the reorganisation of the mental lexicon as a result of language learning processes (Costa et al., 2017, 2019). Costa et al. (2017) developed a learning-based model that describes cross-language effects in unimodal bilinguals based on two main assumptions: parallel activation of both languages during learning, and restricted activation of one language when sufficient proficiency is attained in the second language. Based on these two assumptions, the learning account of Costa and colleagues allows for flexibility in the characterisation of bimodal cross-language effects based on the use of language at different phases of bilingualism. Consider a native signer as an example. When learning an oral language, the repeated activation of

(L1) sign representations as a consequence of parallel activation processes would end up having part of the structure of the sign representations mapped to the (L2) oral representations. In this respect, cross-language effects are driven by parallel activation processes at early stages of learning an oral language. Then, as L2 proficiency increases, cross-linguistic effects are the consequence of a reorganisation of the mental lexicon. Within this framework, results of covert sign language activation during word processing reflect a reorganisation of the oral lexicon as a consequence of the mapped phonological relations within the signed lexicon. We suggest that the learning account presented by Costa et al. could be adapted to bimodal bilinguals considering the developmental stages described in models of lexical development (Hermans et al., 2008; Jiang, 2000). Specifically, in the second stage, based on a reinterpretation of Costa’s model, the repeated coactivation of words and signs would result in dynamic changes within language structures as a result of the relations within the other language (see also Shook & Marian, 2019). In other words, considering the case of deaf signers learning an oral language, the lexical organisation of the oral language would reflect the way their sign language is structured (see Figure 5.3).

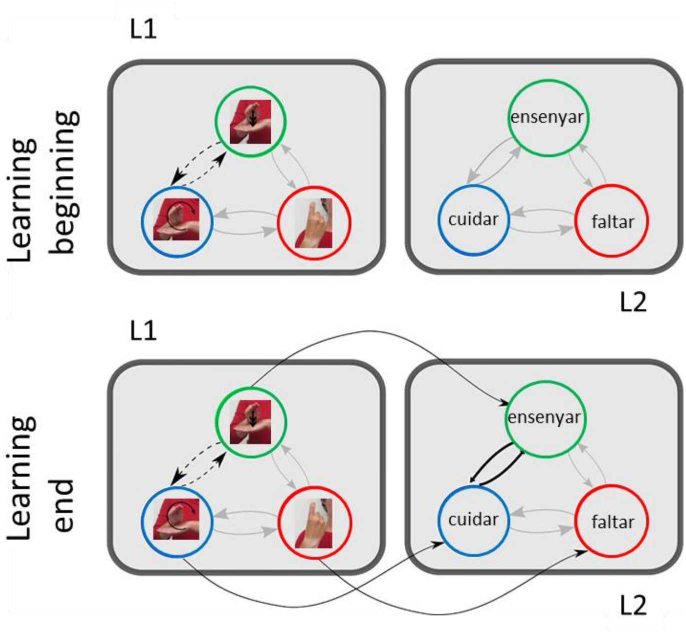

Figure 5.3 Adapted from Costa et al. (2017). Schematic representation of the L1 signs and L2 words and their connections at the beginning (top) and at the end (bottom) of the learning. Each grey boxed represents a language, either LSC or Catalan. Solid black lines in the bottom represent the connections based on L2 learning. The dashed black arrows between the LSC signs TO TEACH (top circle) and TO TAKE CARE OF (bottom left circle) represent the enhanced connections based on their phonological relationship. The thick black arrows between the Catalan words *ensenyar* (to teach) and *cuidar* (to take care of) represent the enhanced connections that develop as a result of their sign translations' relationship. The gray arrows represent the link between lexical representations lacking enhanced connections. Sign captures adapted from ioc.xtec.cat (Jarque Moyano & Vega Llobera, 2017).

Consider a LSC signer learning Catalan. In LSC, the signs TO TEACH and TO TAKE CARE OF form a minimal-pair because they share all sign parameters except one (i.e., movement, see Figure 1.1). When learning the Catalan words *ensenyar* and *cuidar* (‘to teach’ and ‘to take care of’, in English), sign representations, including the association between their forms, would be transferred from the LSC lexicon to the developing Catalan lexicon. As a consequence, *ensenyar* and *cuidar* would also become associated in the Catalan lexicon.

Beyond sign-to-oral cross-language effects, the dynamic nature of the learning-based account presented by Costa et al. allows us to hypothesise on oral-to-sign cross-language effects in deaf bimodal bilinguals (Chapter 3). In this sense, the (L1) sign lexicon would be reorganised as a result of the mapping processes of the linguistic relations within the (L2) oral lexicon. Continuing with the example of the LSC-Catalan deaf bilingual, signs that were a priori not related in the LSC lexicon (e.g., SHIRT and TRUCK) would become related as a result of their form similarity in Catalan (*camisa* and *camió*, respectively). Furthermore, the rationale of this hypothesis could also apply to cross-language effects in hearing signers, for whom sign languages are their L2 and oral languages their L1 (Chapter 4). While these are interesting possibilities, we acknowledge that they are still premature, but they open an inspiring line to pursue in future research.

5.5. Unravelling the early stages of M2L2 sign learning

Having considered the possibility that bimodal cross-language effects may be explained under learning-based accounts, Chapter 4 aimed to explore how fast cross-language interaction occur in the course of learning a new language in a new modality (i.e., M2L2). Specifically, we approached this question by exploring the neural modulations related to the lexical integration of L2 sign language vocabulary. Cross-language N400 effects reflecting covert sign activation during word processing were observed in the third session, that is, after two training sessions. In line with two-stage theoretical accounts of novel vocabulary acquisition (e.g., Leach & Samuel, 2007), this interaction between new and old lexical entries could be taken as an index of lexical integration of the new lexical representations. In theory, a period of lexical configuration, in which word-form features are acquired, should precede this lexical engagement (see Liu & van Hell, 2020, for some nuances in this regard). In our experiment, behavioural (d-prime) measures indicated that, in the second session, participants had improved their lexicality judgements compared to the first session. However, N400 modulations related to lexicality effects were not observed in this second session. In the literature of novel word learning, N400 modulations are usually taken as an index of somewhat automatic processes of lexicosemantic processing. Thus, in the absence of N400 effects, lexicality judgements in the second session would not have been the consequence of automatic processes. Under this idea, then, the semantic effect in this session could be interpreted as related to partially strategic/controlled retrieval processes (Kiefer & Spitzer, 2000). Relatedly, later brainwave modulations of the N400 (late positive complex, LPC) have been interpreted as reflecting more strategic/controlled processes when processing new words. In our study, we focused on the N400 as an index of lexical integration and exploring the influence of strategic processes was beyond its scope. Nevertheless, future studies exploring the relative contributions of automatic and strategic processes in sign processing would be of interest to obtain a more complete picture of how lexical consolidation develops over time and the relation with periods of memory consolidation.

In addition to lexical integration, consolidation processes also appear to interact with variables related to the learning process itself. In an aside work (not included as a chapter in this dissertation), we also investigated vocabulary learning using language production tasks (a picture-naming task and a translation task). In particular, in a series of experiments, we explored whether L2 sign vocabulary learning benefitted from indexical variation in the number of signers (see Appendix). That is, we explored whether learning improves when signs are presented by multiple signers compared to when signs are presented by a single signer. Learning outcomes were evaluated in immediate recall (after training) and delayed recall (two weeks after training) by means of two tasks, a picture naming task in LSC and a sign-to-word translation task. While overall results suggested that hearing non-signers remembered better those signs that were presented by multiple signers, results were not consistent across tasks. Variability in the number of signers improved immediate recall in the sign-to-word translation task, and delayed recall in the picture naming task. Presumably, both tasks differed in the degree to which form-meaning mappings are emphasised in the task (e.g., Kroll & Stewart, 1994). While the picture naming task would be conceptually mediated, the translation task would rely on lexical links between the two languages. Under this assumption, we hypothesise that the differences observed between tasks could be related to the idea that a period of memory consolidation is needed to integrate new lexical entries in the mental lexicon. Offline consolidation would have strengthened form-meaning mappings (Clay et al., 2007) and hence we observed results in the picture naming task, a task that directly induces the activation of the semantic system.

Trying to link results on vocabulary learning with the theoretical models described in the previous section (e.g. Hermans et al., 2008), the consolidation period between sessions would have mediated the transition from the first stage of word association to the second stage of lemma mediation. Only after consolidation, lexical representations would be integrated into semantic memory (Palma & Titone, 2021), hence leading to the effects observed. However, it should be acknowledged that studies in the oral modality have reported effects in both picture-naming and translation tasks immediately after the training (e.g., Barcroft & Sommers, 2005). Thus, it requires further work to better describe the interactions between offline consolidation processes, indexical variation, and the particularities of the sign language modality.

5.6. Afterword: The end of the beginning

Considering both previous studies and the present results, the existence of a wide spectrum of evidence of cross-language effects in bimodal bilingual lexical access seems unquestionable. Broadly speaking, sign and oral languages interact in the process of retrieving lexical items from one language modality. Evidence in this regard has been reported in deaf and hearing populations, from sign to oral languages and vice versa, and from the dominant to the non-dominant language and vice versa. However, far from closing the case, a new era in this field seems to be emerging. The wide range of results also leaves some unanswered questions that will need to be addressed to better understand the underpinnings of lexical processing in bimodal bilinguals.

Given the vast sociolinguistic differences in which deaf and hearing bimodal bilinguals acquire sign and oral languages, it is conceivable that the mechanisms underlying lexical access and cross-language interactions also involve some differences related to endogenous (e.g., linguistic development) and exogenous variables (e.g., language acquisition contexts). For example, it remains to be investigated which variables intervene in the observed non-correspondence between neural response patterns and behavioural data in picture interference tasks. In addition, another question to be addressed in the future is the role of oral phonology and orthography in cross-language interactions. Some accounts propose that, given that deaf bilinguals do not have full access to spoken language phonology, sign-to-oral cross-language effects in deaf bilinguals are driven by direct connections between signs and orthographic representations, almost without spoken phonological influences (e.g., Morford et al., 2017). This explanation is unlikely for hearing signers, who have full access to phonological representations (Shook & Marian, 2010). Moreover, the relative influence of phonology and orthography in oral-to-sign cross-linguistic effects in both bimodal populations is unknown. Other unanswered questions include, for instance, whether the sign lexicon is activated during oral language production in bimodal bilingual populations, or whether covert activation of the oral language influences sign production in hearing bimodal bilinguals. The literature also lacks studies addressing the extent to which lexical processing in one language modality influences semantic processing in the other modality. Covering these lines of research will help to contribute to a better understanding of how links between sign and oral languages develop at a sublexical, lexical and semantic level.

Finally, the similarities between bimodal and unimodal bilinguals have traditionally been used as an argument for accommodating bimodal data into unimodal models of language processing. However, it is quite conceivable that managing two modalities with different articulatory and perceptual mechanisms, and hence different phonological systems, leads to different mechanisms of cross-language interaction (Ormel & Giezen, 2014; Shook & Marian, 2010). With this in mind, the research field would benefit from novel studies going a step further and putting bimodal bilingualism at the centre of new lines of research and theoretical models.

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ANNEX I. Supplementary materials chapter 2

Table S1.1 Stimuli list for iconicity and lexical frequency conditions.

ICONIC				NON-ICONIC			
HF		LF		HF		LF	
Spanish	*(English)*	Spanish	*(English)*	Spanish	*(English)*	Spanish	*(English)*
ala	*(wing)*	abanico	*(hand fan)*	abrigo	*(coat)*	abeja	*(bee)*
anillo	*(ring)*	aguja	*(needle)*	ajedrez	*(chess)*	ajo	*(garlic)*
antena	*(aerial)*	araña	*(spider)*	alfombra	*(carpet)*	almohada	*(pillow)*
arco	*(arch)*	bufanda	*(scarf)*	árbol	*(tree)*	archivador	*(file cabinet)*
avión	*(plane)*	buzón	*(post-box)*	autobús	*(bus)*	aspiradora	*(hoover)*
bandera	*(flag)*	canguro	*(kangaroo)*	bandeja	*(tray)*	berenjena	*(eggplant)*
barco	*(boat)*	caracol	*(snail)*	bebé	*(baby)*	bombero	*(firefighter)*
bigote	*(moustache)*	cepillo	*(brush)*	bicicleta	*(bike)*	bombilla	*(light bulb)*
bola	*(ball)*	cerilla	*(match)*	bolsillo	*(pocket)*	bota	*(boot)*
bolsa	*(bag)*	cesta	*(basket)*	bolso	*(handbag)*	calcetín	*(sock)*
bote	*(jar)*	ciervo	*(deer)*	burro	*(donkey)*	calculadora	*(calculator)*
botella	*(bottle)*	cigarro	*(cigarette)*	caballo	*(horse)*	camello	*(camel)*
botón	*(button)*	cocodrilo	*(crocodile)*	cabra	*(goat)*	candado	*(padlock)*
cadena	*(chain)*	cremallera	*(zipper)*	caja	*(box)*	caramelo	*(candy)*
cama	*(bed)*	cuchara	*(spoon)*	calendario	*(calendar)*	cebolla	*(onion)*
camarero	*(waiter)*	cuerno	*(horn)*	cámara	*(camera)*	cereza	*(cherry)*
camisa	*(shirt)*	dedal	*(thimble)*	campana	*(bell)*	cerrojo	*(bolt)*
carro	*(car)*	elefante	*(elephant)*	castillo	*(castle)*	colador	*(colander)*
casa	*(home)*	enchufe	*(plug)*	cerdo	*(pork)*	conejo	*(rabbit)*
coche	*(car)*	erizo	*(hedgehog)*	cerveza	*(beer)*	delfín	*(dolphin)*
corona	*(crown)*	escoba	*(broom)*	chocolate	*(chocolate)*	espárrago	*(asparagus)*
cruz	*(cross)*	faro	*(lighthouse)*	cinta métrica	*(tape measure)*	fregona	*(mop)*
dado	*(dice)*	flauta	*(flute)*	cinturón	*(belt)*	fresa	*(strawberry)*
dinero	*(money)*	foca	*(seal)*	ciudad	*(town)*	galleta	*(biscuit)*
enfermera	*(nurse)*	gancho	*(hook)*	cocina	*(kitchen)*	gallo	*(rooster)*
escalera	*(stairs)*	gorila	*(gorilla)*	corbata	*(tie)*	guante	*(glove)*
estrella	*(star)*	gusano	*(worm)*	cortina	*(curtain)*	hamburguesa	*(hamburger)*
falda	*(skirt)*	indio	*(Amerindian)*	cura	*(priest)*	hormiga	*(ant)*
flor	*(flower)*	jarra	*(pitcher)*	fábrica	*(factory)*	hoz	*(sickle)*
gafas	*(glasses)*	jeringa	*(syringe)*	familia	*(family)*	hucha	*(money box)*
globo	*(balloon)*	lágrima	*(tear)*	gato	*(cat)*	jirafa	*(giraffe)*
guitarra	*(guitar)*	mariposa	*(butterfly)*	helado	*(ice cream)*	kiwi	*(kiwi)*
huella	*(fingerprint)*	martillo	*(hammer)*	hilo	*(thread)*	lagartija	*(lizard)*
huevo	*(egg)*	mechero	*(lighter)*	hueso	*(bone)*	langosta	*(lobster)*
lata	*(can)*	micrófono	*(microphone)*	iglesia	*(church)*	lazo	*(bow)*
libro	*(book)*	moto	*(motorcycle)*	jamón	*(ham)*	lechuga	*(lettuce)*
llave	*(key)*	nudo	*(knot)*	león	*(lion)*	limón	*(lemon)*
lluvia	*(rain)*	pala	*(shovel)*	luna	*(moon)*	melocotón	*(peach)*
lobo	*(wolf)*	pato	*(duck)*	maíz	*(corn)*	melón	*(melon)*
mesa	*(desk)*	percha	*(hanger)*	manzana	*(apple)*	mochila	*(rucksack)*
montaña	*(mountain)*	pincel	*(brush)*	médico	*(doctor)*	molino	*(windmill)*
oso	*(bear)*	pinza	*(clothespin)*	naranja	*(orange)*	monja	*(nun)*

ICONIC				**NON-ICONIC**			
HF		**LF**		**HF**		**LF**	
Spanish	*(English)*	Spanish	*(English)*	Spanish	*(English)*	Spanish	*(English)*
pelota	*(ball)*	plancha	*(iron)*	nube	*(cloud)*	oliva	*(olive)*
piano	*(piano)*	plátano	*(banana)*	pan	*(bread)*	oveja	*(sheep)*
pico	*(beak)*	rana	*(frog)*	pasta	*(pasta)*	pajarita	*(bow tie)*
pistola	*(gun)*	raqueta	*(racquet)*	periódico	*(newspaper)*	pastilla	*(pill)*
puente	*(bridge)*	rodillo	*(rolling pin)*	perro	*(dog)*	patata	*(potato)*
puerta	*(door)*	semáforo	*(traffic light)*	queso	*(cheese)*	pera	*(pear)*
puro	*(cigar)*	seta	*(mushroom)*	radio	*(radio)*	pimiento	*(pepper)*
rayo	*(lightning)*	silbato	*(whistle)*	reloj	*(watch)*	piña	*(pineapple)*
regla	*(rule)*	tenedor	*(fork)*	roca	*(rock)*	pulpo	*(octopus)*
sierra	*(saw)*	termómetro	*(thermometer)*	sangre	*(blood)*	regadera	*(watering can)*
sombrero	*(hat)*	tigre	*(tiger)*	serpiente	*(snake)*	sándwich	*(sandwich)*
taza	*(mug)*	tijeras	*(scissors)*	silla	*(chair)*	tiburón	*(shark)*
tejado	*(roof)*	tortuga	*(turtle)*	sol	*(sun)*	toalla	*(towel)*
teléfono	*(telephone)*	trompeta	*(trumpet)*	televisión	*(television)*	tomate	*(tomato)*
toro	*(bull)*	valla	*(fence)*	tren	*(train)*	trenza	*(plait)*
vaca	*(cow)*	violín	*(fiddle)*	vestido	*(dress)*	uva	*(grape)*
vaso	*(glass)*	zanahoria	*(carrot)*	zapato	*(shoe)*	ventilador	*(fan)*
vela	*(candle)*	zorro	*(fox)*	váter	*(toilet)*	volcán	*(volcano)*

ANNEX II. Supplementary materials chapter 3

Table S2.1 Target pictures, and distractors grouped by condition: semantic, phonologic and unrelated (English translation in parenthesis).

TARGET		DISTRACTOR					
		Semantic		**Phonologic**		**Unrelated**	
barco	*(ship)*	avión	*(airplane)*	banco	*(bank)*	pistola	*(gun)*
boca	*(mouth)*	nariz	*(nose)*	bolo	*(bowling pin)*	araña	*(spider)*
bota	*(boot)*	zapato	*(shoe)*	botella	*(bottle)*	flor	*(flower)*
caballo	*(horse)*	ciervo	*(deer)*	caja	*(box)*	anillo	*(ring)*
camisa	*(shirt)*	falda	*(skirt)*	camión	*(truck)*	globo	*(balloon)*
cebolla	*(onion)*	zanahoria	*(carrot)*	cebra	*(zebra)*	pluma	*(feather)*
cereza	*(cherry)*	manzana	*(apple)*	cerebro	*(brain)*	llave	*(key)*
copa	*(wine glass)*	vaso	*(glass)*	conejo	*(rabbit)*	tambor	*(drum)*
cuchara	*(spoon)*	tenedor	*(fork)*	cubo	*(bucket)*	ancla	*(anchor)*
escoba	*(broom)*	plancha	*(iron)*	escalera	*(stairs)*	maiz	*(corn)*
gato	*(cat)*	tigre	*(tiger)*	gafas	*(glasses)*	candado	*(padlock)*
limón	*(lemon)*	naranja	*(orange)*	libro	*(book)*	rueda	*(wheel)*
luna	*(moon)*	estrella	*(star)*	lupa	*(magnifying glass)*	cinturón	*(belt)*
maleta	*(suitcase)*	bolso	*(handbag)*	mano	*(hand)*	hoja	*(sheet)*
mesa	*(table)*	silla	*(chair)*	melón	*(melon)*	bandera	*(flag)*
moto	*(motorcycle)*	coche	*(car)*	molino	*(windmill)*	seta	*(mushroom)*
ojo	*(eye)*	dedo	*(finger)*	oso	*(bear)*	jarra	*(pitcher)*
oveja	*(sheep)*	burro	*(donkey)*	oreja	*(ear)*	cañón	*(cannon)*
pato	*(duck)*	gallo	*(rooster)*	pala	*(shovel)*	calcetín	*(sock)*
peine	*(hair comb)*	cepillo	*(brush)*	pelota	*(ball)*	tele	*(TV)*
perro	*(dog)*	zorro	*(fox)*	pera	*(pear)*	sartén	*(pan)*
piña	*(pineapple)*	fresa	*(strawberry)*	pipa	*(pipe)*	madera	*(wood)*
pincel	*(brush)*	lápiz	*(pencil)*	pingüino	*(penguin)*	reloj	*(watch)*
plato	*(plate)*	cazo	*(saucepan)*	plátano	*(banana)*	bombilla	*(light bulb)*
puerta	*(door)*	ventana	*(window)*	puente	*(bridge)*	queso	*(cheese)*
puro	*(cigar)*	cigarro	*(cigarrete)*	puño	*(fist)*	trompeta	*(trumpet)*
rana	*(frog)*	pez	*(fish)*	rama	*(branch)*	patín	*(roller skate)*
regla	*(ruler)*	tijeras	*(scissors)*	regadera	*(watering can)*	guante	*(glove)*
vaca	*(cow)*	cerdo	*(pig)*	valla	*(fence)*	nube	*(cloud)*
vela	*(candle)*	cerilla	*(match)*	velero	*(sailboat)*	foca	*(seal)*

Table S2.2 Descriptive statistics of the distractors grouped by condition. Mean, standard deviation and range measures are reported for word frequency (frequency, log-10), number of phonemes, concreteness, and familiarity.

	Frequency (log-10)			**Number of Phonemes**			**Concreteness**			**Familiarity**		
	M	*SD*	*Range*	*M*	*SD*	*Range*	*M*	*SD*	*Range*	*M*	*SD*	*Range*
Sem	3.40	0.56	2.41 – 4.25	5.37	1.27	3 – 8	6.01	0.53	4.94 – 6.76	6.19	0.54	4.43 – 6.86
Pho	3.34	0.61	2.08 – 4.86	5.23	1.38	3 – 8	5.80	0.58	4.58 – 6.49	6.03	0.61	4.51 – 6.86
Unr	3.45	0.68	2.21 – 4.27	5.33	1.40	3 – 8	6.02	0.39	4.82 – 6.57	5.80	0.73	4.27 – 6.84

Note. Distractor conditions did not differ significantly (at $p < .05$) across these measures.

ANNEX III. Supplementary materials chapter 4

Description of the training tasks in the learning protocol.

Associative learning task

Printed Catalan words were displayed followed by videos of the corresponding LSC translation (see Figure S3.1). Printed words were displayed again after the video played, and remain on the screen until participants pressed the space bar on the keyboard to start a new trial. Participants were informed that they could take the time they needed, and were encouraged to practice mimicking the sign. All 150 word-sign pairs were presented once, pseudo-randomised across participants to include a minimum of five trials between the presentation of phonetic similar signs.

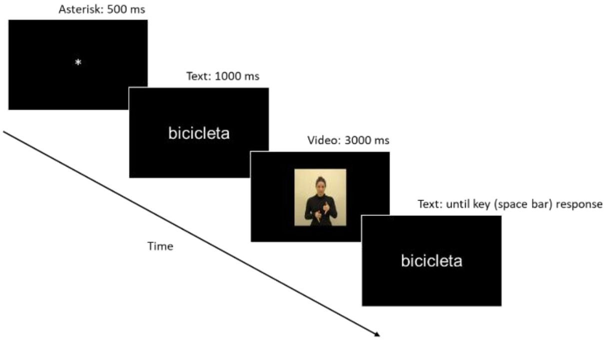

Figure S3.1
Sample trial for the associative learning task.

Forced-choice task

LSC sign videos were displayed followed by two printed Catalan words (see Figure S3.2). One of the words was the translation of the sign presented and the other word was a translation for a different sign of the 150 signs presented in the associative learning task. Participants were asked to press designated keys to select whether the correct translation was the word presented on the right or left side of the screen. Feedback was provided by presenting the correct translation after participants responded.

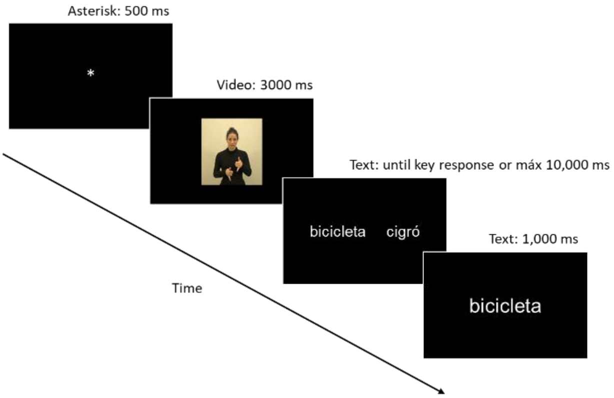

Figure S3.2
Sample trial for the forced-choice task.

Cross-modal translation task

In each trial, a LSC sign video was displayed on the screen after a brief presentation of a printed word in Catalan or Spanish (50ms, lowercase, font = Arial, 60). Participants were instructed to report orally the Catalan translation of the sign, ignoring the printed word (see Figure S3.3).

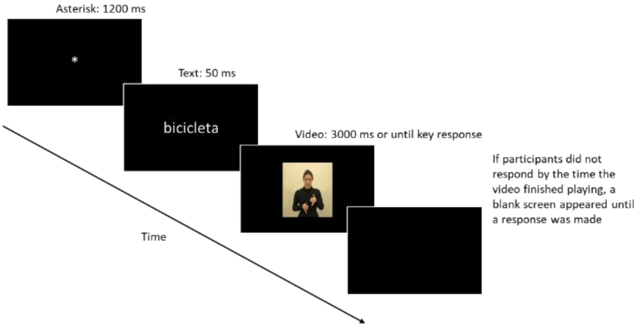

Figure S3.3
Sample trial for the cross-modal translation task

Table S3.1 Significance table displaying *F*-statistics in Experiment 1 and Experiment 2. Significant effects are highlighted in bold.

	Experiment 1: Lexical Decision Task	**Experiment 2: Semantic Decision Task**	
		Sem effect	**Phon effect**
C	**F(3,7506) = 10.95 p < 0.01**	**F(1, 3688) = 349.54 p < 0.001**	p = 0.15
S	**F(2, 7510.6) = 62.53 p < 0.001**	**F(2, 3692.4) = 54.39 p < 0.001**	**F(2, 3692.3) = 19.07 p < 0.001**
A	**F(2, 13) = 26.74 p < 0.001**	**F(2, 13) = 47.34 p < 0.001**	**F(2, 13) = 80.8 p < 0.001**
L	p = 0.75	p = 0.06	**F(2, 13) = 4.44 p = 0.03**
C:S	**F(6, 7506) = 2.52 p = 0.02**	**F(2, 3688) = 14.24 p < 0.001**	**F(2, 3687.9) = 5.23 p = 0.005**
C:A	p = 0.07	**F(2, 3688) = 17.52 p < 0.001**	p = 0.71
S:A	**F(4, 7506) = 16.6 p < 0.001**	**F(4, 3688) = 3.54 p = 0.007**	**F(4, 3687.9) = 3.03 p = 0.02**
C:L	p = 0.97	**F(2, 3688) = 13.54 p < 0.001**	p = 0.98
S:L	p = 0.74	p = 0.88	p = 0.53
A:L	p = 0.23	p = 0.96	p = 0.44
C:S:A	p = 0.64	p = 0.81	p = 0.4
C:S:L	p = 0.99	p = 0.96	p = 0.98
C:A:L	p = 1	p = 0.56	p = 0.99
S:A:L	p = 0.49	p = 0.99	p = 0.99
C:S:A:L	p = 1	0 = 0.99	p = 0.99
C = condition, S = session, A = anteriority, L = laterality			

Table S3.2 List of LSC sign glosses included in the semantically unrelated condition.

Semantically Unrelated				**Target**		**Shared Parameters**
Phonologically Unrelated		**Phonologically Related**				
cosa	*(thing)*	estratègia	*(strategy)*	bessó	*(twin)*	HS, Mov
bacallà	*(cod)*	espasa	*(sword)*	clau	*(key)*	HS, Loc
catifa	*(carpet)*	solter	*(bachelor)*	normal	*(normal)*	HS, Mov
insult	*(insult)*	llibre	*(book)*	vaixell	*(boat)*	HS, Loc
dilluns	*(Monday)*	sabó	*(soap)*	ceba	*(onion)*	HS, Loc
tarda	*(late)*	metge	*(doctor)*	anell	*(ring)*	HS, Loc
fregona	*(mop)*	olimpíada	*(Olympics)*	cadena	*(chain)*	HS, Loc
ocell	*(bird)*	llumí	*(match)*	minut	*(minute)*	HS, Loc
mandarina	*(tangerine)*	família	*(family)*	música	*(music)*	HS, Loc
fluix	*(slack)*	boig	*(crazy)*	ovella	*(sheep)*	HS, Mov
futur	*(future)*	amant	*(lover)*	roca	*(rock)*	HS, Loc
ànec	*(duck)*	pila	*(battery)*	galeta	*(cookie)*	HS, Mov
pitjor	*(worse)*	pasta	*(pasta)*	idioma	*(language)*	HS, Loc
bicicleta	*(bicycle)*	bandera	*(flag)*	bleda	*(chard)*	Loc, Mov
regle	*(ruler)*	caure	*(fall)*	endollar	*(plug in)*	HS, Loc
polític	*(politician)*	espelma	*(candle)*	mòbil	*(mobile)*	HS, Mov
llarg	*(long)*	riure	*(laugh)*	calent	*(hot)*	HS, Mov
elegant	*(elegant)*	sopa	*(soup)*	prova	*(proof)*	Loc, Mov
claror	*(brightness)*	robot	*(robot)*	diari	*(newspaper)*	HS, Loc
porta	*(door)*	raïm	*(grape)*	cicle	*(cycle)*	HS, Loc
arquitecte	*(architect)*	diumenge	*(Sunday)*	teoria	*(theory)*	HS, Loc
acudit	*(joke)*	presoner	*(prisoner)*	formatge	*(cheese)*	HS, Loc
marró	*(brown)*	fulla	*(leaf)*	estrella	*(star)*	HS, Loc
farmàcia	*(pharmacy)*	costum	*(habit)*	prostituta	*(prostitute)*	HS, Mov
televisió	*(television)*	muntanya	*(mountain)*	elefant	*(elephant)*	HS, Loc
escombra	*(broom)*	malament	*(bad)*	paciència	*(patience)*	HS, Loc
cunyat	*(brother-in-law)*	petó	*(kiss)*	mentida	*(lie)*	HS, Loc
dimarts	*(Tuesday)*	xafarder	*(nosy)*	cec	*(blind)*	HS, Loc
discoteca	*(nightclub)*	hamburguesa	*(hamburger)*	hipopòtam	*(hippopotamus)*	HS, Loc
foscor	*(darkness)*	lladre	*(thief)*	cigró	*(chickpea)*	HS, Loc, Mov
feble	*(weak)*	paper	*(paper)*	enfadat	*(angry)*	HS, Loc
provisional	*(provisional)*	marit	*(husband)*	mitjó	*(sock)*	HS, Loc
gandul	*(lazy)*	verd	*(green)*	pipí	*(pee)*	Loc, Mov
sexe	*(sex)*	sou	*(salary)*	goma	*(rubber)*	HS, Loc
curt	*(short)*	blau	*(blue)*	lavabo	*(toilet)*	HS, Loc

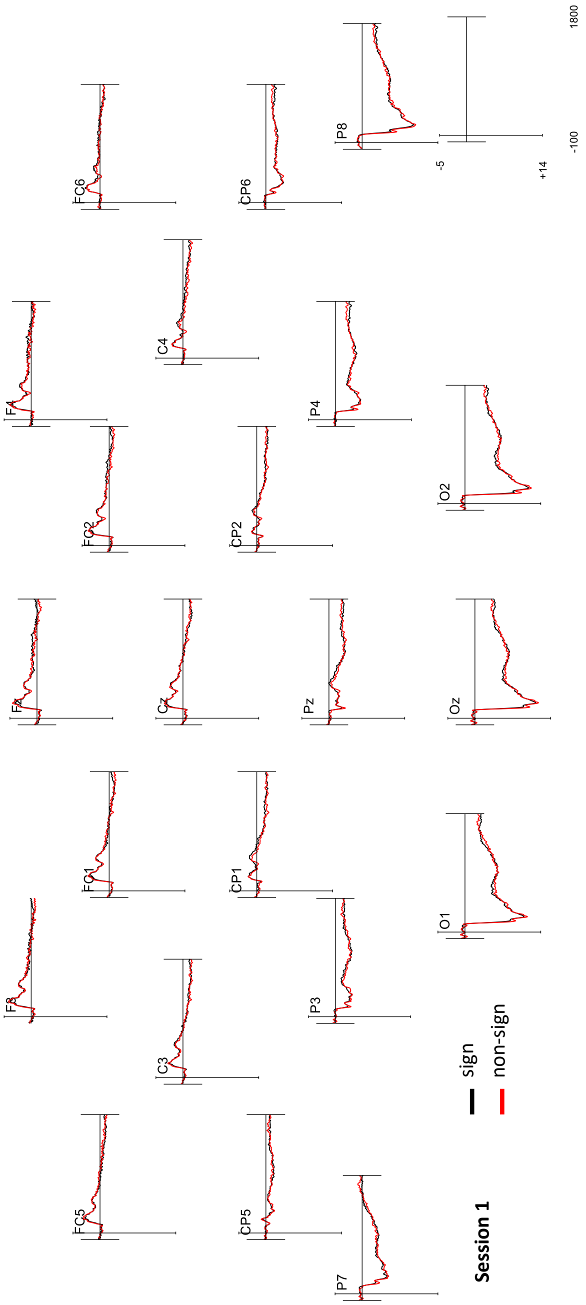

Figure S3.4 Experiment 1. Lexical decision task. Topographical ERPs for the contrast of lexicality (sign vs non-sign) in session 1.

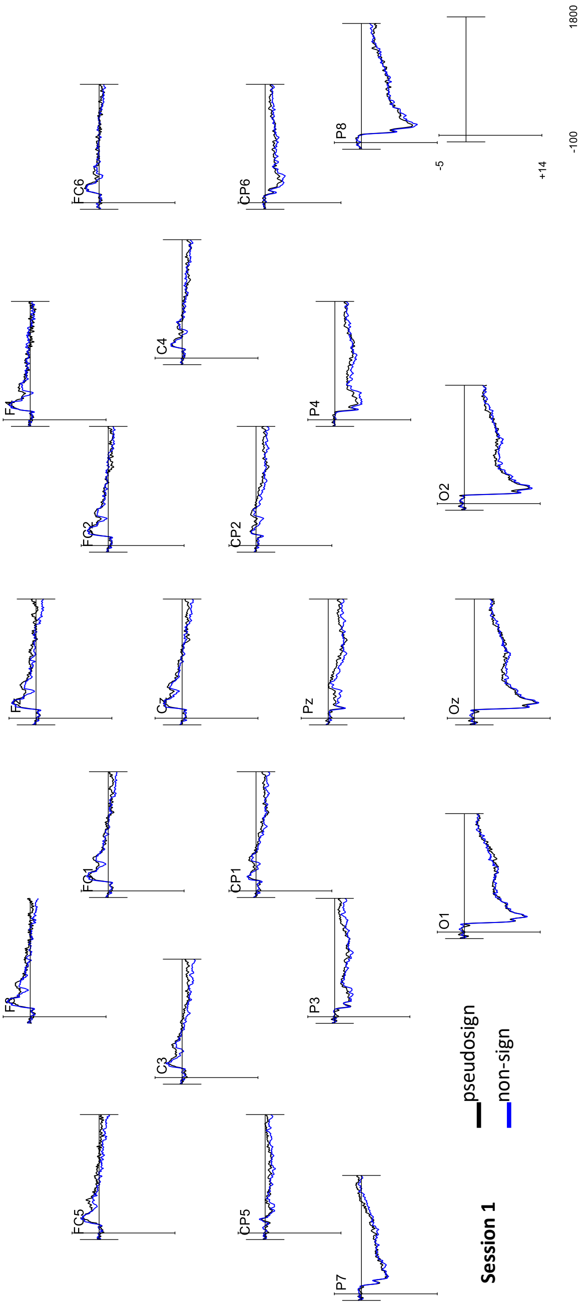

Figure S3.5 Experiment 1. Lexical decision task. Topographical ERPs for the contrast of non-signs (pseudosign vs non-sign) in session 1.

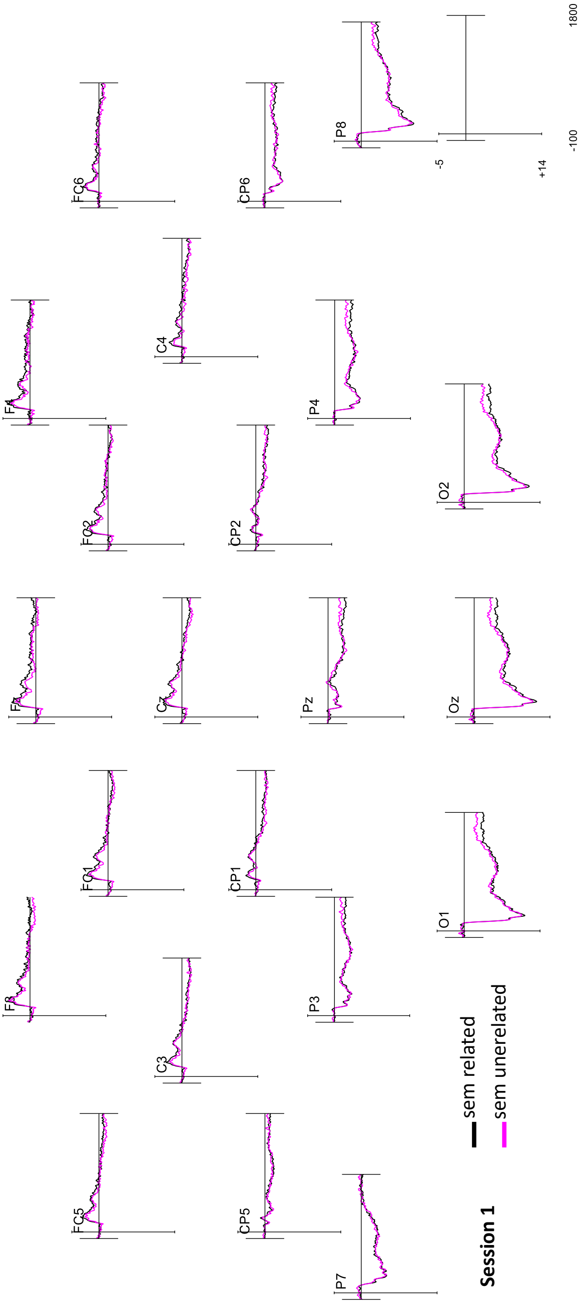

Figure S3.6 Experiment 1. Lexical decision task. Topographical ERPs for the contrast of semantic relatedness (related vs unrelated) in session 1.

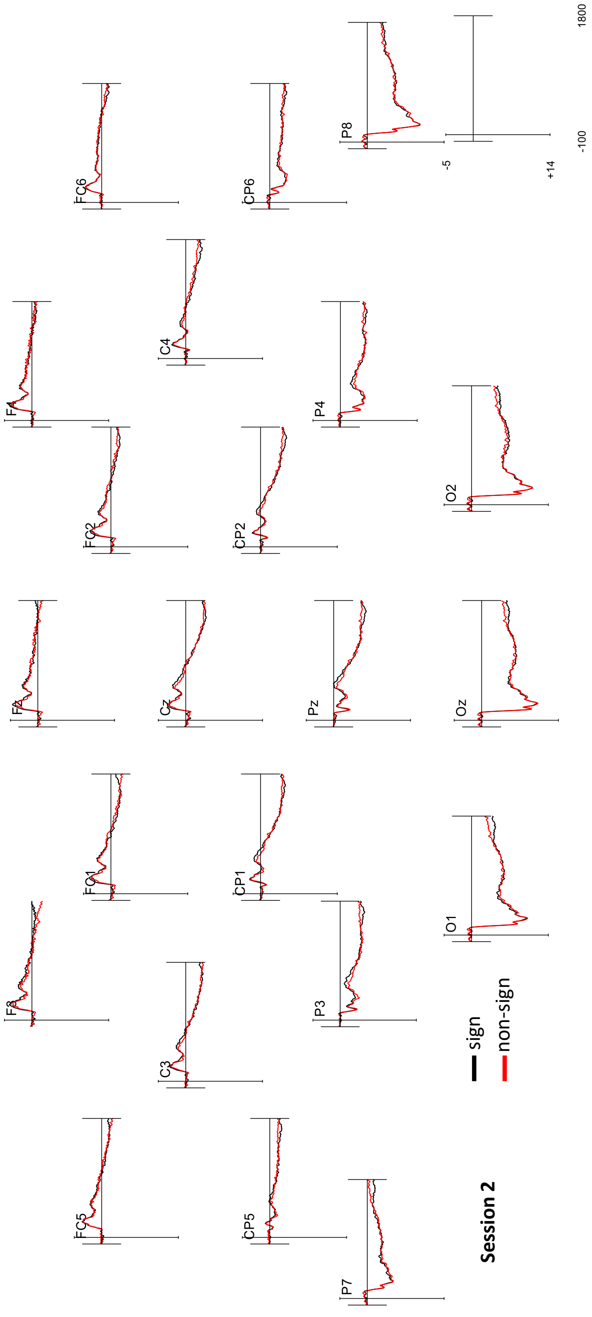

Figure S3.7 Experiment 1. Lexical decision task. Topographical ERPs for the contrast of lexicality (sign vs non-sign) in session 2.

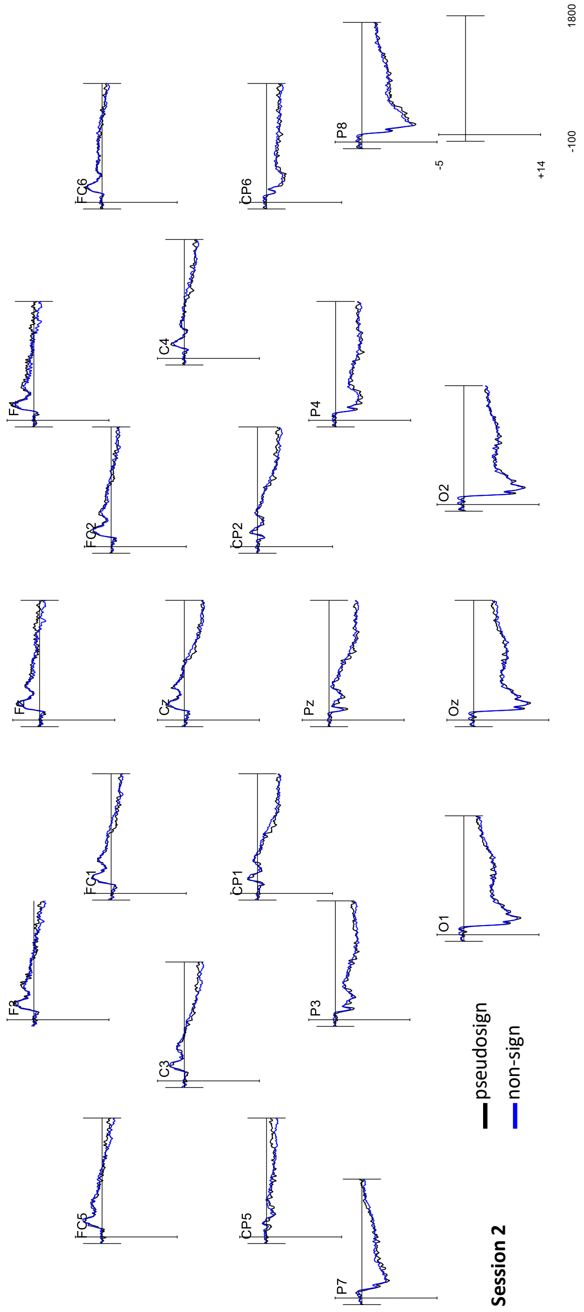

Figure S3.8 Experiment 1. Lexical decision task. Topographical ERPs for the contrast of non-signs (pseudosign vs non-sign) in session 2.

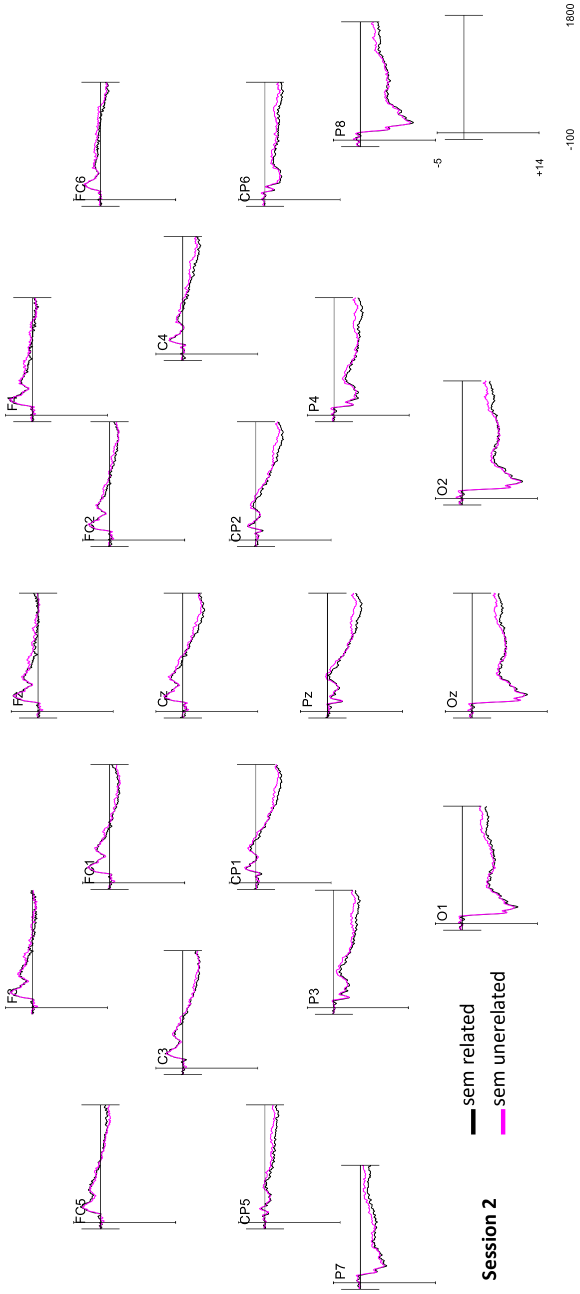

Figure S3.9 Experiment 1. Lexical decision task. Topographical ERPs for the contrast of semantic relatedness (related vs unrelated) in session 2.

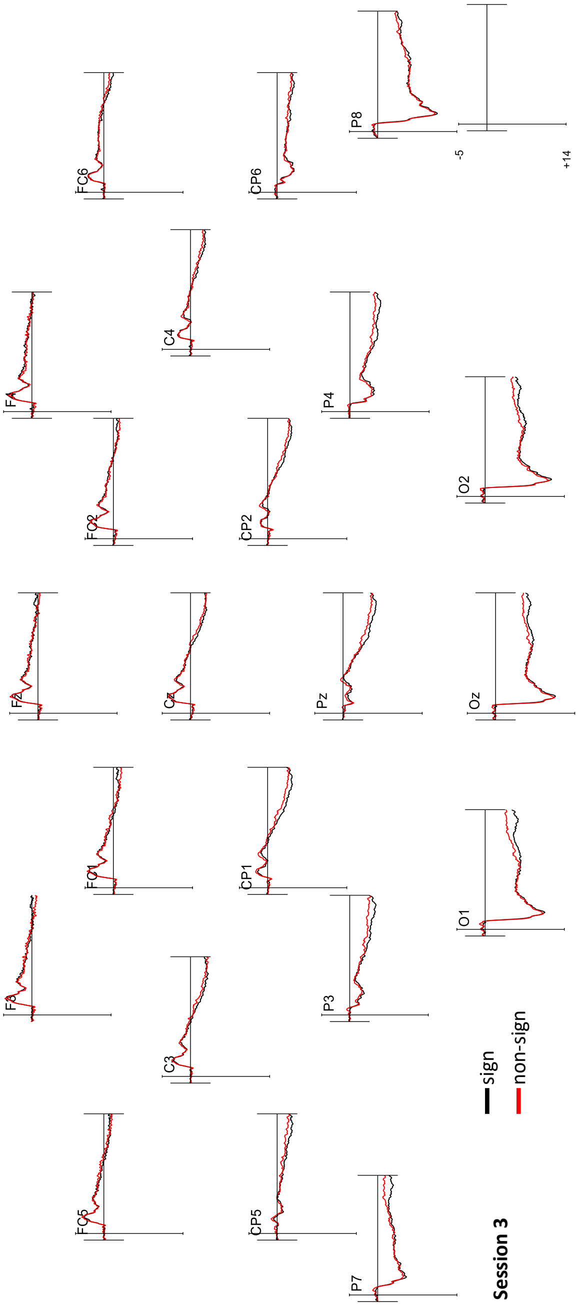

Figure S3.10 Experiment 1. Lexical decision task. Topographical ERPs for the contrast of lexicality (sign vs non-sign) in session 3.

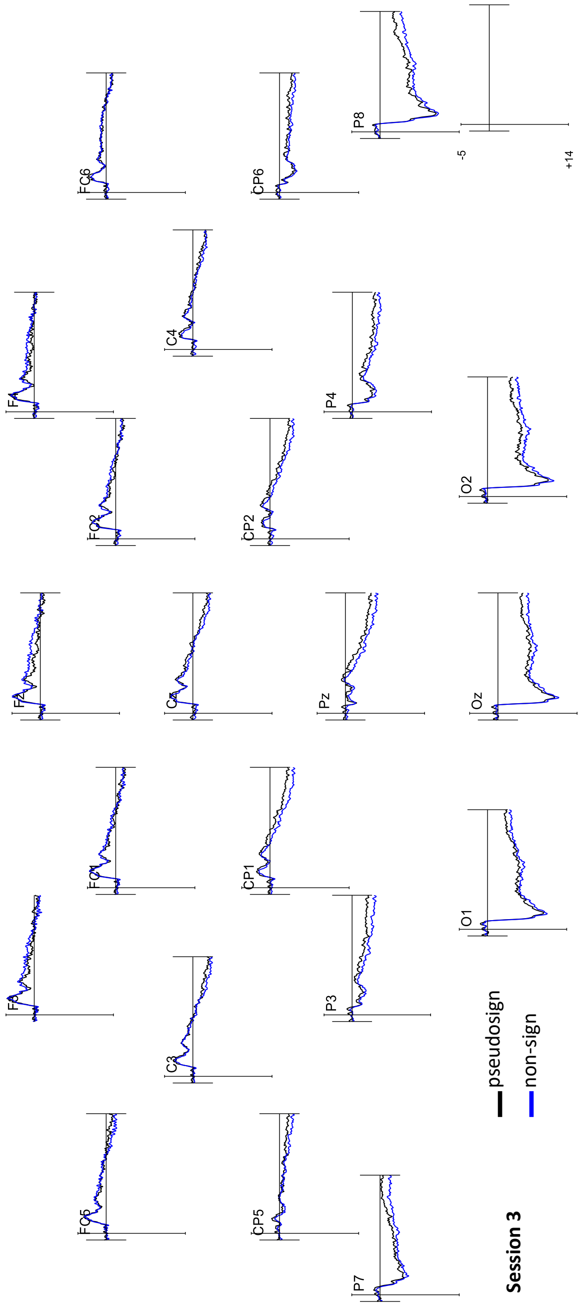

Figure S3.11 Experiment 1. Lexical decision task. Topographical ERPs for the contrast of non-signs (pseudosign vs non-sign) in session 3.

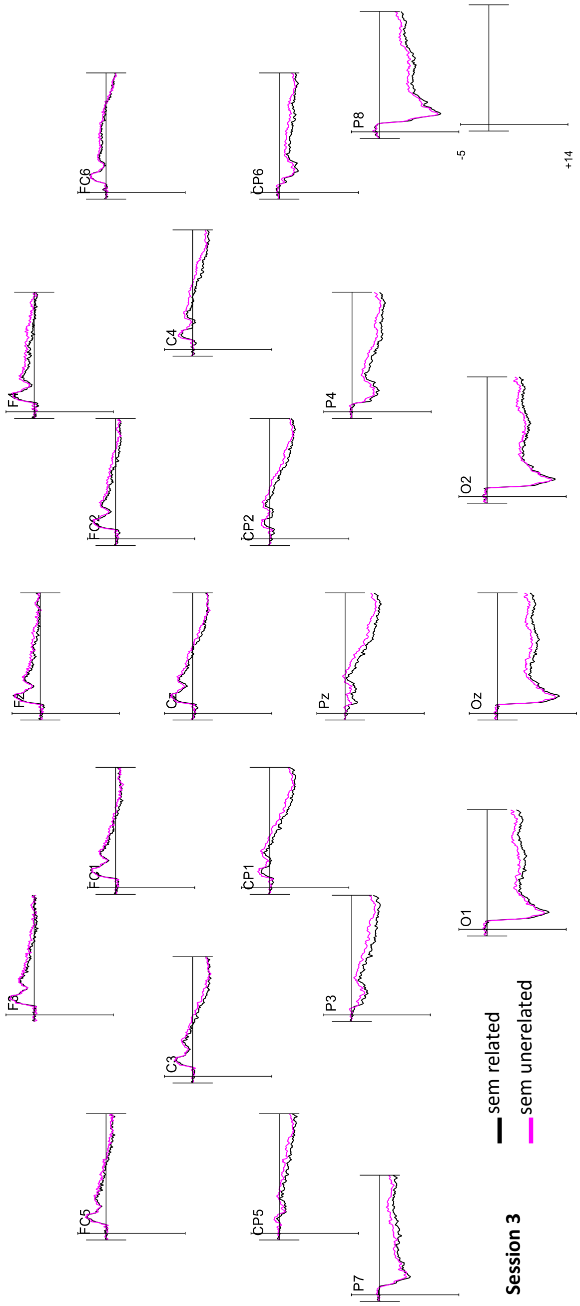

Figure S3.12 Experiment 1. Lexical decision task. Topographical ERPs for the contrast of semantic relatedness (related vs unrelated) in session 3.

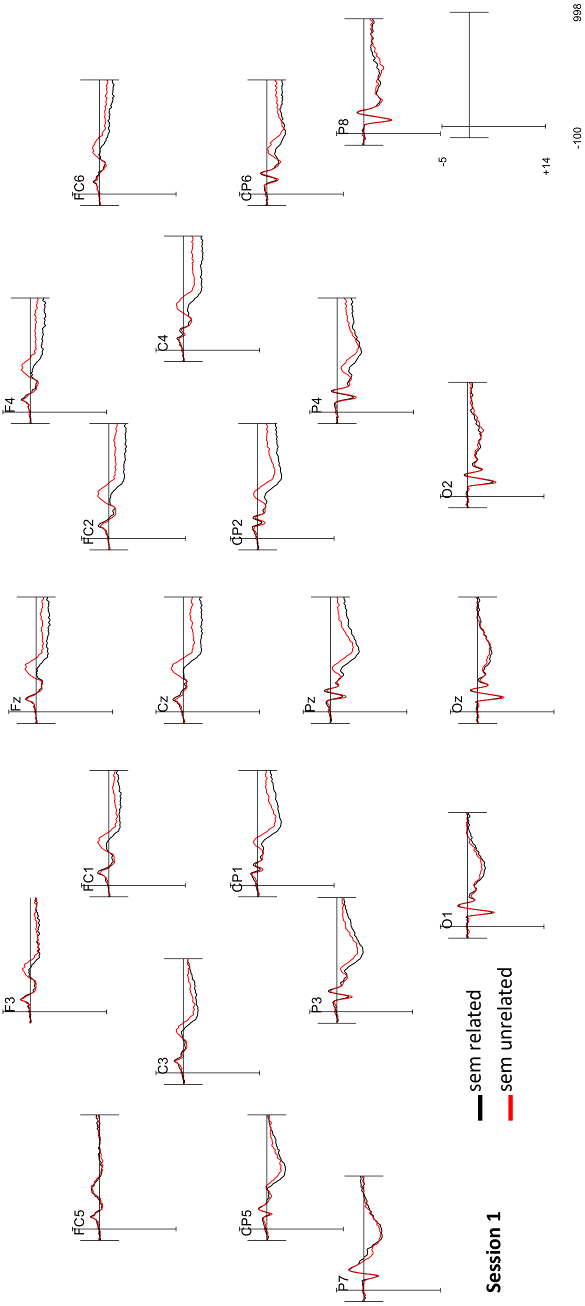

Figure S3.13 Experiment 2. Semantic decision task. Topographical ERPs for the contrast of semantic relatedness (related vs unrelated) in session 1.

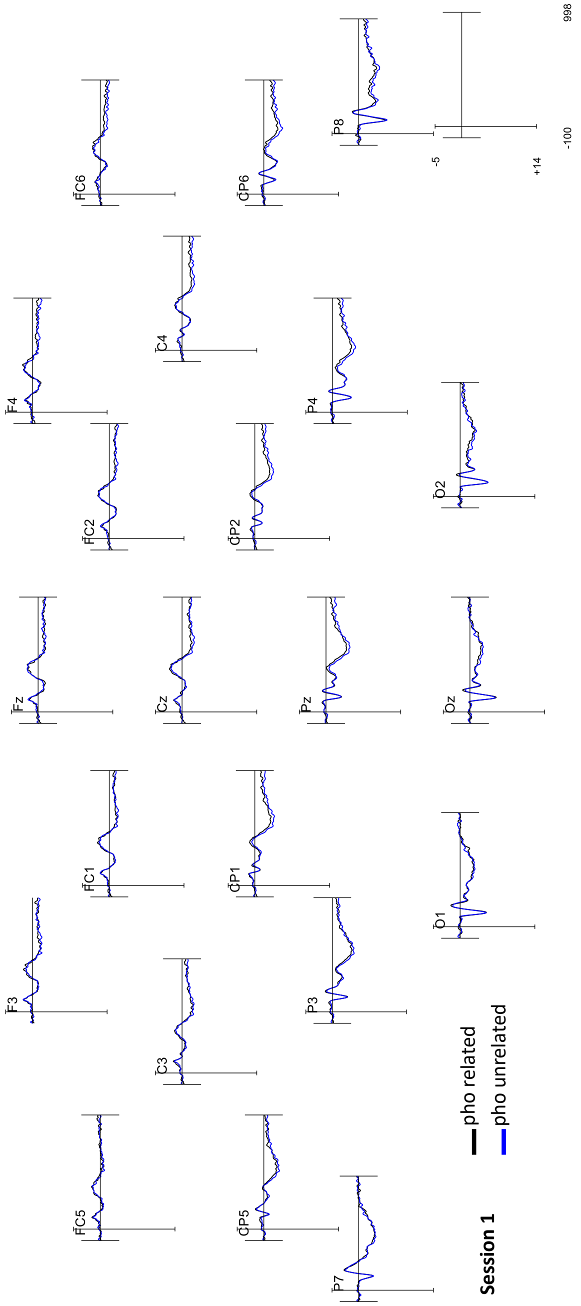

Figure S3.14 Experiment 2. Semantic decision task. Topographical ERPs for the contrast of phonological relatedness (related vs unrelated) in session 1.

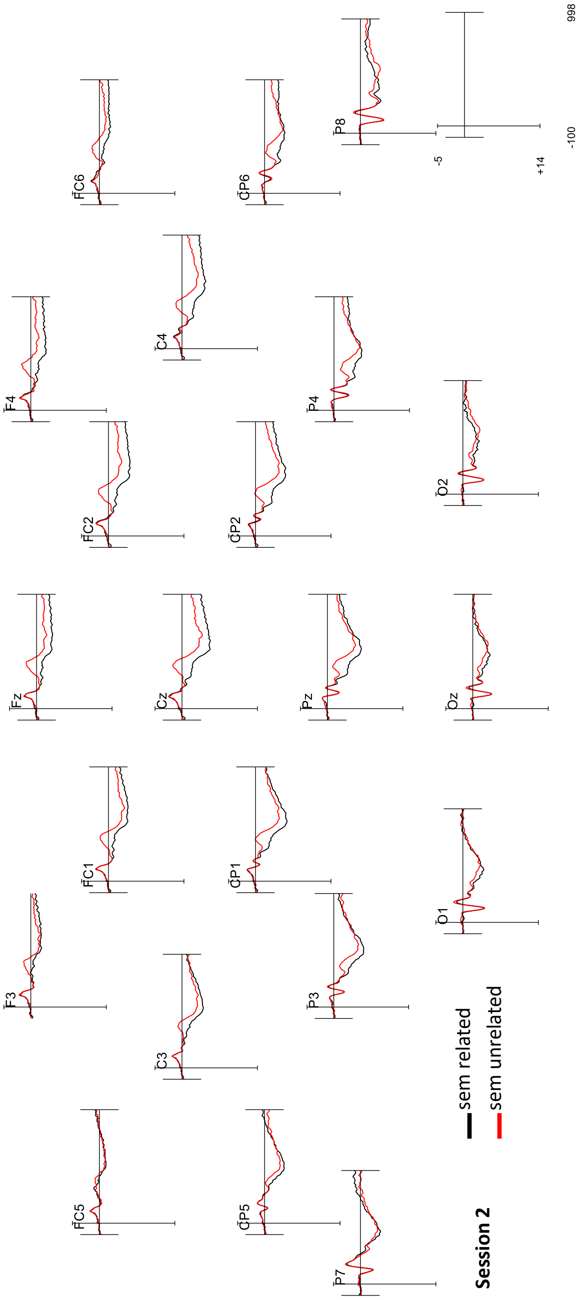

Figure S3.15 Experiment 2. Semantic decision task. Topographical ERPs for the contrast of semantic relatedness (related vs unrelated) in session 2.

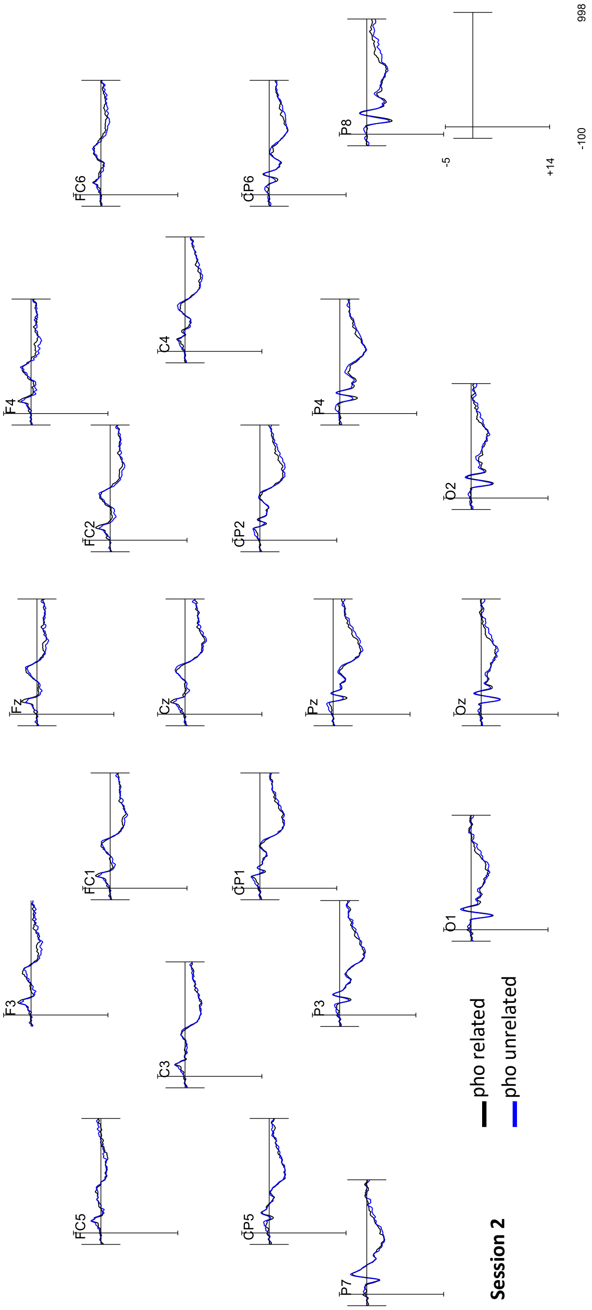

Figure S3.16 Experiment 2. Semantic decision task. Topographical ERPs for the contrast of phonological relatedness (related vs unrelated) in session 2.

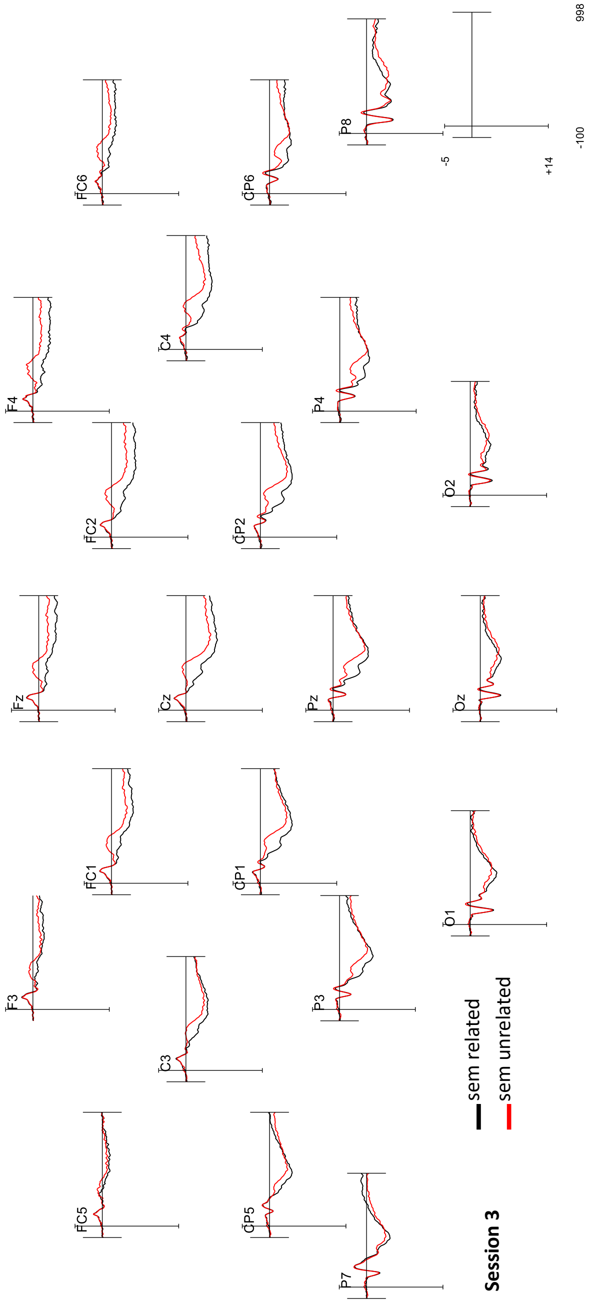

Figure S3.17 Experiment 2. Semantic decision task. Topographical ERPs for the contrast of semantic relatedness (related vs unrelated) in session 3.

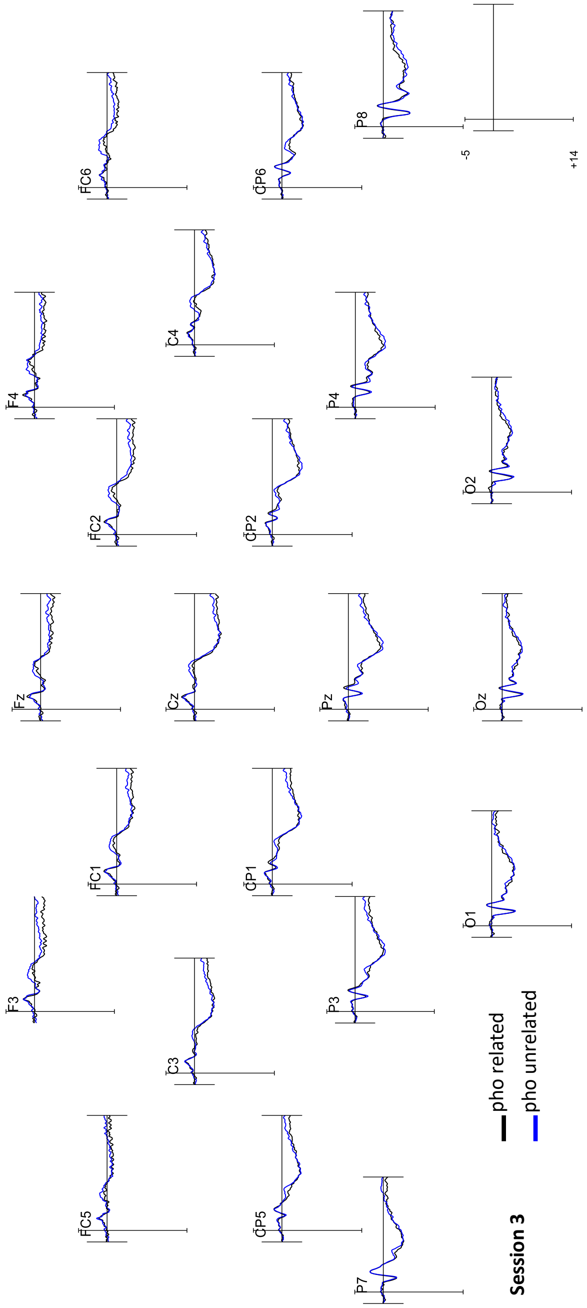

Figure S3.18 Experiment 2. Semantic decision task. Topographical ERPs for the contrast of phonological relatedness (related vs unrelated) in session 3.

THE MORE THE MERRIER? ON THE INFLUENCE OF INDEXICAL VARIABILITY ON SECOND LANGUAGE VOCABULARY LEARNING

Appendix

Gimeno-Martínez, M., Sánchez, R., Baus, C. (2023). The more the merrier? On the influence of indexical variability on second language vocabulary learning. Language Learning, 73(3).

The More the Merrier? On the Influence of Indexical Variability on Second Language Vocabulary Learning

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Keywords: indexical variability; second language; sign learning; second modality learners; recall; translation; replication

A one-page Accessible Summary of this article in non-technical language is freely available in the Supporting Information online and at https://oasis-database.org

Abstract

We investigated indexical variation as a variable that promotes second language (L2) vocabulary learning across language modalities. In three experiments, we presented Catalan Sign Language signs (Experiments 1a and 1b), pseudowords (Experiment 2), and English words (Experiment 3) to participants in three conditions that varied in the number of people who introduced these stimuli (one, three, or six people). We evaluated learning outcomes in two recall tasks: a picture-to-L2 naming task and a L2-to-L1 translation task. For the sign modality, indexical variation benefitted the immediate recall of signs in the translation task (Experiment 1a) and delayed recall after two weeks in the picture naming task (Experiment 1b). For the oral modality, we observed no effect when participants learned pseudowords (Experiment 2), but variability benefited recall in the translation task when participants learned English words (Experiment 3). We discuss these contrastive results, considering the influence of indexical variation in adult L2 sign and oral vocabulary learning.

Introduction

Learning a second language (L2) is often a difficult task, especially for adults. Despite exceptions, for most learners acquiring the multiple subsystems of a L2 (e.g., vocabulary, phonology, grammar) represents an extraordinary cognitive effort. A complex set of variables influences this process with respect to the learner (e.g., age, aptitude; Ellis, 1986), the context of learning (e.g., classroom, immersion; Cummins, 1999), or the learning process itself (e.g., incidental vs. explicit vocabulary learning; Ellis, 1994). As such, a great deal of scientific and pedagogical work has focused on identifying variables that contribute to the success of adult L2 learning. In our study, we were concerned with L2 vocabulary learning so as to gain a better understanding of the influence of indexical variation. We focused on a sign language to determine whether the reported positive effects of indexical variation in the number of speakers on L2 vocabulary learning might occur in a language that is not acoustically based.

Background literature

Influence of indexical variation on speech processing and memory

Speech contains two primary sources of information: linguistic and indexical. Linguistic information conveys the content of an utterance, including its phonological, lexical, syntactic, and semantic aspects (Pisoni & Levi, 2007). Indexical information is obtained from the voice and conveys information about talker identity, including speaker-specific characteristics such as gender, age, emotional states, or personality traits (e.g., Hagiwara, 1997; Munson et al., 2006;

Pisoni & Remez, 2008). For the linguistic content of speech, literature on speech perception has often neglected the role of indexical information. Researchers have accepted the idea that listeners' perceptual system normalizes the speech signal by disregarding any speaker-specific variation (i.e., through what is known as categorical perception of speech). Nevertheless, accumulated evidence has revealed that listeners use speaker-specific information in the process of speech perception. That is, indexical properties of the voice are encoded and retained in memory along with linguistic aspects of speech (e.g., Bradlow et al., 1999; Goldinger, 1996; Goldinger et al., 1991; Johnson, 2006; Martin et al., 1989; Nygaard et al., 1995, 2000).

Several studies have shown that speech processing and memory are affected by variations in indexical information. Of relevance are studies revealing that variation in speaker characteristics (i.e., the number of speakers) has an impact on speech processing and memory. For instance, an inverse relationship between word recognition accuracy and variation in the number of speakers has been reported (e.g., Goldinger et al., 1991; Mullennix et al., 1989; Ryalls & Pisoni, 1997). Recall of words has been found to be more accurate and rapid for lists of words uttered by a single speaker than for lists of words uttered by multiple speakers. A distinctive positive effect of the number of speakers has been reported when sufficient processing time was given to listeners, allowing them to fully encode indexical information from the voice. As an example, Nygaard et al. (1995) found that listeners' memory recall of a list of words improved when the words were produced by multiple speakers in a slow presentation rate but diminished in a fast presentation rate (see also Goldinger et al., 1991; Palmeri et al., 1993). In light of these results, indexical variation in the number of speakers is considered to be a relevant feature of first language (L1) processing and memory, but certain methodological aspects appear to modulate the impact of indexical variation.

Importantly, not all sources of variability are encoded in memory along with the linguistic content (Nygaard et al., 1995; Sommers & Barcroft, 2006). One source of variability is fundamental frequency (F0), which is defined as the lowest rate of repetition of the cycles of air pressure and determines the pitch of a voice. Variations in F0 are lexically contrastive in tonal languages (e.g., Chinese), that is, tonal languages have similar segmental sequences that are only differentiated by changes in F0, and this results in different lexical units with different meanings. The same variation is not relevant in languages such as English or Spanish. Sommers and Barcroft (2006) showed no impact of indexical variation on L1 English word processing when the fundamental frequency of voice (F0) was manipulated as a source of variation. Altogether, studies from the oral modality have revealed that the impact of indexical variation on L1 processing is determined by its relevance in the language.

Influence of speaker variability on adult L2 learning

Studies on L2 learning have shown a positive influence of speaker variability on memory recall of L2 words. Novel L2 words have been shown to be more accurately learned when they are introduced by multiple speakers than by a single speaker (Barcroft & Sommers, 2005; Sommers & Barcroft, 2011; see Rost & McMurray, 2009, for similar results with novel words and babies). Barcroft and Sommers (2005), for example, examined the effect of speaker variability on the ability of L1 English speakers to learn L2 Spanish words by comparing learning rates in three conditions: no variability (six repetitions of each word in the voice of one speaker), moderate variability (two repetitions of each word in the voice of three different speakers), and high variability (one repetition of each word in the voice of six different speakers). Barcroft and Sommers evaluated learning with two recall tasks: a picture-to-L2 naming task and a L2-to-L1 translation task. Accuracy scores in both tasks showed that L2 vocabulary learning improved systematically as a function of variability. Words in the no variability condition resulted in lower accuracy rates than did words learned in the moderate variability condition, and words in the moderate variability condition obtained low accuracy rates compared to words in the high variability condition (but see Barcroft, 2001, for no effect of speaker variability).

In light of these results and subsequent replications (Barcroft & Sommers, 2014; Sommers & Barcroft, 2007, 2011), several theoretical accounts have described the mechanisms behind the positive influence of indexical variability on L2 vocabulary learning. One of those accounts that has received most attention is the exemplar-based model described by Goldinger (1998). This framework suggests that indexically varied conditions produce more associative “hooks” and more robust representations for lexical entries stored in long-term memory. In the context of L2 learning, indexically varied representations of words to be learned would lead to richer encoding (Barcroft & Sommers, 2005), which subsequently would facilitate retrieval.

As reported for L1, L2 learners only benefit from variability if it targets an acoustically relevant feature in the language. Sommers and Barcroft (2007) showed that L1 speakers of English (a nontonal language) did not benefit from variations in F0. Barcroft and Sommers (2014) expanded these results by comparing the learning outcomes of speakers of Zapotec, a tonal language, and the learning outcomes of speakers of English, a nontonal language. The researchers exposed the participants to 24 Russian auditory words while the participants viewed the corresponding pictures. The researchers experimentally manipulated the F0 by providing six instances of each word, presented in three learning conditions: no variability (six repetitions spoken at one F0), moderate variability (two repetitions of three F0s), and high variability (one repetition of six F0s). Only the participants for whom F0 was a relevant language feature in their L1, that is, the Zapotec speakers, benefitted from F0 variability in L2 learning. These results supported the phonetic-relevance hypothesis according to which L2 learners only attend to acoustic variations if these variations are phonetically relevant in the languages in which the L2 learners are proficient.

In sum, indexical variation influences L2 vocabulary learning when this is a relevant property in the language. In our study, we explored indexical variation for the number of signers in L2 adult sign learning to determine how relevant signer variation is in a language that is not acoustically based. The aim of this study was twofold. At the theoretical level, determining the role of signer variability in L2 learning would provide information about indexical aspects of sign processing and how these aspects interact with linguistic content in sign language processing and memory. In this respect, our study would contribute to clarifying whether indexical variation is a general linguistic property that influences vocabulary learning regardless of modality or is restricted to acoustically based languages. Second, at the pedagogical level, these results could inform educational practices that promote L2 sign learning. Exploring L2 sign learning is especially relevant considering the increasing number of people who have chosen to learn a sign language as a L2 in recent years. As an example, in 2016, American Sign Language was the third most frequently taught L2 in the United States (Looney & Lusin, 2018). Given the increasing popularity of learning sign languages as a L2, it is important to know how L2 learning occurs when the L1 and the L2 of the learner are not from the same modality, that is, for second modality L2 learners (Pichler & Koulidobrova, 2016; Schönström, 2021).

Knowledge of which properties are similar between sign and oral languages (i.e., modality-independent) and which properties are determined by the language modality (i.e., modality-dependent) is required for exploring the coupling between linguistic and indexical information in sign languages. At the linguistic level, accumulated evidence has indicated that sign and oral languages are sensitive to the same linguistic phenomena, including lexical frequency (Emmorey et al., 2013; Jescheniak & Levelt, 1994) and categorical perception (Gimeno-Martínez et al., 2020; Kuhl, 2004). This implies that linguistic information is organized and flows across levels of processing (e.g., semantic, lexical, and phonological) similarly in both modalities. Likewise, the same variables described in L2 word learning have been reported to influence L2 sign learning. For example, variables such as learners’ L1 vocabulary knowledge have predicted L2 sign learning in hearing adults (Williams et al., 2017). In addition, other variables specific to the signed modality such as visual sonority, handshape markedness (Williams & Newman, 2016), or perceptuomotor abilities of learners, including short-term memory for hand and arm movements (Martinez & Singleton, 2018), have appeared to influence sign L2 learning as well.

In contrast to the description of the linguistic aspects of sign processing and learning, and perhaps because indexical information has been mainly described as referring to the acoustic properties of the voice, its counterpart in the signed modality has remarkably been barely described. Notwithstanding, under the assumption that signers have mental representations of sign forms (Corina et al., 2011) and that the lexicon is similarly organized in signed and oral languages (e.g., Caselli & Cohen-Goldberg, 2014), it is conceivable that signers encode signer-specific perceptual variations (indexical aspects) during sign processing. In a priming study, Corina et al. (2011) tested perceptual viewpoint as a source of variability in sign language processing. Perceptual viewpoint referred to the angle view of the signer, with front, left, or right views. Identical prime and target signs (same sign) were presented either from the same viewpoint (e.g., front–front) or from a different one (e.g., front–side). Repetition priming was larger when signs were presented from the same viewpoint than when they were presented from a different viewpoint (see also Emmorey et al., 2009; Pyers et al., 2015). This suggested that indexical variation in perceptual viewpoint is integrated along with sign representations during sign processing.

The present study: Influence of signer variability on L2 sign learning

Our study focused on signer variability to explore if it is encoded in memory along with linguistic information from the sign and hence positively influences L2 learning. Specifically, our main research aim was to explore whether L2 sign vocabulary learning is enhanced when signs are presented by multiple signers compared to by a single signer. To achieve this, we adapted the Barcroft and Sommers (2005) study to the signed modality. We compared learning outcomes of signs learned in three variability conditions: no variability, moderate variability, and high variability. As in the oral modality (Barcroft & Sommers, 2014), if variation in the number of signers is a relevant indexical property in sign processing, variability effects should be expected in L2 sign vocabulary learning, both in immediate recall (Experiment 1a) and in delayed recall (Experiment 1b).

In addition, to obtain an estimate of the effect of speaker variability on the oral modality in our study population of bilingual Catalan–Spanish speakers, we conducted two further experiments to investigate speaker variation in L2 word learning. This way, we could evaluate whether the influence of indexical variation on L2 vocabulary acquisition is a general linguistic property that is independent of the modality of the language to be acquired. In Experiment 2, a new group of participants learned words from an invented language (pseudowords). In Experiment 3, another group of participants learned L2 English words.

Experiment 1a. L2 sign learning

Methods

Participants

We recruited 54 Catalan–Spanish speakers (40 females, M_{age} = 22.25 years, range = 18–28) from the Universitat Pompeu Fabra's Center for Brain and Cognition database. All were university students without any hearing difficulty or history of deafness, and they reported no previous knowledge of Catalan Sign Language (LSC) or any other sign language and were not enrolled in sign language courses. The participants completed an informed consent form for image recording and experiment participation before the experiment and were paid for their participation. We excluded three participants because they could not complete the task appropriately and because of technical problems.

Materials

We selected 48 noniconic LSC signs and their related pictures for the experiment. We used sign iconicity ratings (*M* = 1.65, *SD* = 0.48; on a scale where 1 = low iconic and 5 = high iconic) from 12 hearing nonsigners from Baus and Costa's (2015) study. Signs included different semantic categories and were recorded by seven hearing proficient signers (three males, four females). We asked the signers to record the LSC signs with a neutral face. We retrieved black and white pictures corresponding to the signs from Snodgrass and Vanderwart's (1980) study and from the Multipic database (Duñabeitia et al., 2018).

We divided the 48 stimuli into three sets (see Table A1) corresponding to the three learning variability conditions (16 signs in each set): (a) no variability, with six repetitions of the sign performed by one signer; (b) moderate variability, with two repetitions of the sign performed by three signers; and (c) high variability, with one repetition of the sign performed by six signers. Sign iconicity ratings did not differ across the three stimuli sets (p =.23). The same video sign was displayed for all sign repetitions from a given signer to avoid intrasigner variability. We counterbalanced the sets of stimuli and the order in which the conditions appeared throughout the experiment, which resulted in nine experimental lists. In addition, to minimize differences in signer intelligibility across variability conditions, we rotated the six signers from the high variability condition across participants in the no variability and moderate variability conditions (Barcroft & Sommers, 2005). Thus, by incorporating a signers' rotation procedure, we prevented the same signer from appearing in the same condition and producing the same set of signs for all the participants. In this way, each of the nine stimulus lists had six variants based on the identity of the signers, which resulted in 54 training lists.

Table A1 Sets of sign stimuli from Catalan Sign Language used in Experiments 1a and 1b

Sign set	Stimuli
Set 1	windmill, firefighter, mailbox, moneybox, sheep, garlic, onion, sock, camel, cherry, ant, kiwi, lettuce, cucumber, pear, lemon
Set 2	spider, tree, folder, hoover, eggplant, boot, strawberry, melon, pea, hamburger, cookie, deer, lobster, shark, olive, grape
Set 3	tiger, frog, potato, pill, doll, peach, bee, asparagus, light bulb, pineapple, lizard, nun, fox, pepper, brush, watering can

Note. English translations of the signs from Catalan Sign Language are reported.

The experimental session included two phases: learning and test. To avoid repetition of the same signers in both phases, video recordings of six signers (3 males and 3 females) were used in the learning phase. In the test phase, participants were presented with signs performed by a different signer.

Procedure

We tested the participants individually and conducted the experiment online. We sent the participants a video including a recording of the experimental session run under the E-Prime (Version 2.0) software (https://pstnet.com/products/e-prime). We asked the participants to record a video of themselves while they were doing the experiment to ensure that they were attentive to the screen and had no external distractions (e.g., looking at the phone, other interruptions) during the learning phase so that we could evaluate the accuracy of their responses offline.

The experimental design was as follows. First, participants were presented with a video recording that corresponded to the learning phase, and then they were required to perform two tasks in the testing phase: a picture-to-L2 naming task and a L2-to-L1 translation task. In the learning phase, the participants were informed that they would see a series of six repetitions of 48 LSC signs along with the pictures associated with their meaning, which yielded 288 trials. The participants' task was to memorize the signs. Each trial began with a fixation asterisk that was presented at the center of the screen for 500 ms followed by a picture for 750 ms on the left part of the screen. The video of the target sign was then displayed (3,000 ms) on the right part of the screen while the picture was still visible and remained 1,250 ms after the video ended. A final blank of 500 ms completed each learning trial.

In the testing phase, we employed two recall tasks: first a picture-to-L2 naming task and then a L2-to-L1 translation task. In the picture-to-L2 naming task, the participants were required to perform the LSC sign corresponding to the picture displayed for 10,000 ms on the screen after a fixation asterisk displayed for 1,000 ms. A final blank of 1,000 ms completed the trial. In the L2-to-L1 translation task, after a fixation asterisk of 1,000 ms, the participants were presented with

LSC signs displayed for 3,000 ms and were asked to verbally provide their Catalan translation (with a maximum response time of 10,000 ms). A final blank of 1,000 ms completed each trial.

Data analysis

We binary coded the data (correct/incorrect) in both recall tasks, that is, the picture-to-L2 naming task and the L2-to-L1 translation task, after the experiment by analyzing the participants' video recordings (see Sinkeviciute et al., 2019, for a similar analysis approach). In the picture-to-L2 naming task, we coded each sign production as incorrect if the participants did not recall the sign, if they provided a nontarget sign, or if at least one of their signs' sublexical components (i.e., handshape, location, and movement) deviated greatly from the target (see Ortega et al., 2019, for a similar response coding). For the L2-to-L1 translation task, we excluded from the analysis incorrect responses or trials in which the participants did not respond. We considered trials in which the participants provided a similar word to the expected answer (e.g., "peach" instead of "apricot") as correct responses.

We analyzed the two tasks separately with generalized mixed models (binomial family) using the lme4 package (Bates et al., 2011) for R (R Core Team, 2019). Models converged reliably, including fixed effects for the variability condition (no variability, moderate variability, and high variability) and crossed random effects for participants and items (Baayen et al., 2008). The R code for the final statistical model was: accuracy ~ variability condition + (1 |

participants) + (1 | items). We took accuracy in the no variability condition as the intercept to which we compared the moderate and high variability conditions. We considered fixed effects estimates fitted by maximum likelihood (Laplace approximation) to be significant if p was less than .05.

Results

Figure A1 and Table A2 show the percentage of correct responses for each variability condition across tasks for Experiment 1a.

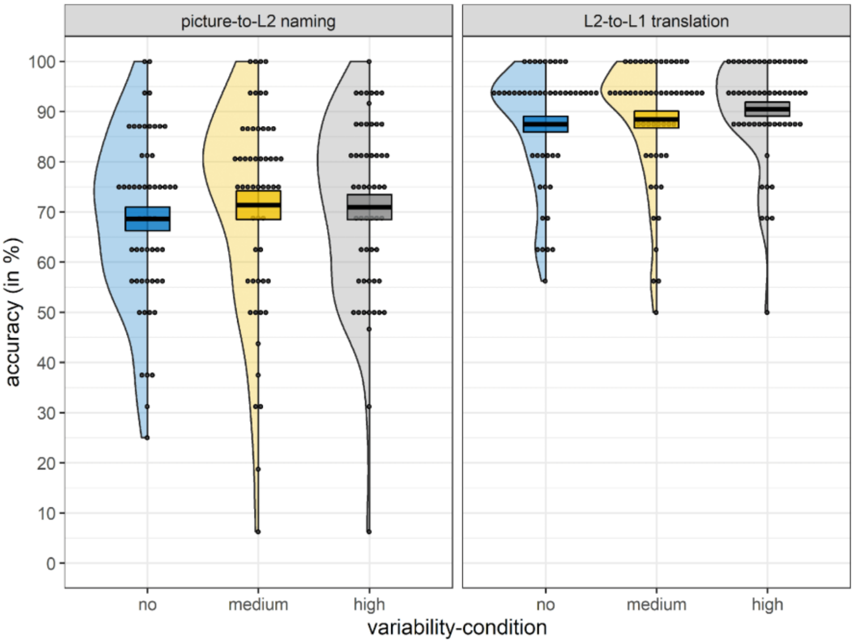

Figure A1 Percentage of correct responses in each variability condition in the two tasks for Experiment 1a. The half violin shape shows the kernel probability density of participants' mean scores. Dots indicate the percentage of correct response for each participant in each variability condition. Box plots indicate mean values and standard error.

Table A2 Descriptive statistics for percentage of correct responses in the four experiments across variability conditions and tasks

	Experiment 1a (*N* = 51)			**Experiment 1b (*n* = 39^{a})**		
	LSC test			**LSC retest**		
Variability condition	***M***	***SD***	**95% CI**	***M***	***SD***	**95% CI**
Picture-to-L2 naming task						
No variability	0.69	0.46	[0.81, 0.56]	0.35	0.48	[0.5, 0.2]
Moderate variability	0.71	0.45	[0.83, 0.59]	0.42	0.49	[0.58, 0.27]
High variability	0.71	0.45	[0.83, 0.59]	0.40	0.49	[0.55, 0.25]
Overall accuracy	0.70	0.46	[0.82, 0.58]	0.39	0.49	[0.54, 0.24]
L2-to-L1 translation task						
No variability	0.88	0.33	[0.96, 0.79]	0.77	0.42	[0.67, 0.41]
Moderate variability	0.88	0.32	[0.97, 0.8]	0.79	0.41	[0.66, 0.39]
High variability	0.91	0.29	[0.98, 0.83]	0.77	0.42	[0.65, 0.38]
Overall accuracy	0.89	0.32	[0.97, 0.8]	0.78	0.42	[0.66, 0.39]

Note. LSC = Catalan Sign Language; L2 = second language; L1 = first language.
^{a}Subsample of Experiment 1a participants.

	Experiment 2 (N = 54)			**Experiment 3 (N = 42)**		
	Pseudowords			**English words**		
Variability condition	***M***	***SD***	**95% CI**	***M***	***SD***	**95% CI**
Picture-to-L2 naming task						
No variability	0.34	0.48	[0.47, 0.22]	0.65	0.48	[0.79, 0.51]
Moderate variability	0.34	0.47	[0.46, 0.21]	0.58	0.49	[0.73, 0.43]
High variability	0.38	0.48	[0.51, 0.25]	0.66	0.48	[0.8, 0.51]
Overall accuracy	0.35	0.48	[0.48, 0.23]	0.63	0.48	[0.78, 0.48]
L2-to-L1 translation task						
No variability	0.54	0.50	[0.67, 0.41]	0.68	0.47	[0.82, 0.54]
Moderate variability	0.53	0.50	[0.66, 0.39]	0.77	0.42	[0.9, 0.64]
High variability	0.51	0.50	[0.65, 0.38]	0.75	0.43	[0.88, 0.62]
Overall accuracy	0.53	0.50	[0.66, 0.39]	0.73	0.44	[0.87, 0.6]

Picture-to-L2 naming task

The mixed-effects model for the picture-to-L2 naming task (based on 2,575 observations), Akaike information criterion (AIC) = 2,598, $R^2_{\text{marginal}} = .001$, $R^2_{\text{conditional}} = .42$, revealed no effect of variability: moderate variability, $b = 0.19$, $SE = 0.12$, 95% CI [–0.06, 0.45], $z = 1.56$, $p = 0.12$; high variability, $b = 0.16$, $SE = 0.12$, 95% CI [–0.11, 0.41], $z = 1.31$, $p = .19$. These results indicated that the number of signers had no influence on the participants’ sign recall accuracy.

L2-to-L1 translation task

The mixed-effects model for the L2-to-L1 translation task (based on 2,592 observations), AIC = 2,598, $R^2_{\text{marginal}} = .005$, $R^2_{\text{conditional}} = .46$, revealed an effect of variability. The participants more accurately retrieved words learned in the high variability condition than they did those words learned in the no variability condition, $b = 0.43$, $SE = 0.17$, 95% CI [0.09, 0.80], $z = 2.52$, $p = .01$. We found no effect in the moderate variability condition, $b = 0.14$, $SE = 0.16$, 95% CI [–0.21, 0.46], $z = 0.8$, $p = .40$.

Discussion

Our results revealed an influence of signer variability on the participants in the L2-to-L1 translation task when we compared the no variability condition to the high variability condition. We observed no differences between signs encoded in the no variability condition and in the moderate variability condition. That is, the participants benefitted from variability in the number of signers but only when the number of signers was sufficiently high. In contrast, we did not observe any benefit of signer variability in the picture-to-L2 naming task.

The absence of effects in the picture-to-L2 naming task contrasted with the results of previous studies in the oral modality showing that indexical variation positively influenced L2 vocabulary recall (e.g., Barcroft & Sommers, 2005). Relative to those studies, accuracy in the picture-to-L2 naming task in our study was noticeably high (70% in our study vs. 40% in previous studies), especially considering the number of signs to be learned (48 in our study vs. 24 in previous studies). Therefore, we reasoned that indexical variability might only benefit L2 vocabulary recall at lower levels of accuracy. That is, it is possible that variation only helps when the task is difficult enough. To further explore whether the lack of effects in the picture-to-L2 naming task was due to high accuracy levels, we tested a subset of participants (n = 40) again approximately two weeks later (M = 15 days, range = 12–18).

Experiment 1b. Retest L2 sign learning

Methods

Approximately two weeks after Experiment 1a (range = 12–18 days) had ended, a subset of 40 participants repeated the tasks from the first experiment. In terms of materials and analysis, the design of Experiment 1b was the same as that of Experiment 1a. Importantly, unlike Experiment 1a, in the retest there was no training phase, so the participants completed only the two recall tasks. We excluded the data from one participant from the picture-to-L2 naming task because the video recording was defective and we could not check his responses properly for accuracy.

Results

Picture-to-L2 naming task

The mixed-effects model for the picture-to-L2 naming task (2,592 observations), AIC = 2,598, R^2_{marginal} = .005, $R^2_{\text{conditional}}$ = .46, showed an effect of signer variability: moderate variability, b = 0.35, SE = 0.14, 95% CI [0.09, 0.60], z = 2.60, p = .01; high variability, b = 0.27, *SE* = 0.13, 95% CI [0.01, 0.53], *z* = 1.99, *p* = .05. This indicated that the number of signers influenced sign recall. The participants recalled the signs learned in the no variability condition less accurately than they did those that they had learned in the moderate variability and high variability conditions (see Figure A2 and Table A2).

L2-to-L1 translation task

The mixed-effects model for the L2-to-L1 translation task (1,920 observations), AIC = 1,643, R^2_{marginal} = .0007, $R^2_{\text{conditional}}$ = .51, revealed no effect of variability: moderate variability, *b* = 0.15, *SE* = 0.16, 95% CI [–0.18, 0.51], *z* = 0.97, *p* = .33; high variability, *b* = 0.01, *SE* = 0.16, 95% CI [–0.31, 0.36], *z* = 0.07, *p* = .94. This indicated that the number of signers had no influence on the participants' sign translations (see Figure A2 and Table A2).

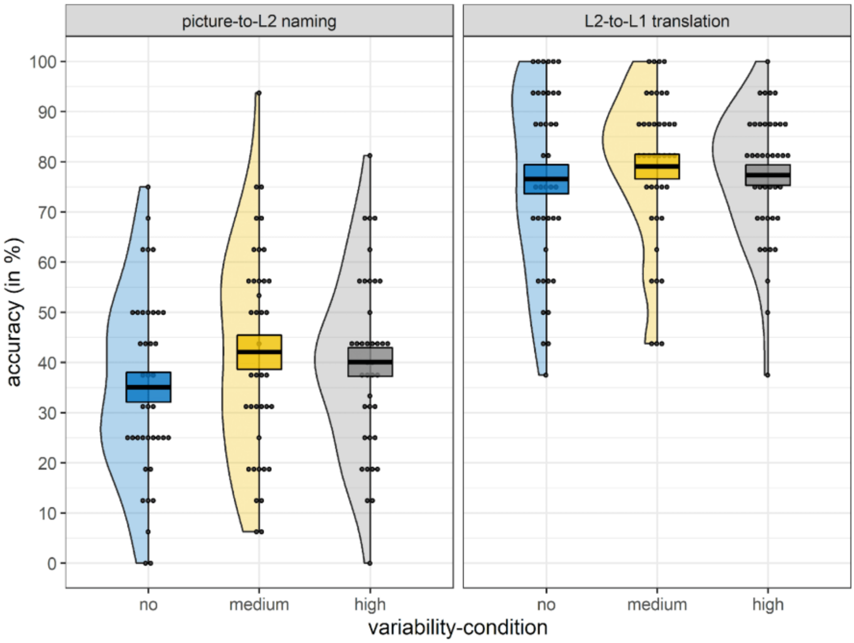

Figure A2 Percentage of correct responses for each variability condition across tasks for Experiment 1b. The half violin shape shows the kernel probability density of participants' mean scores. Dots indicate the percentage of correct responses for each participant in each variability condition. Box plots indicate mean values and standard error.

Discussion

Our results for both the test (Experiment 1a) and retest (Experiment 1b) indicated that signer variability influenced the participants' L2 sign learning. The participants learned better the signs learned in a context of multiple signers than those that they had learned from a single signer. Once again, our results partially replicated previous results in the oral modality (Barcroft, 2001; Barcroft et al., 2007; Barcroft & Sommers, 2005). In Experiment 1a, we observed the effect of variability only in the L2-to-L1 translation task and only when the number of signers was sufficiently high. In Experiment 1b, we observed the effect of signer variability only in the picture-to-L2 naming task. Both variability conditions (moderate and high) showed better accuracy than did the no variability condition.

Altogether, our results supported the notion that signs contain lexical and indexical information and that both sources of information influence learning. However, our results also showed that signer variability might not be as relevant in sign L2 learning as has been reported in the oral modality. Before we made further conclusions about differences between modalities and the influence of indexical variability on L2 learning, we conducted two experiments testing L2 learning of spoken words with L2 learners from the same population. In Experiment 2, the participants learned words from an invented language, that is, pseudowords, and we manipulated acoustic variability in the number of speakers. In Experiment 3, the participants learned new words in English, their L2, and we manipulated acoustic variability in the number of speakers.

Experiment 2: Learning words from an invented language

Methods

Participants

We recruited 54 bilingual Catalan–Spanish speakers (38 females, M_{age} = 21 years, range = 18–34) from the Universitat Pompeu Fabra’s Center for Brain and Cognition database. None of them had participated in the previous experiment learning LSC signs.

Materials

We used the same set of 48 pictures used in Experiments 1a and 1b for this experiment. In this case, we matched pictures with words from an invented language (i.e., pseudowords) instead of with LSC signs (see Table A3). We generated pseudowords based on Spanish subsyllabic elements with the Wuggy pseudoword generator (Keuleers & Brysbaert, 2010). We formed target items by combining the objects' corresponding real names that varied in length from one to four syllables (*M* = 2.72 syllables). Fifteen native Spanish speakers (eight females, seven males) recorded the pseudowords in a soundproof room using the audio recording and editing software Audacity. We asked the speakers to record target pseudowords in a neutral voice type. We constructed stimulus lists following the same criteria as in Experiment 1, that is, the list for the training phase included the rotation of speakers used in the no variability and moderate variability conditions, which resulted in 54 experimental lists.

Table A3 Groups of pseudoword stimuli used for the three different conditions of variability in Experiment 2

Pseudoword set	**Stimuli**
Set 1	cecefo (*windmill*), minón (*firefighter)*, ina (*mailbox*), pemalero (*moneybox*), anlecalora (*sheep*), rufeso (*garlic*), arpel (*onion*), oraka (*sock*), salana (*camel*), vansusta (*cherry*), tisbilla (*ant*), hosmurcue (*kiwi*), nafleta (*lettuce*), jibi (*cucumber*), leta (*pear*), beceserca (*lemon*)
Set 2	vetruza (*spider*), tisbero (*tree*), suntilla (*folder*), ócemo (*hoover*), médano (*eggplant*), ricuento (*boot*), aliza (*strawberry*), cacebla (*melon*), percel (*pea*), lepón (*hamburguer*), morba (*cookie*), sama (*deer*), cunvo (*lobster*), edo (*shark*), angrebador (*olive*), harniza (*grape*)
Set 3	nívuton (*tiger*), mecosar (*frog*), sorano (*potato*), cerocho (*pill*), faumante (*doll*), acefo (*peach*), cardetus (*bee*), mafralo (*asparagus*), lufón (*light bulb*), jobro (*pineapple*), crena (*lizard*), sible (*nun*), gubra (*fox*), sira (*pepper*), vavecoa (*brush*), miza (*watering can*)

Note. English words referred to the pictures assigned to each pseudoword are reported in parentheses.

Procedure

As in our previous experiment, we tested the participants individually and online. The design of the experimental variability conditions was the same as for Experiments 1a and 1b. The sequence and procedure of the tasks (learning phase and test phase) were, with some exceptions, the same as in Experiment 1a. First, the participants were told that they had to memorize words from a new language. Second, stimuli (pseudowords) were presented in their auditory form. Third, in the test phase, the participants were presented with a combination of nine speakers who were different from those speakers used in the learning phase. The trial structure of the two tasks was the same as in

Experiment 1a with one exception. In the L2-to-L1 translation task, the participants listened to a L2 word and translated it into their L1.

Data analysis

As in Experiments 1a and 1b, we binary coded the data (correct/incorrect) in the picture-to-L2 naming task and the L2-to-L1 translation task after the experiment. In the picture-to-L2 naming task, to maintain the same exclusion criteria adopted for the experiments on sign learning, we considered responses correct only if the participants produced all the phonemes of the pseudoword correctly. Likewise, we considered as correct responses trials in which the participants provided a different but acceptable word for the chosen picture (e.g., participants named a picture of a doll as “doll” or “baby”). We considered other responses, including mispronunciations, intrusions (naming the picture in another language), and no responses, as incorrect responses. For the L2-to-L1 translation task, we considered incorrect responses or trials in which the participants did not respond to be errors. As in Experiments 1a and 1b, we analyzed accuracy with generalized mixed models, including fixed effects for the variability condition (no variability, moderate variability, and high variability) and crossed random effects for participants and items. The R code for the final statistical model was: accuracy ~ variability condition + (1 | participants) + (1 | items).

Results

Picture-to-L2 naming task

The mixed-effects model for the picture-to-L2 naming task (2,592 observations), AIC = 2,580, R^2_{marginal} = .002, $R^2_{\text{conditional}}$ = .52, revealed no effect of variability: moderate variability, *b* = –0.04, *SE* = 0.13, 95% CI [–0.01, 0.49], *z* = –0.30, *p* = .76; high variability, *b* = 0.23, *SE* = 0.13, 95% CI [–0.28, 0.19], *z* = 1.87, *p* = .06, with only a trend for participants' recalling pseudowords learned in the high variability condition more accurately than those pseudowords that they learned in the no variability condition (see Figure A3 and Table A2).

L2-to-L1 translation task

The mixed-effects model for the L2-to-L1 translation task (2,592 observations), AIC = 2,928, R^2_{marginal} = .0007, $R^2_{\text{conditional}}$ = 0.43, also revealed no effect of variability: moderate variability, *b* = –0.07, *SE* = 0.12, 95% CI [–0.31, 0.16], *z* = –0.63, *p* = .53; high variability, *b* = –0.16, *SE* = 0.12, 95% CI [–0.39, 0.07], *z* = –1.40, *p* = .16. This indicated that the number of speakers had no influence when the participants translated pseudowords into their L1.

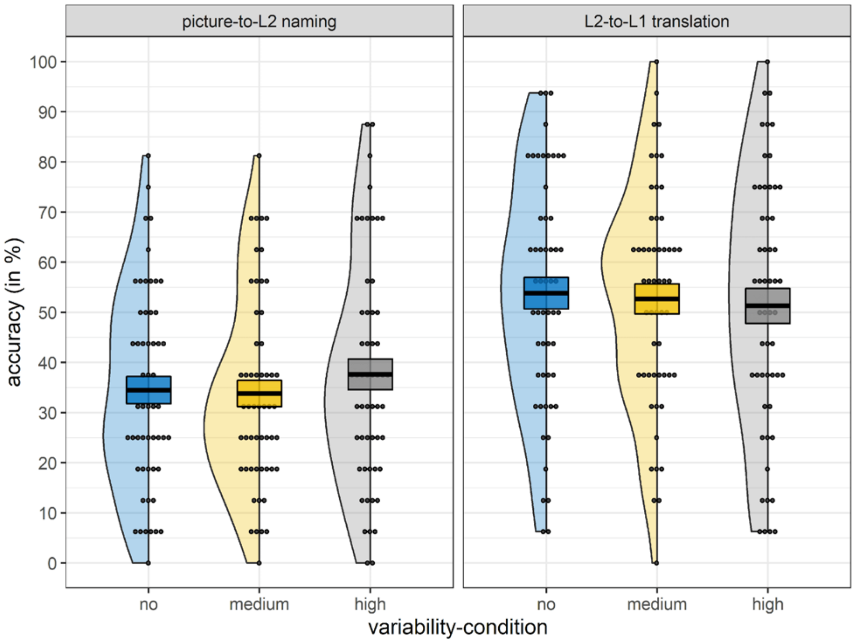

Figure A3 Percentage of correct responses for each variability condition across tasks for Experiment 2. The half violin shape shows the kernel probability density of participants' mean scores. Dots indicate the percentage of correct responses for each participant in each variability condition. Box plots indicate mean values and standard error.

Discussion

The results from Experiment 2 showed no differences between variability conditions. That is, the participants' learning rate was not modulated by variation in the number of speakers. Even though we evaluated speaker variability in the oral modality, our results were at odds with previous results in the literature on spoken language that has revealed a systematic increase in L2 recall accuracy with an increased number of speakers (e.g., Barcroft & Sommers, 2005; Barcroft & Sommers, 2014). Differences in learning outcomes between our studies could not be attributed to methodological differences, considering the rotation procedure across conditions (see

Barcroft, 2001, for no effect of variability when a rotation procedure was not applied). In our study, following Barcroft and Sommers (2005), we rotated different speakers across conditions.

However, we must acknowledge other relevant differences between the studies. First, the number of words to be learned was twice as high in our experiment as it was in previous studies. Most of the previous experiments tested 24 items (Barcroft & Sommers, 2005), and here we used 48 items. This might have reduced the learning rate, which could have obscured the effect of variability. However, in Experiment 1b, we observed that variability influenced learning outcomes in the picture naming task only when accuracy rates were reduced in delayed recall. Second, in our experiment, the stimuli were pseudowords that we had generated from Spanish phonemes/syllables, Spanish being one of the participants' two native languages, as e tested bilingual Catalan–Spanish speakers. In that sense, Experiment 2 may not have matched the conditions of learning vocabulary in an unknown language but may have required the participants to acquire new Spanish words for existing concepts. To our knowledge, only Runge et al. (2017) tested speaker variability in L1 recall and obtained no evidence for it. However, Runge et al. interpreted their findings as the result of task difficulty—because words were paired with written definitions—rather than an effect of testing L1 words.

Given these experimental differences in number of items and in word status (i.e., pseudowords generated from a language in which the participants were proficient instead of being unknown L2 words), we conducted a new experiment in which we brought our design as close as possible to that of Barcroft and Sommers (2005). To achieve this, we reduced the number of items for the participants to learn and used words in the L2 of our participants, that is, English.

Experiment 3: L2 (English) words

Methods

Participants

We recruited 42 participants (31 females, 11 males; M_{age} 22.30 years, range = 18–40) from the Universitat Pompeu Fabra’s Center for Brain and Cognition database. None of them had participated in the two previous experiments. All of them were bilingual Catalan–Spanish speakers who had learned English as their L2 and had a B1 level of English according to the Common European Framework of Reference for Languages, corresponding to intermediate proficiency, the minimum level required to undertake undergraduate studies in Spain.

Materials

We divided a set of 24 English words into three groups (see Table A4) and selected related pictures for them for the experiment. The words were concrete nouns from different semantic categories (animals, fruits, vegetables, tools, and vehicles) that we selectively chose to avoid the use of Catalan/Spanish–English cognates. To avoid words that the participants already knew, we chose words that the CELEX database (Baayen et al., 1995) classifies as low-frequency (*M* = 3.45, *SD* = 4.26). The words ranged in number of syllables from one to three (*M* = 1.71), but we controlled this across word sets. We confirmed the appropriateness of the set of selected words by presenting these words and their corresponding pictures to a different group of Catalan–Spanish bilingual participants. Eight speakers recorded the words in a soundproof room using the Audacity software. We used six speakers for the learning phase (three females, three males), whereas we used the remaining two speakers (one female, one male) for the testing phase to ensure the use of novel voices that were the same for all participants. The speakers were all native speakers of American English. The experimental design followed the same rotation procedure as in Experiments 1a, 1b, and 2, that is, we counterbalanced each word set across variability conditions. This yielded six subvariations to rotate speakers' identity in the no variability and moderate variability conditions (Barcroft & Sommers, 2005).

Table A4 Groups of English word stimuli used for the three conditions of variability in Experiment 3

Word set	Stimuli
Set 1	rake, pickle, whip, thimble, crib, sideburns, acorn, gown
Set 2	chalk, owl, elbow, faucet, crutch, muffler, skunk, dreadlock
Set 3	funnel, sling, apricot, peacock, stapler, plunger, clover, crane

Procedure

We tested the participants individually in a soundproof cabin in front of the computer. We randomly assigned the list used for each participant. We executed the stimuli presentation in the learning phase through the E-Prime (Version 2.0) software (https://pstnet.com/products/e-prime). We used the DMDX display system (Forster & Forster, 2003) in the testing phase, and we subsequently checked responses with the CheckVocal software (Protopapas, 2007). Prior to beginning the experiment, we presented the list of pictures to the participants and asked them to state the word in English if they knew it. For each participant, we noted preknown words and excluded them from the analysis (1.8% of the data on average).

The procedure of the experimental session was as follows. In the learning phase, the participants saw an asterisk on the screen for 500 ms, and then they were presented a picture for 4,250 ms. This picture was accompanied by an audio recording of the word that the picture represented 750 ms after the onset of the picture presentation. Finally, the participants saw a blank screen for 500 ms. After the learning phase, we first administered the picture-to-L2 naming task to avoid the participants’ hearing the L2 words before the pictures had been named. In the picture-to-L2 naming task, we presented the participants with pictures, and they had to provide the corresponding English names. An experimental trial comprised first an asterisk that was present 500 ms in the screen, then a blank of 300 ms, followed by the picture presentation that remained on the screen for a maximum of 10,000 ms. In the L2-to-L1 translation task, the participants heard the English word that they had to translate into Spanish. A fixation asterisk was presented for 500 ms, then a blank of 300 ms, followed by the auditory presentation of the word in English. When the word finished, a blank screen appeared for a maximum of 10,000 ms.

Data analysis

As in Experiments 1a, 1b, and 2, we binary coded the data (correct/incorrect) in both the picture-to-L2 naming task and the L2-to-L1 translation task after the experiment. In the picture-to-L2 naming task, we considered responses correct only if the participants produced all the phonemes of the English word correctly or had only one incorrect phoneme in a single syllable. We considered other responses, including mispronunciations, intrusions, synonymous, and no responses, as incorrect responses. For the L2-to-L1 translation task, we excluded from the analysis incorrect responses or trials in which the participants did not respond. As in the previous experiments, we analyzed accuracy with generalized mixed models, including fixed effects for variability conditions (no variability, moderate variability, and high variability) and crossed random effects for participants and items. The R code for the final statistical model was: accuracy ~ variability condition + (1 | participants) + (1 | items).

Results

Figure A4 and Table A2 show the percentage of correct responses for each variability condition across tasks.

Picture-to-L2 naming task

The mixed-effects model for the picture-to-L2 naming task (895 observations), AIC = 1,068, $R^2_{\text{marginal}} = .006$, $R^2_{\text{conditional}} = .32$, revealed no effect of variability: moderate variability, $b = -0.32$, $SE = 0.19$, 95% CI [–0.76, 0.09], $z = -1.67$, $p = .10$; high variability, $b = 0.09$, $SE = 0.19$, 95% CI [–0.32, 0.52], $z = 0.47$, $p = .64$. This showed that the number of speakers had no influence on the recall of new English (L2) words[7].

L2-to-L1 translation task

The mixed-effects model for the L2-to-L1 translation task (895 observations), AIC = 955, $R^2_{\text{marginal}} = .012$, $R^2_{\text{conditional}} = .30$, revealed an effect of variability: moderate variability, $b = 0.57$, $SE = 0.20$, 95% CI [0.18, 0.98], $z = 2.80$, $p = .005$; high variability, $b = 0.41$, $SE = 0.20$, 95% CI [0.01, 0.83], $z = 2.03$, $p = .04$. The participants more accurately translated English L2 words that they had learned in the

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[7] We also analyzed learning outcomes following the scoring procedure (0, 0.5, ^{1} points) of Barcroft and Sommers (2005), giving partial credit to productions that were missing or used one incorrect phoneme within a single syllable. The results revealed the same pattern of no effect of variability that we had observed with binary scoring (0, 1): moderate variability, $b = 0.01$, $SE = 0.03$, 95% CI [–0.05, 0.07], $t = 0.56$, $p = .57$; high variability, $b = 0.04$, $SE = 0.03$, 95% CI [–0.02, 0.11], $t = 1.60$, $p = 0.11$.

moderate and high variability conditions than they did those English L2 words that they had learned in the no variability condition.

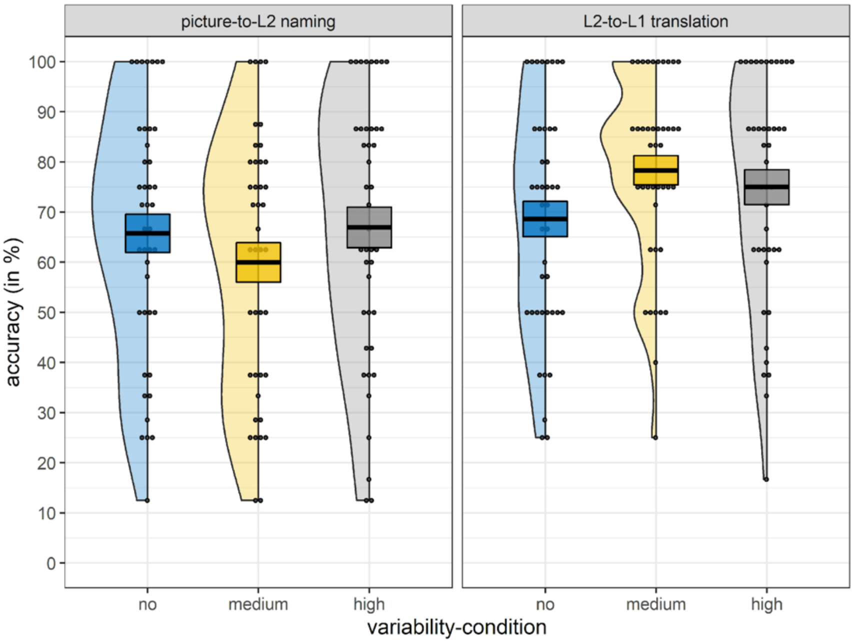

Figure A4 Percentage of correct responses for each variability condition across tasks for Experiment 3. The half violin shape shows the kernel probability density of participants' mean scores. Dots indicate the percentage of correct responses for each participant in each variability condition. Box plots indicate mean values and standard error.

Discussion

The results of this experiment revealed an effect of speaker variability limited to the L2-to-L1 translation task. In this task, the participants more accurately translated words from their English L2 to their Spanish L1 for words encoded in moderate and high speaker variability contexts than for words encoded without such variability. In the picture-to-L2 naming task, we did not observe the positive effect of variability that we had found in the translation task. The absence of indexical variation effects in the picture-to-L2 naming task differed once again from the results of previous studies in L2 spoken vocabulary learning (e.g., Barcroft & Sommers, 2005). Even though we intended the design of Experiment 3 to be a close replication of the Barcroft and Sommers (2005) experiment, one difference between the studies was notable. The participants in our study had preexisting knowledge of English as a L2 when they performed the task. That is, unlike the participants in the Barcroft and Sommers (2005) study, our participants were learning new words in a familiar language. However, it is unlikely that preexisting knowledge of the L2 was responsible for the differences between the studies considering the results of Experiments 1a and 1b. The participants had no preexisting knowledge of LSC, and we found an effect of indexical variability in the translation task but not in the picture naming task. In any case, what seemed clear was that the influence of variability in L2 learning was not determined by the modality in which L2 vocabulary was acquired (i.e., signs vs. spoken words). Thus, an explanation for the pattern of results obtained should include both modalities.

General discussion

The reason for our study was to investigate the influence of signer variability on L2 sign learning. This was based on observation in the oral modality that indexical variability in the number of speakers boosts L2 vocabulary learning in adults (e.g., Barcroft & Sommers, 2005). These results were important in revealing that linguistic and nonlinguistic (indexical) information are codified in parallel in speech processing and that nonlinguistic variation enhances encoding of lexical representations in a new language (Goldinger, 1998). The extrapolation of this phenomenon to the signed modality was our main objective. In an attempt to determine whether nonlinguistic information is encoded from signs (as in speech) and influences memory and L2 learning, we evaluated the impact of signer variability on L2 sign learning in adults. Overall, our results indicated that indexical information is encoded along with linguistic information from signs (phonological parameters, meaning) and influences the learning of signs. The participants more accurately recalled L2 signs from memory when they had encoded the L2 signs from multiple signers than when they had encoded them from one signer. The effect of variability remained for days, as revealed in Experiment 1b, which involved posttesting, when the participants had not trained with the materials but performed only the two recall tasks.

The results on indexical variation in L2 sign learning only partially replicated previous reports in the oral modality (Barcroft & Sommers, 2005; Sinkeviciute et al., 2019; Sommers & Barcroft, 2007, 2011). First, we did not consistently obtain the effect of variability in the two recall tasks that we employed. In Experiment 1a, we obtained a positive effect of variability in the L2-to-L1 translation task but not in the picture-to-L2 naming task. Conversely, in Experiment 1b, the retest, we observed the effect of variability in the picture-to-L2 naming task but not in the L2-to-L1 translation task. Researchers have often interpreted null effects of speaker variability on L2 learning as a ceiling effect (i.e., task too easy; Sinkeviciute et al., 2019; Uchihara et al., 2021) or a floor effect (i.e., task too difficult; Runge, 2018) in overall performance. As we have described, numerically, accuracy in the picture-to-L2 naming task of Experiment 1a was far better than has previously been reported in L2 oral languages (e.g., Barcroft & Sommers, 2005, 2014). Thus, we interpreted our results in Experiment 1a as a ceiling effect that could have affected the variability effect in the picture-to-L2 naming task. Indeed, in Experiment 1b, accuracy in the picture-to-L2 naming was notably reduced (0.70 vs. 0.39, see Table A2), and signer variability facilitated retrieval. Although relatively high accuracy is a variable that could mask the benefits of indexical variation, it noticeably does not entirely fit with the results of the L2-to-L1 translation task. Between Experiments 1a and 1b, accuracy was only slightly reduced (0.89 vs. 0.79), but variability only influenced recall in the L2-to-L1 translation task in Experiment 1a. Second, we did not observe a systematic increase in accuracy with variability. In the L2-to-L1 translation task, we observed a significant difference only when the variation was sufficiently high (six signers vs. one signer). The lack of variability effects in the moderate variability condition has been interpreted as insufficient variation for the L2 form–meaning connections to be established (Rott, 1999; van Zeeland & Schmitt, 2013). Once again, this explanation does not fully apply to our data since, in the picture-to-L2 naming task in Experiment 1b, both variation conditions benefitted production, and if anything, the effect was larger in the moderate variability condition (7% gain) than in the high variability condition (5% gain).

In sum, our data generally support the idea that multiple signers benefit L2 vocabulary learning. However, they also suggest that other undescribed variables related to the learner, such as movement and/or visuospatial short-term memory (Martinez & Singleton, 2018) or phonological short-term memory (Martinez & Singleton, 2019), to the items to be learned (e.g., L1 or L2 items, number of items), and to the tasks employed, such as the use of novel words associated with pictures or definitions (Runge, 2018), are interwoven with signed variation in the process of L2 memory encoding, which influences the learning outcomes. Importantly, as our data show, the modality of the language to be learned (sign/oral) does not seem to interact with variation in L2 learning.

The results from Experiments 2 and 3 also suggest some limitations in the effects of speaker variation on L2 learning. When we tested pseudowords in Experiment 2, we observed no variability effects in any of the recall tasks. At first, we hypothesized that the absence of variability could be due to the fact that we were not evaluating L2 vocabulary learning but rather learning new words from a language in which the participants were very proficient. Pseudowords were constructed following the phonology and morphology of Spanish, a language in which the participants had a native or nativelike proficiency. Thus, even though the participants had been told that their task was to learn words in an invented language, it is possible that the participants treated the pseudowords as new L1 Spanish words. However, considering previous evidence from L1 studies, one would expect a negative influence of variability, similar to negative effects reported in L1 processing (Choi et al., 2018; Magnuson et al., 2021; Martin et al., 1989). Thus, a more plausible explanation for the null effect of variability when our participants were learning pseudowords relates to the low accuracy reached in the experiment (0.35 in the picture-to-L2 naming task and 0.51 in the L2-to-L1 translation task). For instance, no benefits for speaker variability were found when participants learned novel L1 words or L2 words via written definitions (Runge et al., 2017) or embedded in written/auditory sentences (Runge, 2018). Runge et al. (2017) suggested that accessing a word’s meaning through a multiword description or definition entailed increased difficulty and increased demands on working memory, and this cancelled out variability effects. In line with this observation, the low accuracy rates that we observed in Experiment 2 might have indicated greater working memory demands that learning a large number of new words entails, thus limiting resources to encode indexical variation that benefits later memory and learning.

Experiment 3 was the closest replication of Barcroft and Sommers (2005). However, the results did not fully replicate the benefit of multiple speakers on L2 vocabulary learning. Here, we observed a variability effect in the L2-to-L1 translation task but not in the picture-to-L2 naming task. These results replicated those obtained in Experiment 1a, which revealed a benefit of multiple signers/speakers in the L2-to-L1 translation task but not in the picture-to-L2 naming task. Only when we tested L2 vocabulary a second time (signs in Experiment 1b), did multiple signers benefit in the picture-to-L2 naming task. To account for the results in both modalities, we built upon Jiang's (2000) psycholinguistic model of adult L2 vocabulary learning. According to this model, L2 lexical learning undergoes at least two stages. In an initial stage, new L2 words are mapped to their L1 translations and not directly to meaning. Therefore, each time a L2 word is encountered, its L1 translation is activated, and meaning is only accessed through L1 activation. As suggested, during this initial stage, L2 learners experience more difficulties in retrieving L2 word/sign forms than they do in retrieving meanings (e.g., Ortega & Morgan, 2015; VanPatten, 1990). As experience in L2 increases, L2 words rely less on L1 translations to access meaning, and direct mappings between L2 forms and meaning are created (see also de Groot, 1992; Kroll & Stewart, 1994).

In our experiments, we exposed the participants to a set of new L2 signs/words that they had never seen before. After a few minutes of exposure to new vocabulary, it is likely that sign forms/acoustic representations were still fragile, in the sense that they entailed fuzzy lexical representations (Gor et al., 2021), leaving the participants with limited resources for establishing direct L2 form–meaning mappings (Barcroft, 2015). This imprecise encoding of L2 forms would explain the differences found in the influence of indexical variability between the picture naming task, a task requiring production in L2 of the learners, and the translation task, a task requiring production in L1. As shown by Kroll and Stewart (1994), the picture-to-L2 naming task and the L2-to-L1 translation task differ in the degree to which form-to-meaning mappings are emphasized in the task. While the picture-to-L2 naming task is conceptually mediated, the L2-to-L1 translation task relies on lexical links between the two languages. In this context, if the L2-to-L1 translation task relies on lexical links between the two languages, then it could be a more sensitive task for detecting the effects of variability at the initial stages when a word or a sign is learned.

Within this framework, accounting for the results obtained at retest in the picture-to-L2 naming task (Experiment 1b) would necessarily require assuming that between test and retest, the L2 form–meaning mappings were sufficiently strengthened to reveal effects of variability in the picture-to-L2 naming task. Perhaps, because of memory consolidation, novel L2 sign meanings might have been sufficiently integrated in the semantic system. This would result in more sensitivity to signer variation in the task tapping into semantics. Several studies have provided evidence that offline consolidation and sleep facilitates novel word integration (Davis et al., 2009; Dumay & Gaskell, 2007; Gaskell & Dumay, 2003; Tamminen & Gaskell, 2013). For instance, Tamminen and Gaskell (2013) reported that, despite the recall rate's declining over time, priming effects as an index of integration into the lexicon increased over time of consolidation (see also Clay et al., 2007). In this realm, our results in Experiment 1 might indicate that from test to retest, L2 signs benefitted from time for being integrated into the semantic system despite a decline in the overall recall performance. Although this is an interesting possibility, it requires further work to elucidate the effect of offline consolidation on L2 learning and its interaction with indexical variation.

Limitations and future directions

The results of our study across experiments and tasks are not fully consistent with previous studies on the influence of indexical variation on L2 vocabulary learning, which makes it difficult to develop a theoretical framework that encompasses present and past results. We did not design our experiments to be full replications of previous experiments but to cover broad aspects of L2 vocabulary learning so as to draw common lines between studies. In doing so, some methodological differences were warranted (languages of learners, number of items) that could have influenced the pattern of results observed within our experiments and between our research and previous studies. Likewise, other learner-related variables might have impacted achievement in L2 vocabulary learning (Martinez & Singleton, 2019). As an example, Perrachione et al. (2011) reported that individual differences in pitch perception influenced whether participants benefitted from high variability training of phonological contrasts. Thus, individual differences in sign/word perception might have modulated the extent to which our participants benefitted from high variability training.

Further experiments considering methodological and individual differences are needed to provide a better understanding of the strength of the indexical variability effect or the aspects that may influence it. For methodological differences, experiments that replicate the same design where only the variable of interest (e.g., number of items) is changed would be useful for establishing direct comparisons. To explore individual differences, accuracy scores related to indexical variability could be correlated with cognitive measures that influence sign language learning. Variables such as movement short-term memory and visuospatial short-term memory (Martinez & Singleton, 2018) and fluid intelligence and sign phonological short-term memory (Martinez & Singleton, 2019) have been reported as contributing to sign learning. Thus, it is possible that effects of indexical variation interact at individual level with these variables.

Conclusion

Our results provide evidence that signs and words are composed of lexical and indexical information. Both sources of information interact during processing and memorization. In a series of experiments, we showed that indexical variation in the number of signers is a relevant cue that influences L2 sign learning in adults. In terms of sign language teaching practices, our study addressed a question appropriate for effective L2 vocabulary instruction: Is it beneficial to use different signers when new signs are presented? Overall, our data suggest that learners benefit from seeing multiple signers when they learn signs. With a closer look at the results, we did not observe a robust benefit of signer variability across experiments and tasks. Thus, we remain cautious about drawing strong conclusions and giving pedagogical suggestions at this point. Finally, our results indicate some limitations of the positive effect of variability on learning pseudowords and L2 words and suggest that variability effects might interact with L2 lexical development.

Acknowledgements

This work was supported by the Spanish Ministry of Science and Innovation (RTI2018-096238-A-I00) and the ACELERA research network (RED2018-102615-T). Cristina Baus was supported by the Ramon y Cajal research program (RYC2018-026174-I). We thank Veronica Bernardini for her assistance in Experiment 3.

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