# Lexical Access in Bimodal Bilinguals

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# Resumen

La capacidad humana para el lenguaje se puede concretar tanto en forma de lengua oral como de lengua signada. Ambos tipos de lenguas presentan los mismos niveles de análisis lingüístico: fonológico, morfológico, sintáctico y semántico. Sin embargo, la modalidad de cada una de estas lenguas condiciona su organización. La modalidad auditiva-oral favorece que los fonemas de las lenguas orales se perciban de forma secuencial, uno después de otro, siguiendo el mismo orden temporal en el que se emiten. En cambio, la modalidad visual-gestual permite que distintas unidades sub-léxicas de la lengua de signos estén presentes casi simultáneamente al articular un signo.

Los modelos fonológicos de las lenguas signadas describen tres unidades sub-léxicas principales en los signos: localización, configuración manual y movimiento. Estos modelos abordan también la simultaneidad y secuencialidad en estas lenguas. La simultaneidad se concentra en la localización y en la configuración manual, ya que son componentes del signo que permanecen estables durante su realización. En cambio, la secuencialidad recae principalmente en el movimiento del signo.

Estudios previos indican que la localización y la configuración impactan en el procesamiento de los signos. Sin embargo, por un lado, los experimentos realizados han agrupado unidades sub-léxicas (por ejemplo, estudiando signos que compartían tanto localización como movimiento, o que compartían tanto movimiento como configuración) y, por otro, sus resultados son tan dispares que aún no está claro el papel de cada unidad de forma aislada. Uno de los fines de este estudio es, por tanto, esclarecer el papel diferenciado que localización y configuración desempeñan de forma independiente en el procesamiento de la lengua de signos.

Una población ideal en la que investigar el procesamiento de la lengua oral y de la lengua de signos es la de personas oyentes competentes en estos dos tipos de lengua, es decir, bilingües bimodales oyentes. Algunas de estas bilingües bimodales son hijas de padres sordos signantes y son, por tanto, nativas expuestas desde el nacimiento a la lengua de signos. Otras bilingües aprenden la lengua de signos como una segunda lengua (L2) en la edad adulta para, por ejemplo, trabajar como intérpretes. La edad de adquisición de la lengua de signos afecta su procesamiento. Las personas que aprenden tarde la lengua de signos experimentan más dificultades que las nativas al procesar las unidades sub-léxicas, especialmente la configuración manual. En este estudio investigamos el acceso

al léxico oral y signado tanto en signantes nativas como en signantes que han aprendido la lengua de signos como L2.

El objetivo del presente trabajo ha sido investigar la coactivación de las unidades sub-léxicas de forma aislada, no agrupada, es decir, entre signos de la lengua de signos española (LSE) que compartían o bien su localización o bien su configuración. En concreto, estudiamos el rol de la localización y la configuración en dos contextos. Uno, en un contexto intra-modal e intra-linguístico en el que el signo se presenta de forma explícita. Otro, en un contexto inter-modal e inter-lingüístico en el que el signo se activa en paralelo de forma encubierta, puesto que lo que se presenta de forma explícita es una palabra oral del castellano. El estudio se ha completado con los mismos contextos en el entorno de la coactivación del castellano: un contexto intra-modal e intra-lingüístico en el que la palabra oral se presenta de forma explícita y se investiga la coactivación de la sílaba inicial de la palabra y de su rima; y otro contexto inter-modal e inter-lingüístico en el que se presenta un signo y se estudia la activación en paralelo de la lengua oral a través de la coactivación del inicio y la rima de palabras del castellano.

Para estudiar la coactivación, tanto explícita como encubierta de lengua oral y de lengua de signos, observamos los movimientos oculares usando el paradigma del mundo visual. Cada experimento se compuso de una serie de presentaciones. En cada presentación los participantes escucharon una palabra, o vieron un signo en el centro de una pantalla, según el caso, y buscaron la imagen correspondiente entre cuatro dibujos en la pantalla, teniendo que pulsar el botón adecuado en función de dónde estaba la imagen (en alguna de las esquinas de la pantalla). En muchas presentaciones no había una imagen para la palabra o signo, por lo que no había que pulsar ningún botón. En estos casos aparecían otros dibujos que se correspondían con palabras o signos que compartían alguna parte con la palabra escuchada o el signo visto (es decir, competidores). Cuando se buscaba coactivación del castellano, un competidor era de inicio de palabra y otro de rima. Cuando, en cambio, se esperaba coactivación de la LSE, un competidor era de localización y otro de configuración. Los otros dos dibujos de cada presentación eran meros distractores. En nuestro estudio hemos analizado las presentaciones en las que aparecieron los competidores (y no había imagen correspondiente de la palabra o signo percibido) para comprobar si esos competidores habían sido coactivados o no y, en el caso de haberlo sido, estudiar la magnitud del efecto de coactivación y su evolución en el tiempo que duraba la presentación. Para ello, examinamos los resultados realizando *growth curve analysis*, un tipo de análisis que compara las curvas que obtenemos con los datos del desarrollo temporal de las miradas a cada una de las imágenes de las presentaciones. Así, sabemos a qué imagen se está mirando en cada momento (medido en milisegundos) y cómo varía el comportamiento de la mirada para cada imagen a lo largo de cada presentación.

La primera tanda de experimentos de nuestro estudio se centró en la coactivación del castellano y de la lengua de signos española (LSE) en contextos intra-lingüísticos. Es decir, la coactivación de una lengua desde esa misma lengua. Estos experimentos los realizaron dos grupos de bilingües bimodales: un grupo de 28 oyentes nativos en LSE y otro grupo de 28 oyentes que aprendieron la LSE como L2.

En el experimento 1.a investigamos la coactivación fonológica en castellano de palabras que comparten el mismo inicio o la misma rima. Por ejemplo, en las presentaciones de interés, escuchaban la palabra **estrella** y veían el dibujo de una espada (**estrella** y **espada** comienzan por 'es') y el dibujo de una botella (**estrella** y **botella** riman). Como todos nuestros participantes eran nativos en castellano y no había razones para esperar comportamientos diferentes en el procesamiento de la lengua oral, el experimento 1.a lo realizaron todos los bilingües bimodales formando un único grupo de 56 personas. Los resultados de este experimento en castellano confirmaron que la competencia del inicio de palabra aparece antes y es más prominente que la competencia de rima (tal y como han establecido estudios anteriores con otras lenguas orales). Este resultado refleja la dinámica de la señal hablada, que se produce y percibe secuencialmente a medida que los fonemas van apareciendo sucesivamente.

En el experimento 1.b investigamos la coactivacion entre signos que compartían o bien la misma localización o bien la misma configuración. En las presentaciones de interés veían, por ejemplo, el signo de **PAYASO**, y un dibujo competidor era el de un pie (los signos de **PAYASO** y **PIE** comparten localización, se articulan en la nariz), y otro era el de un grifo (**PAYASO** y **GRIFO** se articulan con la mano en puño). Los resultados de este experimento fueron diferentes entre los dos grupos de bilingües bimodales. Los nativos en LSE mostraron coactivación de localización y configuración, siendo la coactivación de configuración mayor y posterior que la de localización. Los oyentes que aprendieron LSE como una L2 también mostraron coactivación de ambas unidades sub-léxicas, aunque en este caso la coactivación de localización y configuración fue similar en tamaño y tiempo. Comparado con los signantes nativos, los que aprendieron LSE como L2 mostraron una coactivación más tardía de localización y otra más débil de configuración.

La siguiente tanda de experimentos se produjo en contextos inter-lingüísticos. Dos experimentos, el 2.a y el 2.c, los realizaron dos grupos de bilingües bimodales oyentes: un grupo de 28 signantes nativos y un grupo de 28 signantes que aprendieron la LSE como L2. En el experimento 2.a la lengua que vieron los participantes era la LSE, pero esta vez se esperaba coactivación encubierta del castellano, es decir, que los competidores se correspondían con imágenes que compartían o su inicio o su rima con la traducción al castellano del signo que habían visto (por ejemplo, vieron el signo de **ESTRELLA** y los competidores fueron las palabras del castellano **espada** y **botella**). Los resultados de este experimento no fueron diferentes entre los dos grupos de bilingües bimodales y ambos mostraron activación paralela del castellano al ver signos a través de la coactivación del inicio de la palabra (**ESTRELLA** coactivó **espada,** pero no **botella**).

En el experimento 2.c, el cruce de lenguas iba en la otra dirección. Los bilingües bimodales escuchaban palabras del castellano mientras que una de las imágenes competidoras compartía la localización con la traducción a LSE de la palabra escuchada y otra imagen compartía la configuración (por ejemplo, oyeron la palabra **pie** y los competidores eran los signos de **PAYASO** y **GRIFO**). De nuevo no hubo diferencias en los resultados de los dos grupos. Los bilingües bimodales mostraron activación paralela de la LSE al oír palabras del castellano a través de la coactivación secuencial de, primero, la localización y, después, la configuración manual (**pie** coactivó antes **PAYASO** que **GRIFO**).

Con el fin de comparar la activación paralela del castellano desde una lengua signada (experimento 2.a) con la activación paralela desde otra lengua oral, un grupo de 33 bilingües equilibrados en dos lenguas orales (castellano y euskera) adquiridas en la infancia, sin conocimiento de LSE, hicieron también un experimento. Se trata, por tanto, de bilingües unimodales (sus dos lenguas orales comparten la misma modalidad). En este caso oyeron palabras del euskera y los competidores eran de inicio y de rima de la traducción al castellano de las palabras en euskera (experimento 2.b). Por ejemplo, escucharon la palabra ***izar*** - estrella en euskera - y los competidores fueron **espada** y **botella**, del castellano. Los resultados de este experimento con bilingües castellano-euskera también mostraron activación paralela del castellano (al oír palabras del euskera). La coactivación de los competidores de inicio y de rima del castellano ocurrió de forma simultánea y sin diferencia de magnitud entre ellas (***izar*** coactivó **espada** y **botella**).

El análisis e interpretación de los resultados de los experimentos descritos en este estudio demuestran que la naturaleza del input de la señal influye en el acceso léxico. En la modalidad oral, la señal auditiva se procesa consecutivamente a medida que se desarrolla en el tiempo: la coactivación del inicio de la palabra precede a la de la rima (experimento 1.a). En LSE, la modalidad visual influye en el reconocimiento permitiendo que distinta información sub-léxica se procese de forma más simultánea (experimento 1.b). Sin embargo, el patrón secuencial mostrado por los signantes nativos (localización antes de configuración) indica que, además de la información disponible simultáneamente, otros factores, tales como las propiedades lingüísticas de la localización y la configuración y la edad de adquisición de la lengua de signos, entran en juego en el procesamiento.

Esta tesis deja también claro que hay activación paralela bidireccional entre lengua oral y lengua de signos en los bilingües bimodales (experimentos 2.a y 2.c), así como activación paralela del castellano en bilingües unimodales castellano-euskera (experimento 2.b). La activación paralela está condicionada por la modalidad de las lenguas: en el caso bimodal solo se coactivó el inicio de la palabra en castellano (experimento 2.a), mientras que los bilingües unimodales castellano-euskera coactivaron tanto el inicio como la rima (experimento 2.b). Por tanto, el cambio de modalidad hizo que disminuyera el número de efectos. Otro factor que hay que tener en cuenta para explicar la ausencia de efecto de rima en los bilingües bimodales es la dominancia del castellano. Así, al ver signos, pudieron haber inhibido el castellano (su lengua dominante) hasta el punto de que no ocurriera el efecto de rima.

La diferencia entre la coactivación del castellano intra-lingüística (fuerte inicio antes de rima) e inter-lingüística (solo inicio en los bilingües bimodales; inicio y rima simultáneamente y sin diferencia de magnitud en los bilingües unimodales) indica que la activación de una palabra desde otra lengua (oral o signada) no es equivalente a "escuchar" esa palabra en nuestra cabeza. No procesamos de la misma manera una palabra que escuchamos que una palabra que evocamos.

En cuanto a la coactivación de la LSE desde el castellano, todos los bilingües bimodales mostraron un patrón de activación de localización anterior a configuración (experimento 2.c). Este orden coincide, además, con el de los nativos signantes en el contexto intra-lingüístico (experimento 1.b). Este patrón de procesamiento puede ser reflejo, por un lado, de la diferente complejidad lingüística de cada una de estas unidades sub-léxicas. La localización incluye menos rasgos fonológicos, con menos valores cada uno de ellos, que la configuración, y es más sencilla de procesar. Por otro lado, este patrón temporal podría indicar un procesamiento jerárquico: la localización debe resolverse antes de la configuración.

Los signantes que aprendieron la LSE como L2 no mostraron este patrón en el contexto intra-lingüistico. La presencia explícita del signo hizo que procesaran la localización de forma más lenta y que, por tanto, coincidiera en el tiempo con el procesamiento de la configuración (experimento 1.b). En cambio, cuando el signo estaba encubierto, su patrón temporal coincidió con el de los signantes nativos: localización antes de configuración (experimento 2.c). Esto sugiere que los signantes oyentes que aprendieron la LSE como L2 tienen representaciones fonológicas consolidadas de la LSE, aunque muestran dificultades para procesar la señal visual presente.

Esta tesis contribuye a esclarecer el papel que desempeñan la localización y la configuración en el acceso léxico. Los modelos fonológicos de las lenguas signadas pueden beneficiarse de esta información sobre el procesamiento de la lengua de signos, desde el punto de vista de la percepción, para incorporarla en sus propuestas que, normalmente, se basan en la producción. Además, este estudio ayuda a entender el bilingüismo como un fenómeno general en el que tienen cabida diferentes modalidades de lenguas que pueden relacionarse, aunque no compartan fonología. Así, partiendo de un modelo existente de procesamiento de lenguaje bilingüe, adaptamos su arquitectura para integrar la modalidad signada y proponemos un sistema de interacción de lenguas en bilingües para la comprensión de palabras y signos.

# Abstract

This study investigated the effect of modality on lexical access. Various experiments examined the role of sub-lexical units in spoken Spanish and in Spanish Sign Language (LSE) in 56 hearing bimodal bilinguals, who were native or second language (L2) signers. These experiments investigated the time course of lexical access using the visual world paradigm, focusing on onset and rhyme for the spoken language, and handshape and location in the signed language. The main aim was to determine whether this access is modulated by modality-specific characteristics of the sub-lexical structure of each language and by the age of acquisition (AoA) of the signed language.

Firstly, two experiments explored lexical access in a within-language context for Spanish, on the one hand, and LSE, on the other. The results demonstrated that the nature of the linguistic input signal influences lexical access. In the spoken modality, the auditory signal is processed in a sequential fashion as it unfolds in time: as the input became available, onset co-activation preceded (and was stronger than) rhyme co-activation. For LSE, the visual modality impacts sign recognition by allowing the presence of concurrent sub-lexical information that is co-activated at the same time. However, native signers showed processing of location that was slightly earlier (but weaker) than that of handshape; the L2 signers showed a different pattern. This indicates that, in addition to the simultaneous sub-lexical information available in the input, other factors should be considered, such as the linguistic properties of the sub-lexical units or the AoA of the signed language. This temporal organization of signed lexical processing is, in fact, the reverse of the temporal structure of sign (in which handshape typically precedes location). Compared to native signers, L2 signers showed a weaker handshape effect and a later location effect. This suggests that: (i) the early signing experience of native signers allows for a greater role for handshape in processing signs as adults; and (ii) the overt processing of the sign causes delays in L2 signers relative to native signers, so that the location effect appears later, possibly due to less robust phonological representations of these sub-lexical units in L2 signers.

Secondly, we tested lexical access in cross-language, cross-modal contexts: LSE signs co-activating Spanish words and vice versa. The results showed bidirectional parallel activation between Spanish and LSE in native and L2 signers (with no modulation

of AoA of the sign language). Parallel activation of Spanish was evidenced through onset competition while viewing LSE signs. This implies that changing modality and/or the inhibition of the dominant language (Spanish) reduced co-activation in the spoken language, as the rhyme effect was lost. Parallel activation of LSE was evidenced by sequential co-activation of location and handshape, confirming the stability of sub-lexical co-activation effects in sign language and the relevance of these sub-lexical units for sign language processing. The consistent temporal order of sub-lexical processing (location before handshape) leads us to speculate whether this ordering is driven by relative complexity – location is a simpler sub-lexical component compared to handshape – or is a reflection of hierarchical processing in which location has to be resolved before handshape.

Overall, the differences between native and L2 signers in signed lexical access in the within-language setting suggest that AoA of the sign language has a stronger impact on overt sign processing (when the sign is present) than it does on covert processing (when signs are co-activated through spoken words). The absence of such AoA differences in the cross-modal, cross-language setting points towards common mechanisms underlying lexical processing in native and L2 signers.

In sum, this study contributes to a better understanding of language processing and bilingualism, in general, and of signed language processing and bimodal bilingualism, in particular. Looking at languages across different modalities allows us to identify what aspects of language processing are driven by a particular type of signal (an auditory word versus a visual sign) and what is intrinsic to language *per se*. In the case of signed language processing, this study teases apart the contribution of location and handshape, and the time-course of each. Concerning bilingualism, this thesis makes a contribution in disentangling the connections between a bilingual's languages when those connections do not rely on phonological overlap or any kind of shared phonology. The results of this study advance models of bilingual language processing and of signed language phonology.

# Spanish Sign Language (LSE) abstract

Available at https://osf.io/v2dpn/

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# Abbreviations and acronyms

| | |
|---|---|
| AoA | Age of Acquisition |
| ASL | American Sign Language |
| BIA+ | Bilingual Interactive Activation+ |
| BLINCS | Bilingual Language Interaction Network for Comprehension of Speech model |
| BIMOLA | Bilingual Model of Lexical Access |
| BSL | British Sign Language |
| CODA | Children of Deaf Adults |
| DGS | German Sign Language (*Deutsche Gebärdensprache*) |
| EEG | Electroencephalography |
| ERP | Event-Related Potential |
| L1 | First Language |
| L2 | Second Language |
| LSE | Spanish Sign Language (*lengua de signos española*) |
| NGT | Sign Language of the Netherlands (*Nederlandse Gebarentaal*) |
| SOMBIP | Self-Organizing Model of Bilingual Processing |

# Chapter 1. Introduction

Language is a remarkable cognitive ability that can be expressed through different modalities, including visuo-spatial (sign languages) and audio-oral (spoken languages) modalities. Both spoken and signed languages are acquired naturally and share many properties that can be characterized at similar levels of linguistic analysis, such as phonology, morphology, syntax and semantics (Sandler & Lillo-Martin, 2006). However, the organization of each type of language is conditioned by modality and this impacts how the language is processed. Words in spoken languages are organized mostly sequentially, while phonological and morphological information in signs is organized mostly simultaneously. In spoken language, the onset of a word is uttered first and, therefore, perceived earlier than the final part of the word. In a signed language, sub-lexical units, such as the location and the handshape of a sign, are available at the same time. In consequence, speech involves the perception of *sequential* phonological units (consonants and vowels) while the majority of sub-lexical units that make up signs, such as the location and the handshape of a sign, appear almost *simultaneously*. For this reason, the two types of language provide a critical test bed to investigate modality-independent and modality-specific processes. This thesis investigates the influence of modality on the temporal dynamics of lexical co-activation during recognition of auditory words and visual signs in two different contexts: within-language and cross-language and/or modality.

This introduction provides a review of the issues pertaining to language modality and the population of interest. Firstly, in section 1.1, we review the sub-lexical structure of sign language and focus on signed phonology: we consider the different models of signed phonology and we explore the function in sign language processing of the sub-lexical units that we investigate in this study, namely handshape and location. Secondly, we define what we mean by a bimodal bilingual and how this population allows us to explore the processing of both spoken and signed languages in within- and cross-language/modal contexts (section 1.2). At the end of section 1.2 we look at the role of age of acquisition in sign language processing. Next, in section 1.3, we review the most relevant models of language processing in bilinguals, bearing in mind to what degree they are applicable to bilinguals in a spoken and a signed language. Section 1.3 also looks at cross-language activation in (unimodal and bimodal) bilinguals. At this point, we will present the visual world paradigm used in our experiments (section 1.4). Finally, section 1.5 sets out the research questions that this study aims to answer. The chapter concludes with an overview of the structure of this thesis (section 1.6).

## 1.1 Sub-lexical units in signed languages

Models of speech processing, such as the TRACE (McClelland & Elman, 1986) or the Cohort Models (Marslen-Wilson, 1987; Marslen-Wilson & Welsh, 1978) incorporate a fundamental aspect of the spoken signal: sequentiality. We recognise words as the audible signal unfolds in time. Spoken words are made up of smaller discrete sub-lexical units: phonemes are strung together one after the other to form words. This characteristic is related to modality: speech is produced by the vocal tract, which permits the articulation of a sequence of sounds. However, the visual signed modality permits the production and perception of simultaneous sub-lexical information and this impacts how visuospatial languages are processed. In this section we look at the sub-lexical structure of signs.

### 1.1.1 Models of sign language phonology

Most current models of sign language phonology agree on three sub-lexical units for signs: handshape, location (place of articulation) and movement (e.g. Brentari, 1998; Sandler, 1989; Stokoe, 1960; see example in Figure 1.1). Handshape refers to the form that the hand or hands adopt while articulating a sign. Location concerns the body region(s) or the space around the signer where the hands are placed to perform a sign. Movement is the path the hands follow and/or changes in the hand configuration during the execution of a sign. These sub-lexical units have a structure composed of different features. The possible values that these units can take vary across sign languages: in the same way that spoken languages have a specific phonological repertoire, each sign language has a specific set of handshapes, locations and movements bound by linguistic and perceptual constraints.

Models of signed phonology address the question of simultaneity and sequentiality of the sub-lexical units: are handshape, location and movement simultaneously organised within a sign, or are they organized sequentially, as vowels and consonants are in spoken languages? In what follows, I provide an overview of those models of sign language phonology that are relevant to sub-lexical processing, the topic of this thesis (for an exhaustive review of models of sign phonology, see Brentari, 2012).

**VENTANA**

**Figure 1.1**. The sign VENTANA[1] [window] in Spanish Sign Language is articulated with both hands in a closed fist (handshape); the dominant hand on top of the forearm (location); and a short bouncing movement of the dominant hand performed twice (movement).

At the beginning of linguistic research into signed languages, the Cheremic Model (Stokoe, 1960; Stokoe, Casterline, & Croneberg, 1965) described handshape, location and movement as the three sub-lexical units in American Sign Language (ASL) that were comparable to phonemes. These sub-lexical units allowed the differentiation of minimal pairs. An important difference between these cheremes (as Stokoe called them) and spoken language phonemes was that they occur simultaneously instead of sequentially. This model represented the first linguistic analysis of a signed language, and made the striking observation that simultaneity is central to the signed form, as opposed to sequentiality, favoured by the spoken modality. Subsequent models recognised the need to account for the sequential structure of signs.

The Movement-Hold Model developed by Liddell and Johnson (1989) moved away from the three parameters identified by the Cheremic Model (Stokoe, 1960; Stokoe et al., 1965) and aimed to capture the sequentiality present in signs. According to the Movement-Hold Model, signs are made up of two types of sequential segments: holds, the segment where a set of features are simultaneously held; and movements, the

[1] The convention to gloss signs is the use of small caps.

segments where the hand(s) move(s). As words sequentially present vowels and consonants, signs present holds (consonants) and movements (vowels). The Movement-Hold Model had an important impact on how subsequent models dealt with simultaneity and sequentiality but faced various shortcomings. For example, the model included detailed phonetic description, which gave rise to redundancy by specifying multiple features for handshapes and locations that failed to exploit predictable properties of signs.

The Hand Tier Model (Sandler, 1986, 1987, 1989) shares important aspects with both the Cheremic and the Movement-Hold models. Hand configuration and location are again taken as the core components, in line with the Cheremic Model, while sequentiality is also dealt with, as in the Movement-Hold Model. Both sub-lexical units have internal hierarchical structure. Hand configuration, which consists of handshape and hand orientation, is unchanging throughout the sign and co-occurs with the other sub-lexical features of the sign. (The handshape of a sign may undergo modification of certain sub-features, such as the flexion of the fingers, but this does not result in a different phonological value for the handshape.) Location includes place of articulation and settings. Each place of articulation, or major body area, includes various settings (minor areas). Settings are typically the start and the end points for the hand during the sign articulation. Thus, there are normally two sequentially-ordered settings in a sign, but both must belong to the same major body area. As a result, place of articulation is normally constant in a sign. Therefore, according to the Hand Tier Model, hand configuration and place of articulation do not change during the sign duration; they are simultaneously articulated while settings and movement represent the sequential structure.

According to the Prosodic Model (Brentari, 1998), the simultaneous structure of a sign is based on a “root-as-lexeme”, following from the observation that phonologically distinctive features occur once per lexeme/sign, instead of once per syllable or segment (more common in many spoken languages). From this root stems the inherent feature structure and the prosodic structure: the inherent feature structure includes handshape and place of articulation, while the prosodic structure takes care of movement. Inherent features of a sign do not change, while prosodic features are dynamic. The stable, simultaneous properties of signs rely mainly on handshape and place of articulation. As in Sandler’s Hand Tier Model, handshape and place of articulation have a more complex hierarchical structure compared to movement. Movement involves a change over time, so its characterization requires a different structure than that of handshape and location.

Moreover, movement is not always categorised as a core sub-lexical unit and can be treated as a transition between two values of other units (van der Kooij, 2002), leaving handshape and location as the major units of signed phonology.

A common property of all these phonological models is the relevance of handshape and location as sub-lexical components. When it comes to simultaneity, developed models such as the Hand Tier Model or the Prosodic Model judge handshape and location as the sub-lexical units that hold constant throughout the sign, while movement (and some aspect of location, understood as settings or minor body areas) introduces sequentiality. Because of the consistent status accorded to handshape and location in the different models of the sub-lexical structure of signs, we will focus on these units in this study.

### 1.1.2 The role of handshape and location in sign language processing

Models of sign language phonology identify handshape and location as major phonological categories and we, therefore, expect that these sub-lexical units will also have a relevant role in sign language processing. Research on the processing of signs has established that lexical access of signs occurs automatically (Dupuis & Berent, 2015) and yields, as for spoken words, lexicality effects (Carreiras, Gutiérrez-Sigut, Baquero, & Corina, 2008; Emmorey, 1991; Emmorey & Corina, 1993; Gutiérrez-Sigut & Carreiras, 2009), familiarity effects (Carreiras et al., 2008; Ferjan Ramirez et al., 2016), and semantic priming (Bosworth & Emmorey, 2010; Gutiérrez-Sigut & Carreiras, 2009).

When it comes to the role of sub-lexical information in lexical access in sign language, the findings are mixed. For example, phonological priming studies, in which prime and target share one or more sub-lexical signed units, provide divergent support for the influence of contrasting sub-lexical units. In ASL, inhibitory effects have been shown for location, facilitation for movement, and no effects for handshape (Corina & Emmorey, 1993). Inhibition from location has also been reported in Spanish Sign Language (LSE, *lengua de signos española*) although handshape showed facilitation (Carreiras et al., 2008). In British Sign Language (BSL), facilitation has been described for signs sharing location and movement (Dye & Shih, 2006). Conversely, the same combination of location and movement showed no priming effects in a different study on ASL (Corina & Hildebrandt, 2002).

Other studies and paradigms have also yielded relevant results concerning the processing of these sub-lexical categories. Orfanidou, Adam, McQueen, and Morgan (2009) found that handshape was more often misperceived than location in a sign spotting experiment with deaf BSL signers, suggesting that handshape may be less reliable than location in constraining lexical access. In addition, a form-based priming experiment measuring ERPs (event-related potentials) revealed that handshape overlap produced later effects than location overlap (Gutiérrez, Müller, Baus, & Carreiras, 2012). Together, these results suggest that handshape and location may play different roles in sign recognition and may be associated with different temporal dynamics in sign perception.

The separate contribution of handshape and location in lexical access of signs was explicitly tested by Caselli and Cohen-Goldberg (2014) using computational simulations in a lexical network based on activation principles from Chen and Mirman (2012). In this network, weak phonological neighbours facilitate target processing, while strong neighbours inhibit target processing. Whether a lexical item is weak or strong depends on sub-lexical properties that influence the activation levels of phonological neighbours. Caselli and Cohen-Goldberg (2014) simulated three different possible explanations for opposing effects of handshape and location overlap in phonological priming studies. In particular, they focused on inhibitory effects for location competitors and facilitatory effects for handshape competitors. These explanations were: 1) the timing with which the two sub-lexical units are perceived; 2) differences in their resting activation in the lexical network; and 3) differences in neighbourhood density. The simulations showed that earlier perception of location than handshape, and higher resting activation of location than handshape could both account for inhibitory effects of location competitors and facilitatory effects of handshape competitors; conversely, variation in lexical neighbourhood density could not.

Despite the discrepancies between studies on the role of sub-lexical units in sign language processing, these results demonstrate that location and handshape differentially impact lexical processing. The current study intends to shed further light on the role on handshape and location in sign language processing by looking at location and handshape activation in a within- as well as cross-language, cross-modal context.

### 1.1.3 The temporal dynamics of sign recognition

In signed languages, the visual nature of the articulators makes it possible to produce multiple sub-lexical units simultaneously. As explained in section 1.1.1, the presence of movement in the phonological structure of signs means that there is also sequential change (Liddell & Johnson, 1989; Perlmutter, 1992; Sandler, 1986), but simultaneity pervades the sub-lexical structure of signs, especially in terms of handshape and location, which appear together and remain constant throughout the sign. In this section we examine the time course of sign recognition.

Only a few previous studies have investigated the time course of the processing of sub-lexical units of signs. A gating study in ASL, in which deaf native and late signers were shown progressively more video frames of a sign from the beginning, showed that the location of the sign was identified first, followed by handshape and, finally, movement (Emmorey & Corina, 1990). This suggests that sign recognition proceeds incrementally as the parameters are processed over time. In contrast, Morford and Carlson (2011) found no differences between the identification of handshape and location in deaf native signers in a gating task and reported earlier identification of handshape than location in hearing non-native signers. The divergent results between these two gating studies may be due to methodological differences. In Morford and Carlson (2011) the signs were taken from signed sentences instead of using decontextualized signs, and the sentence context may have affected the temporal structure of the signs. Additionally, the duration of the shortest gate was different in both studies: Morford and Carlson (2011) used a first gate that was four times longer than Emmorey and Corina (1990) did. The results of both gating studies are at odds with the temporal order of the articulation of signs, as handshape precedes location (Hosemann, Herrmann, Steinbach, Bornkessel-Schlesewsky, & Schlesewsky, 2013). This suggests that the processing of signs does not follow the temporal properties of signs.

The temporal order of sub-lexical units might not be the only factor conditioning the processing of signs. An eye-tracking study in BSL using the visual world paradigm looked at the co-activation of combinations of sub-lexical units during lexical access and found that a temporally salient combination – such as handshape and location, which both appear at the beginning of a sign – yielded smaller competitor effects than a perceptually salient combination – such as movement and location, which can be seen under visually noisy circumstances (Thompson, Vinson, Fox, & Vigliocco, 2013; see also Lieberman, Borovsky, Hatrak, & Mayberry, 2014). This combination of location and movement also influenced phonological similarity judgements in ASL to a stronger extent than other combinations (Corina & Hildebrandt, 2002; Hildebrandt & Corina, 2002). However, while the combination of movement and location may be perceptually salient, it is also temporally informative since movement conveys the sequential structure of the sign.

Importantly, the previous studies looking at sub-lexical co-activation effects in sign language have used phonological competitors that share more than one parameter with the target. This creates stronger effects, since the target and competitor signs are more similar, but makes it difficult to interpret the contribution of individual parameters. The combination of two or more parameters might yield competition effects that go beyond the mere summation of the individual overlapping parameters. In this study, we manipulate each sub-lexical unit individually to compare the time course of co-activation of signs sharing a single parameter, either location or handshape, during lexical access. Specifically, we look at the role of location and handshape during sign recognition, when there is *overt* presentation of the sign itself, and during cross-language co-activation, when the sign is activated *covertly* through the presentation of a spoken word.

## 1.2 Bimodal bilingualism

Bilingualism, the ability to use two languages, is more the rule than the exception: more than half of the world's population is bilingual (Grosjean, 2010). However, bilingualism comes in all shapes and sizes. Although most of the scientific research on bilingualism has focused on spoken languages, the general umbrella of bilingualism covers not only different languages but also different modalities. For most bilinguals, their two spoken languages share the same channels of production and perception: speech and hearing, respectively. In this sense, they are unimodal bilinguals, as their languages share modality. The same could be said, for instance, for a bilingual person proficient in two signed languages: both languages share the gestural channel for production and the visual channel for perception, making the individual a unimodal bilingual (although in a different modality compared to a spoken language bilingual). In contrast, for bilinguals whose two languages do not share modality, such as individuals who use a signed and a spoken language, the articulatory and perceptive channels between languages do not overlap, making them bimodal bilinguals.

Unimodal spoken bilinguals show a great deal of variability in a range of factors such as age of acquisition (AoA) of their languages or their proficiency, and the same holds true for bimodal bilinguals. Bimodal bilinguals can be classified according to a variety of relevant factors, including their hearing status, the AoA of their languages and their proficiency (for a recent review of bimodal bilingualism, see Thompson & Gutiérrez-Sigut, 2019). The following sections discuss different types of bimodal bilinguals and specify the type of bimodal bilingual that took part in the current research.

### 1.2.1 Deaf bimodal bilinguals

Put simply, being a signer means being bilingual. Most signers are also competent, to some degree, in a spoken language and/or in its written form. Individuals who sign are thus considered to be bimodal bilinguals, and they may be deaf or hearing. Deaf bimodal bilinguals are also referred to as sign-print bilinguals, highlighting that they are normally competent in the written form of a spoken language as well as a signed language. Strictly speaking, deaf bimodal bilinguals are not actually using two modalities, as both of their codes, the signed language and the written form of a spoken language, use the visual modality. However, the reality is more complex as many deaf people have some access to the spoken modality, especially if, for instance, they have some residual hearing. Given this, the label of sign-print bilingual seems restrictive and inaccurate: the written form of the language is a visual representation of a language that is auditory in its primary form. Moreover, even in congenitally profoundly deaf people, some representation of the phonology of the spoken language has been reported (MacSweeney, Goswami, & Neville, 2013; MacSweeney, Waters, Brammer, Woll, & Goswami, 2008). In consequence, deaf bimodal bilinguals are sometimes described as a type of speech-sign bilinguals.

Deaf bimodal bilinguals may be native sign language users who have learnt a signed language from birth from their deaf signing parents. However, this is not the most frequent scenario: the majority of deaf people are born in hearing families and they are only able to access a signed language when they enter school (Costello, Fernández Landaluce, Villameriel, & Mosella, 2012; Mitchell & Karchmer, 2004). Thus, they are normally categorized as early bilinguals. Late deaf bilinguals are individuals who have spent most of their childhood in a spoken language environment and have only had access to the signed language in their teenage years or even later.

A more complex issue is how to categorize deaf bimodal bilinguals in terms of their age of acquisition of the spoken language. All deaf infants are exposed to the spoken language from birth (whether that be at home or in the wider community), but the quantity and quality of their spoken language exposure is hard to characterize. A deaf child may see the lip patterns of speech from birth and encounter written language at school (or earlier), but clearly this combined input is much more restricted than that of a typical hearing infant. The complexity of defining the spoken language capacity in deaf individuals led us to consider a different type of bimodal bilingual for this study of the relationship between spoken and signed language representations: hearing bimodal bilinguals.

### 1.2.2 Hearing bimodal bilinguals

Hearing bimodal bilinguals are competent in both a spoken and a signed language, independent of their knowledge of the written form of the spoken language. (They may also be identified as bimodal speech-sign bilinguals, emphasising that they have access to the primary forms of both languages: spoken and signed.) Since the current study examines the role of the sub-lexical units of both speech and sign during lexical access, hearing bimodal bilinguals offer a unique opportunity to probe how both modalities impact language processing within the same individual. Hearing bimodal bilinguals generally consider the spoken language their dominant language (Emmorey, Petrich, & Gollan, 2013). This is the case even if the signed language is their first language (like many Children Of Deaf signing Adults, CODAs); the spoken language is much more present in the wider community, and their dominance normally switches as they come into contact with other speakers (Emmorey, Giezen, & Gollan, 2016), a situation that frequently happens when entering school (Pizer, Walters, & Meier, 2013).

Hearing bimodal bilinguals who are CODAs normally acquire both languages from birth, making them native bimodal bilinguals. Curiously, although signed languages are an integral feature of deaf communities, the majority of individuals exposed to a signed language from birth are hearing CODAs. Hearing native bimodal bilinguals achieve the same milestones of language learning as children who acquire two spoken languages, and their language development is very similar to that of children who acquire only one language, whether signed or spoken (Petitto et al., 2001). Apart from hearing native signers, other hearing bimodal bilinguals come into contact with a signed language later in life. This frequently happens when they learn the signed language for professional purposes, to become sign language interpreters or teachers, for example. Previous research, mostly with deaf bimodal bilinguals, has shown that AoA of the signed language impacts how the mental lexicon is organized (e.g. in terms of phonological neighbourhoods or lexical familiarity) and how the sub-lexical units are processed (Carreiras et al., 2008; Corina & Hildebrandt, 2002; Emmorey & Corina, 1990; Emmorey, Corina, & Bellugi, 1995; Mayberry & Eichen, 1991). Of interest to this study, AoA might also affect the relationship between the signed and the spoken language in hearing bimodal bilinguals, and how lexical items of one language are linked to those of the other language. Thus, the current study includes both hearing native and late signers to assess the influence of the AoA of the signed language on the activation of spoken and signed sub-lexical units in language processing. (Language proficiency may vary as a function of AoA or other factors, such as frequency of language use and language attitudes. To avoid introducing a confound of sign language proficiency, we limited the sample in this study to hearing bimodal bilinguals who were highly proficient in the sign language.)

For hearing late signers, the spoken language is their first language (L1). When learning the signed language, late signers rely more on iconicity, that is, similarities between the form of a sign and its meaning (Baus, Carreiras, & Emmorey, 2013; Campbell, Martin, & White, 1992; Ortega, 2017). Furthermore, there is robust neurological evidence that AoA affects how hearing bimodal bilinguals process signed and spoken language (Neville et al., 1997; Newman, Bavelier, Corina, Jezzard, & Neville, 2002; Zachau et al., 2014). We will come back to these differences between native and late signers later in the next section.

The aim of this study is to understand how bilinguals process languages from different modalities, and how those languages interact with one another. For this purpose, hearing bimodal bilinguals who are proficient in a spoken and a signed language represent a cognitive system that handles linguistic information from both modalities.

### 1.2.3 The role of AoA in sign language processing

A critical factor that modulates the recognition of lexical items is the AoA of the language in question. For example, highly proficient second language (L2) learners of spoken languages show overall increased and longer activation of competitors than native listeners do as a result of inaccurate phonetic processing (Broersma & Cutler, 2008, 2011; Weber & Cutler, 2004).

For sign languages, various studies have shown that compared to deaf native signers, deaf late learners have difficulties in processing language input (for a review and discussion of AoA effects on sign language processing, see Carreiras, 2010). Deaf late learners show slower and/or poorer performance in a variety of tasks, including sentence comprehension (Mayberry & Eichen, 1991), shadowing different kinds of utterances (Mayberry & Fischer, 1989), rejecting phonologically related probes in a probe recognition task (Emmorey et al., 1995), and isolating signs in a gating task (Emmorey & Corina, 1990). In a primed lexical decision task with signs that were identical except for one parameter (minimal pairs), the phonological overlap produced a facilitative effect in deaf early signers, and an inhibitory or no effect in deaf late signers (Dye & Shih, 2006; Mayberry & Witcher, 2005). In an eye tracking study with ASL signers, deaf late signers showed later semantic and phonological competition than deaf native signers (Lieberman, Borovsky, Hatrak, & Mayberry, 2015). Differences in phonological processing of signed language have been found in the brain for late learners compared to native signers, whether deaf (MacSweeney, Waters, et al., 2008) or hearing (Newman et al., 2002).

Handshape appears to be the sub-lexical unit most sensitive to AoA. Late learners of ASL are slower to respond to handshape changes than native signers in a phonological monitoring task (Corina & Hildebrandt, 2002). Two studies with categorical perception tasks have shown that, compared to early learners, late learners of sign language have less well-defined phonological categories for handshape (Best, Mathur, Miranda, & Lillo-Martin, 2010; Morford, Grieve-Smith, MacFarlane, Staley, & Waters, 2008). Morford and Carlson (2011) compared the performance of deaf native signers, deaf late learners and hearing L2 signers on a gating task and found that both deaf late learners and hearing L2 signers identified signs more slowly than deaf native signers did. In a sign detection task, native signers made most errors perceiving movement, while late signers made more errors perceiving handshape (Orfanidou et al., 2009). A lexical decision task in LSE showed that late signers were slower and less accurate than native signers when signs had a handshape with a dense lexical neighbourhood (Carreiras et al., 2008). These findings suggest that late learners (whether deaf late first language signers or hearing L2 signers) have phonological processing difficulties with handshape compared to deaf native signers.

Overall, the literature on AoA suggests two main findings: late learners experience difficulties processing sign language phonology in general, and handshape is particularly challenging for them. It should be noted that most of the research on sign language AoA focuses on deaf signers. Comparing early and late deaf signers is complex since late signers make up a very heterogeneous population: some late deaf signers have been exposed to spoken language in the first years of life, while others have little or no exposure to any language until later in life. These confounding factors can be obviated by targeting hearing bimodal bilinguals; both early and late signers have acquired their first language in a typical, early setting. In the current study we will, therefore, investigate within- and cross-language co-activation during lexical access in hearing native signers and L2 signers.

## 1.3 Bilingual language processing

Understanding how both languages are processed and influence each other in bilinguals is a challenge that has given rise to various models of bilingual language processing. These proposals normally focus on two distinct types of linguistic input related to the spoken language: visual (written) words and/or speech. These models contribute to our understanding of how bilinguals access phonological, lexical and semantic representations of the words (or signs) of their languages, that is, their mental lexicon. For the purpose of this study, such models serve as the starting point to develop an architecture that can account for bimodal bilingual language processing.

In the first part of this section (1.3.1) we will briefly go over the most influential models of bilingual language processing, highlighting, when applicable, the adaptations that some of these models have so far incorporated to accommodate bimodal bilingual input. We then focus on the relationship between a bilingual's two languages by revising a specific case of language interaction that relates to a central aspect of the current study:

non-selective or parallel activation in unimodal (section 1.3.2) and bimodal bilinguals (section 1.3.3).

## 1.3.1 Models of bilingual language processing

A number of models set out to explain how bilinguals process two or more languages. For the purpose of this study, we are interested in models that deal with bilingual comprehension, as we are investigating language processing elicited by perceiving the linguistic signal, whether spoken or signed. This review of different models does not attempt to be exhaustive but concentrates on those proposals that are germane to (bimodal) bilingual lexical access.

### 1.3.1.1 BIA+

A highly developed model is the Bilingual Interactive Activation+ model, BIA+ (Dijkstra & van Heuven, 2002), based on the BIA model (Dijkstra & van Heuven, 1998). The original BIA model focused on orthographic processing, while the BIA+ model broadened the processing to phonology and semantics, although the input for the model is still orthographic information (bilingual word recognition). This model is an extension of the (monolingual) Interactive Activation Model for visual word perception (McClelland & Rumelhart, 1981). The BIA+ model (Figure 1.2) maintains that the bilingual orthography, phonology and lexicon are integrated.

According to this model, bilingual lexical access is non-selective: the linguistic input in one language may give rise to the co-activation of both languages. When a letter string acts as input (at the level of sub-lexical orthography in Figure1.2), various lexical orthographic candidates are activated in parallel based on two considerations: 1) similarity between the input string and the lexical orthographic candidates, and 2) on the resting level activation of each item (determined by frequency of access: the more frequent the access, the greater the resting activation). For example, in an English-Spanish bilingual, the written English word ***actually*** will also activate the similar Spanish word ***actualidad***, and, to a lesser extent, the low-frequency English word ***actuary***. The lexical candidates then activate the corresponding phonological and semantic representations. The more overlap there is between the input and the lexical representation, the more activation there is. Thus, if the bilingual's two languages have very dissimilar orthographical codes, there might be very few orthographically similar lexical candidates from the other language, or even none (e.g. when the languages do not share orthography at all). However, phonological similarity between words in the two languages could, in that case, still lead to activation of lexical candidates from the other language. The BIA+ model includes language nodes that serve to identify which language a lexical item belongs to.

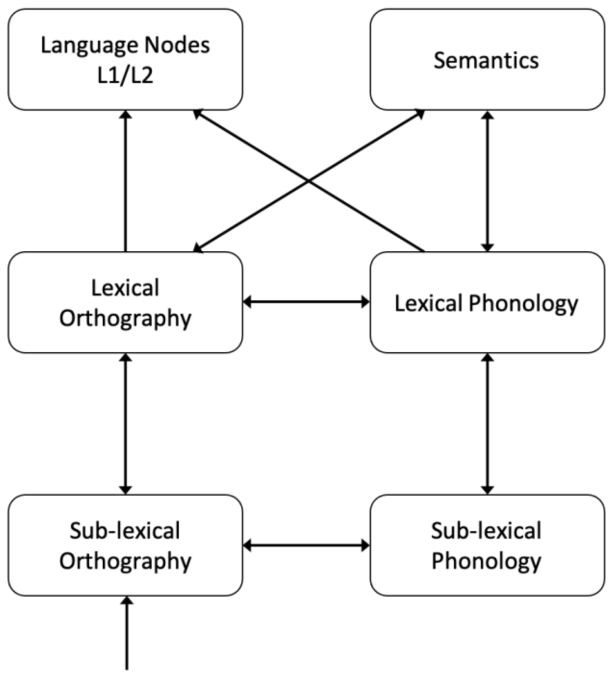


**Figure 1.2**. BIA+ model (adapted from Dijkstra & van Heuven, 2002, p. 182).

According to Dijkstra and van Heuven (2002: 183), "when particular input aspects are language specific, we will (of course) find evidence of language specific access". This is crucial when thinking about bimodal bilinguals, as their phonological systems are language specific, with no overlap. Ormel, Hermans, Knoors, and Verhoeven (2012) took the BIA+ model and proposed the Deaf Bilingual Interactive Activation model, Deaf BIA (Figure 1.3), to explain the results of a study with deaf children performing a word-picture verification task that showed sign co-activation while reading words. Ormel et al. (2012) found that deaf children responded more slowly and less accurately when the mismatching word and image overlapped phonologically in their corresponding signed equivalents; while when the signed equivalents were highly iconic, they responded more quickly and accurately. In this proposal, written words and signs are linked to each other during vocabulary development in deaf children (Hermans, Knoors, Ormel, & Verhoeven, 2008), and as a result there are lateral connections between the lexical orthography of the spoken language and the lexical phonology of the signed language (see Figure 1.3).

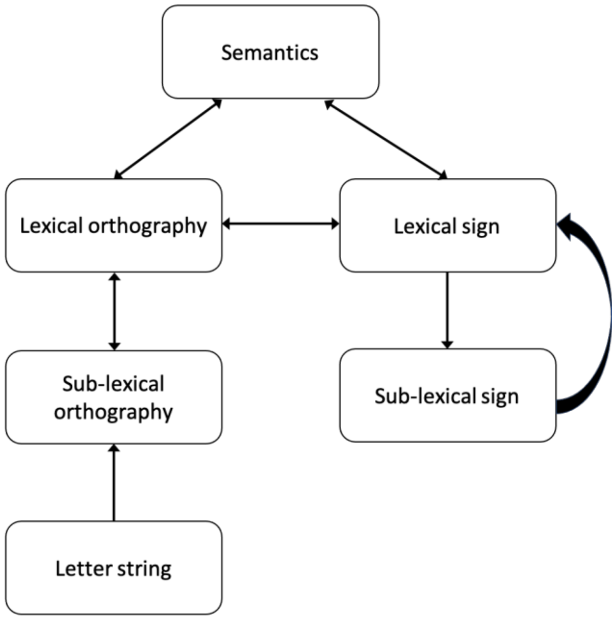


**Figure 1.3**. Deaf BIA (adapted from Ormel et al., 2012, p. 301).

The Deaf BIA was refined by another study that looked at the time course of cross-modal activation in deaf bimodal bilingual adults (Morford, Occhino-Kehoe, Piñar, Wilkinson, & Kroll, 2017). This new model, shown in Figure 1.4, confirmed the link between lexical orthography and the signed lexical phonology: since deaf signers learn to read through the mediation of their signed language, the orthographic lexical forms forge a strong link with semantics and with the phonological forms of the sign language. In contrast, the connection between the orthographic lexical forms and the phonological forms of the spoken language is weaker.

The BIA+ model has been expanded upon and adapted for deaf bimodal bilinguals, but it is constricted by the need for visual written words as input of the model. This limits the model when considering spoken language input, the primary form of the language that we are interested in studying in the context of bimodal bilingualism. We now turn to bilingual models that do consider speech perception.

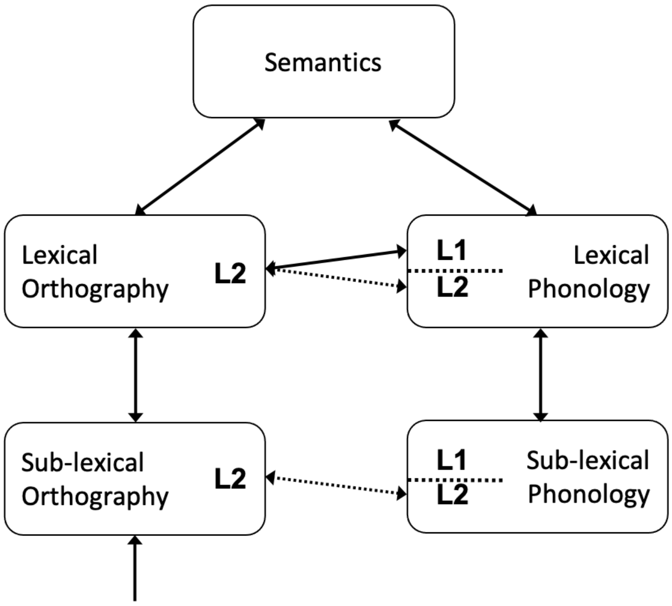


**Figure 1.4**. Modified BIA+ model for sign-print bilinguals (adapted from Morford et al., 2017, p. 340).

### 1.3.1.2 BIMOLA

In the Bilingual Model of Lexical Access, BIMOLA (Grosjean, 2008), the input to the model is the auditory signal of speech. This model was inspired by the (monolingual) TRACE model of speech perception (McClelland & Elman, 1986). BIMOLA has three levels: a feature level, which is shared between languages, and phoneme and word levels, which are independent for each language (Figure 1.5).

In the visual schema of the model in Figure 1.5, a unit's shading and proximity represent closer or further neighbours. At the word level, size of the units represents frequency. Activation between the phoneme and the word nodes (in both directions) depends on the word nodes and the phoneme nodes that make up the word. Top-down pre-activation may come to the word nodes from the global language mode (a continuum that goes from a monolingual to a bilingual mode) or other higher linguistic information. Within the word and phoneme level, the connections between units are within language; between the word and phoneme level, connections are also within language. In contrast to BIA+, there is no specific language node, as the two languages have independent sets of processes (inhibition is also a within-language mechanism).

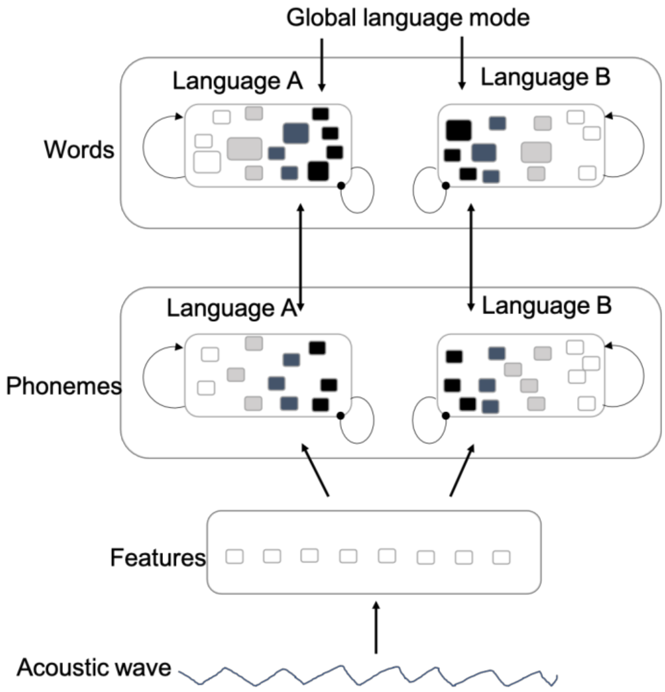


**Figure 1.5**. BIMOLA (adapted from Grosjean, 2008, p. 204).

Thinking of the bimodal bilingual case, BIMOLA has the advantage of considering spoken input. Additionally, the model captures the lack of phonological overlap between languages; having this separation at the lexical level also would seem to fit well with the difference between a bimodal bilingual's two languages. However, at the lowest level the system integrates feature information from both languages, assuming that the input is of the same type (i.e. spoken words). This is precisely not the case for bimodal bilingual input, and the model needs to be able to account for two very different types of input, namely, *auditory* words and *visual* signs. This raises the question of the larger sets that contain both languages at the phoneme and word levels. As pointed out by Shook and Marian (2009), even if the model contemplated information from two modalities at the feature level, how would that feed into a system where both languages are part of the same set at the phonological and lexical level? Finally, the model provides a very modular architecture for each language: the lack of lateral connections between the languages makes it difficult to account for the growing evidence of cross-language activation in the absence of phonological overlap, including bimodal bilinguals (see section 1.3.3).

#### 1.3.1.3 BLINCS

Dynamic approaches relying on principles of learning mechanisms have opened the way for the Bilingual Language Interaction Network for Comprehension of Speech (BLINCS) model (Shook & Marian, 2013). Such approaches make use of self-organising maps that receive input and distribute it according to an unsupervised learning algorithm. Each level of the model may consist of a self-organizing map that describes the distribution of that level's units according to the patterns extracted from the input. This may result in language-specific spaces, or language-shared spaces, or language-specific spaces with some overlap between languages.

In the case of previous models that use self-organizing maps, such as SOMBIP (Self-Organizing Model of Bilingual Processing, Li & Farkaš, 2002), the self-organising maps describe robust relations between translation equivalents in the bilingual lexicon, although each language has its own set of semantic representations. Alternatively, DevLex-II (Zhao & Li, 2010) highlights the impact of the onset of learning the L2 on the self-organizing maps. Importantly, SOMBIP and DevLex-II do not contemplate any kind of visual input, so the languages of the models always come from the spoken modality.

Building on the architectures of SOMBIP and DevLex-II, the BLINCS model (Shook & Marian, 2013) is a dynamic network that includes a learning mechanism and that aims to explain lexical activation during speech comprehension. BLINCS consists of various interconnected self-organizing maps at different representational levels: phonological, phono-lexical, ortho-lexical and semantic (Figure 1.6). The input to the phonological level is the auditory signal, but visual input can also be accommodated at this level (as well as through the semantic level). The phonological and semantic levels have language-shared representations, while the phono-lexical and ortho-lexical levels have language-specific representations integrated in their self-organizing maps. Although the phonological system is shared, the model allows for language-specific units, which means that phonemes that exist in one language but not the other can be represented. The network has between-level and within-level excitatory connections (depicted by pointed arrows in Figure 1.6). There are inhibitory connections within levels at the phono-lexical and at the ortho-lexical levels (depicted as rounded arrows in Figure 1.6).

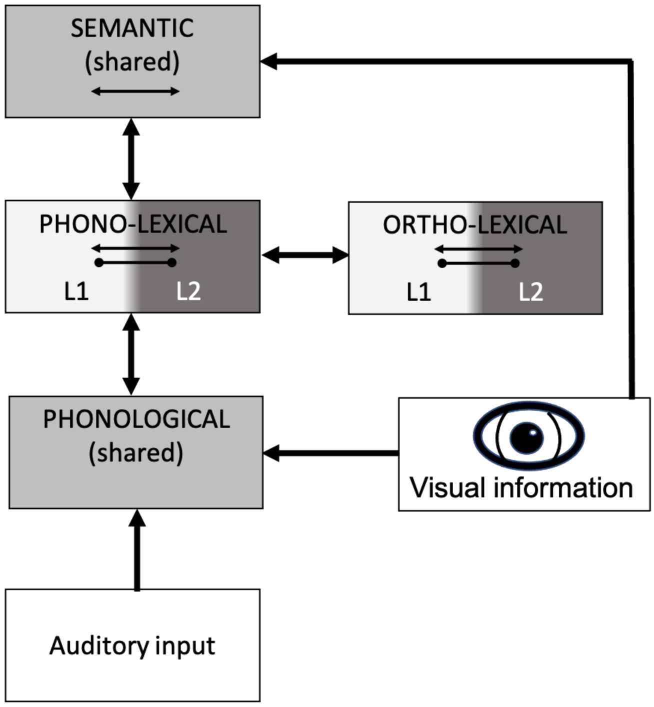


**Figure 1.6**. BLINCS model (adapted from Shook & Marian, 2013, p. 306).

In the BLINCS model, activation is related to the unfolding of the spoken signal. The first phoneme of the input gives rise to activation at the phonological level, which in turn causes activation at the phono-lexical level of many candidates which start with that phoneme. As the spoken signal develops, candidates from both languages that overlap with the input increase activation, while the activation gradually diminishes for candidates that no longer overlap. Activation leaves a trace that remains active after the phoneme presentation and this explains rhyme activation. Activated phono-lexical units transmit activation to equivalent ortho-lexical and semantic candidates. At each level, this activation spreads to neighbours and to cross-language items thanks to lateral connections. The ortho-lexical and semantic levels feed back to the phono-lexical level, which also feeds back to the phonological level.

A recent adaptation of BLINCS for deaf sign-print bilinguals (Hosemann, Mani, Herrmann, Steinbach, & Altvater-Mackensen, 2020) has accommodated visual signed input as L1 for parallel activation of the written form of the spoken language (Figure 1.7). Hosemann et al. (2020) carried out an ERP-study in which they found cross-language activation of written words (the participants' L2) while viewing German Sign Language (*Deutsche Gebärdensprache*, DGS) sentences (their L1). The DGS sentences included two signs that served as prime and target. Prime and target signs could have an overt phonological overlap, or could be phonologically unrelated but with a covert orthographic overlap in their written German translation. In both cases, the results showed priming effects. In their adaptation of the model for deaf bimodal bilinguals, at the phono-lexical level there is no representation of German words, as they are only represented at the ortho-lexical level. (I return to the details of this adaptation in section 4.3.2.3).

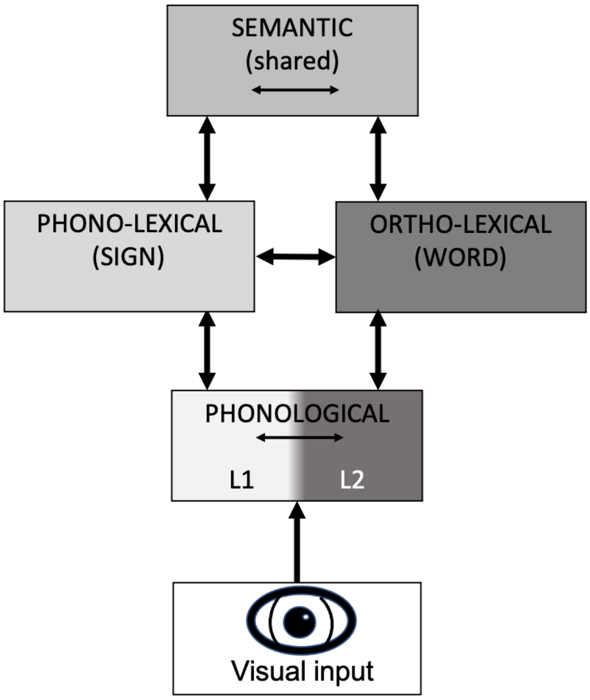


**Figure 1.7**. BLINCS version for deaf bimodal bilinguals (adapted from Hosemann et al., 2020, p. 17).

The BLINCS model is amenable to incorporating bimodal language combinations for various reasons. Firstly, the model allows for visual input to the phonological level: this mechanism was proposed for the inclusion of multimodal speech input (i.e. lip patterns) but provides a means to include visual signed input. Additionally, the phonological level can also accommodate language-specific representations: this was designed for spoken languages with different phonological repertoires but can be exploited to allow for two very different types of phonological representations: speech and sign. Finally, the model has already been adapted to certain types of bimodal bilingualism (Hosemann et al., 2020; Shook & Marian, 2012) and represents a promising candidate for accounting for cross-modal, cross-language co-activation.

So far, none of the proposed models for bilingual language processing has been implemented for both signed and spoken languages in the same network. At the end of this thesis, in the general discussion (chapter 4), I will revisit the proposals that could be adjusted to a hearing bimodal bilingual scenario to determine whether these models can accommodate the results of this study. In the next section we review previous research on the interaction between languages and whether one language activates the other.

### 1.3.2 Parallel activation in unimodal bilinguals

A central question in bilingualism is whether activating one language necessarily involves activating the other, or whether the two languages are accessed independently. Neuroimaging studies have revealed overlapping activation of the same brain regions for both languages (e.g. Chee, Tan, & Thiel, 1999; Illes et al., 1999; Klein, Milner, Zatorre, Meyer, & Evans, 1995), suggesting that the languages share the same neural circuitry. In contrast, claims have been made for language independence concerning bilinguals in monolingual tasks given the strong inhibition of the unused language (Rodriguez-Fornells, Rotte, Heinze, Nösselt, & Münte, 2002).

A large body of research supports the idea that bilinguals access words in parallel in both languages when they speak or process input in one language (reading words: Schwartz, Kroll, & Diaz, 2007; Thierry & Wu, 2007; reading sentences: Libben & Titone, 2009; hearing words: Marian & Spivey, 2003; Spivey & Marian, 1999; naming pictures: Bobb, Von Holzen, Mayor, Mani, & Carreiras, 2020; Costa, Caramazza, & Sebastian-Galles, 2000). In many of these studies, non-selective access to words in both languages is driven by phonological ambiguity in the input (e.g. Canseco-Gonzalez et al., 2010; Ju & Luce, 2004; Marian, Blumenfeld, & Boukrina, 2008; Weber & Cutler, 2004). For example, when Spanish-English bilinguals hear the English word **beans**, they also activate the Spanish word **bigote** [moustache] (Canseco-Gonzalez et al., 2010). This suggests a strong relationship between orthographies and phonologies across languages, and an important role for phonological mediation in parallel activation.

However, recent studies have also provided evidence for interactivity between languages in the absence of overt phonological overlap between words in the input and the unused language, mostly from different-script bilinguals (Japanese-English: Hoshino & Kroll, 2008; Hindi-English: Mishra & Singh, 2014; Chinese-English: Wu & Thierry, 2010; Zhang, van Heuven, & Conklin, 2011). Furthermore, using the visual world paradigm, Shook and Marian (2019) found that English-Spanish bilinguals looked more to the image of a shovel than to unrelated distractors when asked to click on an image of a duck. The authors' explanation was that the English word **duck** activates its Spanish translation **pato**, which in turn co-activates the phonologically-overlapping Spanish word **pala** and its English translation equivalent **shovel** (i.e. Spanish-English bilinguals, but not English monolinguals, activate shovel when hearing the word **duck**). This study shows that, in addition to phonologically overt cross-language activation (co-activation of the **beans-bigote** type), unimodal bilinguals also exhibit co-activation through lexical connections or shared semantic representations (co-activation of the **duck-shovel** type).

### 1.3.3 Parallel activation in bimodal bilinguals

Focusing on the bimodal bilingual brain, neuroimaging studies of sign language reveal a similar, although not always identical, neural network for signed language and spoken language processing (Braun, Guillemin, Hosey, & Varga, 2001; Corina, 1998; Corina, San Jose-Robertson, Guillemin, High, & Braun, 2003; Emmorey, Mehta, & Grabowski, 2007; Gutierrez-Sigut et al., 2015; Gutierrez-Sigut, Payne, & MacSweeney, 2016; Leonard et al., 2012; MacSweeney, Capek, Campbell, & Woll, 2008; MacSweeney, Waters, et al., 2008; MacSweeney et al., 2002; Neville et al., 1998; Petitto et al., 2000; Poizner, Klima, & Bellugi, 1990). Some brain areas are linked to language production or perception independent of its modality (Bavelier, Corina, & Neville, 1998; Emmorey et al., 2003; Hickok, Love-Geffen, & Klima, 2002; Neville et al., 1998; Söderfeldt et al., 1997; Zou, Ding, Abutalebi, Shu, & Peng, 2012), while other regions are modality-specific (Bavelier et al., 1998; Braun et al., 2001). Furthermore, the neural underpinnings vary between bimodal bilinguals as a function of their proficiency or AoA of the languages (Neville et al., 1997; Zou et al., 2012) and also due to hearing status (Emmorey & McCullough, 2009; MacSweeney et al., 2006, 2002; Neville et al., 1997).

Despite the different structural and physical properties of signs and words, a growing body of studies has also provided evidence of cross-modal, cross-language co-activation in bimodal bilinguals. In particular, a variety of paradigms and techniques have shown that bimodal bilinguals co-activate sign language while hearing spoken words (ASL: Giezen et al., 2015; Shook & Marian, 2012; Spanish Sign Language: Villameriel et al., 2016) or reading words (ASL: Meade, Midgley, Sevcikova Sehyr, Holcomb, & Emmorey, 2017; Morford, Kroll, Piñar, & Wilkinson, 2014; Morford et al., 2017; Morford, Wilkinson, Villwock, Piñar, & Kroll, 2011; German Sign Language: Kubus, Villwock, Morford, & Rathmann, 2015). For example, Morford et al., (2011) asked deaf

ASL-English bilinguals to perform a semantic judgement task on printed English word pairs. For some of the word pairs, the ASL translation equivalents overlapped in ASL phonology (for example, the ASL translations of the English words **bird** and **duck** share the same handshape and location). The ASL-English bilingual participants were slower to reject semantically-unrelated word pairs when the ASL translations overlapped in ASL phonology compared to pairs without ASL phonological overlap. Additionally, they were faster to accept semantically-related word pairs when the ASL translations overlapped in ASL phonology compared to pairs without ASL phonological overlap. This finding suggests that printed words co-activate their signed translations, which subsequently leads to cascading activation to other phonologically-overlapping signs and then back to the translation equivalent of the phonologically-overlapping item (Shook & Marian, 2013). Similar evidence has been obtained with hearing bimodal bilinguals and auditory stimuli (Giezen et al., 2015; Shook & Marian, 2012; Villameriel et al., 2016).

Research investigations of co-activation in the opposite direction – activation of spoken words while perceiving signs – are still relatively scarce. Two recent electroencephalography (EEG) studies showed evidence in the EEG response of activation of the spoken language while deaf bimodal bilinguals processed signs (ASL: Lee, Meade, Midgley, Holcomb, & Emmorey, 2019) or signed sentences (German Sign Language: Hosemann et al., 2020), but activation of spoken words while perceiving visual signs has not been shown in behavioural studies.

Moreover, relatively little is known about the underlying dynamics of phonologically covert co-activation as observed in studies with bimodal bilinguals and in the study by Shook and Marian (2019). Therefore, in this study we investigate the time course and the contribution of different sub-lexical units in within- as well as cross-language activation in bimodal bilinguals. The next section describes the experimental paradigm used in this study.

## 1.4 This study: eye-tracking and the visual world paradigm

This study investigates the impact of modality-specific aspects of sub-lexical organization on the temporal dynamics of lexical processing in two different contexts: a within-language context, and a cross-language, cross-modal setting. For this purpose, we use the visual world paradigm, which has been instrumental in the study of the time course of spoken word recognition (e.g. Dahan, Magnuson, & Tanenhaus, 2001; Huettig & Altmann, 2005; Magnuson, Dixon, Tanenhaus, & Aslin, 2007; Yee & Sedivy, 2006).

The visual world paradigm relies on eye-tracking, a technique with high temporal sensitivity, making it possible to examine when and how the unfolding speech input modulates language processing. Usually, participants hear a word while they observe a computer screen displaying a series of pictures (typically four, one in each quadrant of the screen, also known as areas of interest). Some pictures bear no relation to the word while others, for example, hold a semantic, phonological or visual relation with the word. For instance, if the auditory word is **door**, individuals will turn their gaze to the related images, such as a key (semantically related) or a boar (phonologically related). The underlying assumption of this paradigm is that increased looks to a semantically, phonologically or visually-related picture (compared to unrelated pictures) reflect higher lexical activation of that word and associated concept. The temporal sensitivity of the eye-tracking technique makes it possible to estimate when the looks occur as well as the magnitude of the effect.

This study is made up of two sets of experiments conducted with hearing bimodal bilinguals of Spanish and LSE. Half of the participants were native signers, the other half L2 signers, thus allowing us to probe the effect of AoA on lexical access and cross-language co-activation processes.

The first set of experiments examines within-language co-activation for the spoken language and for the signed language. Previous experiments using the visual world paradigm with spoken language stimuli have shown that looks were first directed towards phonological neighbours with the same onset as the target, and subsequently to rhyme competitors (Allopenna, Magnuson, & Tanenhaus, 1998; see Magnuson, Tanenhaus, Aslin, & Dahan, 2003, for comparable results with an artificial language). The first experiment of the current study investigates the time course of co-activation of onset and rhyme competitors to replicate these results for Spanish. The second experiment adapts the visual world paradigm to a signed language scenario by presenting the linguistic stimulus as a video of a sign to study the time course of co-activation of location and handshape. This experiment will also be a means of testing whether the paradigm can be adapted for sign language with competition from a single sub-lexical unit (combined sub-lexical units have been used with the visual world paradigm in Lieberman & Borovsky, 2020; Lieberman et al., 2015; Thompson et al., 2013).

The second set of experiments explores cross-language, cross-modal co-activation of the spoken and signed languages in the same sample of bimodal bilinguals. One experiment studies co-activation of word onset and rhyme while seeing signs. A within-modal version of this experiment was run with unimodal Spanish-Basque bilinguals to contrast cross-language activation between cross-modal and within-modal settings. The final experiment examines the co-activation of location and handshape while hearing words. This experiment was also performed by Spanish-Basque bilinguals with no knowledge of the signed language to make sure that any effects are due to knowledge of sign language and not the characteristics of the experimental design.

## 1.5 Research questions

The main aim of this doctoral thesis is to examine the effect of modality on language processing by looking at the impact of the linguistic signal on the time course and role of different sub-lexical units in lexical access within and across a signed and a spoken language. The specific research questions this study addresses are set out in this section.

1. **Does a language's modality influence the temporal dynamics of sub-lexical co-activation of that language?**

   For spoken languages, words that share onset or rhyme are co-activated when a given word is accessed, and this activation mirrors the structure of the word: onset effects occur before rhyme effects (Allopenna et al., 1998). This suggests that the sequential structure of words, a feature of the spoken modality, impacts how co-activation takes place. However, what happens with languages in a different modality? Looking at a signed language, which operates in a different modality and thus has a different sub-lexical structure, provides a unique opportunity to investigate the relation between modality and language processing. Previous work with bimodal bilinguals has made use of lexical items with a high degree of similarity, namely, signs that share several sub-lexical units (e.g. Lieberman et al., 2015; MacDonald, LaMarr, Corina, Marchman, & Fernald, 2018; Thompson et al., 2013). To identify the contribution of individual sub-lexical units in sign language, we use signs that share a single sub-lexical feature. Related to the specific issue of lexical processing in sign language, we can also establish two more detailed questions:

- Do the sub-lexical units of handshape and location play a role in lexical co-activation and, if so, how is this organised temporally?
- If such co-activation does occur, is this processing modulated by AoA of the signed language?

Experiments 1.a and 1.b address these questions (chapter 2).

**2. Is there cross-language, cross-modal parallel activation between a spoken and a signed language?**

The growing body of evidence for cross-language activation in spoken bilinguals has relied on co-activation between words with a high degree of phonological overlap (e.g. Marian et al., 2008; Marian & Spivey, 2003a; see section 1.3.2 for more references). The evidence for cross-language activation in bimodal bilinguals has largely focused on co-activation of the sign language during spoken language processing and made use of signs that shared several sub-lexical units (e.g Giezen et al., 2015; Shook & Marian, 2012; Villameriel et al., 2016). Here, we investigated parallel activation of different sub-lexical units in both directions, and also considered effects of AoA on parallel activation:

- Do bimodal bilinguals activate Spanish in parallel while seeing LSE signs? If so, is this parallel activation modulated by the AoA of the signed language?
- Do bimodal bilinguals activate LSE in parallel while hearing Spanish words? If so, is this parallel activation modulated by the AoA of the signed language?

Experiments 2.a and 2.c address these questions (chapter 3). If parallel activation is observed in these experiments, the cross-modal, cross-language set-up of our study will allow us to address two additional questions:

**3. Does modality impact cross-language co-activation?**

The results of the cross-modal, cross-language experiment will characterize co-activation between languages of different modalities. By applying the same experimental paradigm to bilinguals of two spoken languages, we will be able to gauge the effect of modality on cross-language co-activation. Since the visual world paradigm allows us to capture the time course of the different sub-lexical effects, we can express this question in more specific terms:

- How are spoken sub-lexical units temporally processed in cross-language co-activation when bimodal bilinguals view signs compared to when unimodal bilinguals hear words in their other language?

This question is addressed by experiments 2.a and 2.b. (chapter 3)

4. **Does sub-lexical co-activation differ when it is overt (within-language) or covert (cross-language)?**

In the within-language setting, the target word/sign itself is perceived; in the cross-language experiment, the target word/sign is activated by means of the other language. The results of the within- and cross-language experiments furnish us with the opportunity to look at the impact of the explicit linguistic signal on lexical co-activation. Specifically, how is sub-lexical co-activation affected by directly perceiving a lexical item in that language? We can look at this question for each modality:

- Is the time course of sub-lexical spoken co-activation equivalent in within- and cross-language settings?
- Is the time course of sub-lexical signed co-activation equivalent in within- and cross-language settings?

These questions will be addressed by comparing the within-language experiments of chapter 2 with the between-language experiments of chapter 3.

This set of research questions has guided the design of the experiments conducted for this thesis. Furthermore, they served as a framework to generate specific predictions and hypotheses that were generated for each experiment and are included in the corresponding experimental chapters.

## 1.6 Structure of the thesis

This thesis is structured in five chapters: this General Introduction, two experimental chapters (one chapter on within-language, within-modal co-activation; another on cross-language, cross-modal co-activation), the General Discussion and Conclusions.

The current chapter has provided the background for this study. Firstly, we have looked at sign language phonology and reviewed models that describe sub-lexical units that make up signs: handshape and location. We have also looked at the current mixed evidence for the role of these units in sign language processing. Secondly, we have defined our population of interest, namely, hearing bimodal bilinguals, a unique population to study the impact of modality on bilingual language processing and we have considered the impact of AoA on how the signed language is processed. Thirdly, we have reviewed models of bilingual language processing, including adaptations for deaf print-sign bilinguals, and explored evidence for cross-language activation in bilinguals. Finally, we have defined the research questions that this thesis sets out to answer.

Chapter 2 explores how hearing bimodal bilinguals deal with sub-lexical units when perceiving spoken words, on the one hand, and visual signs, on the other. Comparing a spoken and a signed language allows us to ascertain the impact of modality on lexical processing. Experiment 1.a investigates sub-lexical co-activation (of onset and rhyme competitors) in Spanish; Experiment 1.b looks at the sub-lexical co-activation (of location and handshape competitors) in LSE. The spoken language results essentially replicate previous work on spoken languages; the sign language results serve to confirm that the experimental paradigm can be adapted to a signed language, and provide novel findings concerning the role of location and handshape in sign recognition, as well as the impact of AoA.

Chapter 3 focuses on cross-language lexical access by adapting the experiments from the previous chapter to a cross-modal setting. Experiment 2.a looks at sub-lexical co-activation of words when seeing signs; Experiment 2.c examines sub-lexical co-activation of signs while hearing words. This provides insight into cross-language co-activation of sub-lexical units, and the influence of AoA on this process. To provide a fuller picture of cross-language activation of the spoken language, Experiment 2.b examines cross-language, within-modal co-activation of Spanish words while hearing words of another spoken language (Basque). This allows us to compare cross-language co-activation in a cross-modal and a within-modal setting.

The General Discussion (chapter 4) opens with a summary of the whole study and goes on to compare the within- and cross-language co-activation findings for both languages from chapters 2 and 3, respectively. For both languages, the differences between within- and cross-language co-activation are considered by focusing on the temporal processing of handshape and location and the distinct impact that crossing languages and/or modality has on bimodal bilinguals' lexical processing. The discussion revisits the models of bilingual language processing that were described in chapter 1 to see how these can accommodate bimodal input and language combinations in the bilingual network. The results for the signed modality are also evaluated in terms of what they can contribute to models of sign language phonology (presented in section 1.1.1). The chapter closes by considering the limitations of the study and directions for future research in this area.

Chapter 5 presents the main conclusions of this study by revisiting the research questions formulated in section 1.5. The final chapter sets out the contributions of this study to the different areas that it touches upon, such as language processing and bilingualism, and closes by highlighting some potential applications of the study.

# Chapter 2. Within-Language Lexical Access[2]

## 2.1 Introduction

The current chapter investigates how bimodal bilinguals compute phonological units to perceive signs and spoken words, and how language modality influences the temporal dynamics of these computations during recognition of visual signs and auditory words.

The difference in modality between speech and sign raises the question of whether understanding spoken words and gestural signs is influenced by the sequential or simultaneous nature of each modality. Additionally, other factors might modulate language processing. The age of acquisition (AoA) of the language in question may also influence the recognition of lexical items (Broersma & Cutler, 2008, 2011; Carreiras, 2010; Emmorey & Corina, 1990; Lieberman et al., 2015; Mayberry & Witcher, 2005; Morford & Carlson, 2011; Weber & Cutler, 2004). Most of the available studies on AoA effects in sign language processing have investigated deaf late first language signers who were raised orally and acquired a sign language as adolescents or (young) adults. The unique and heterogeneous language acquisition experience of deaf late first language signers means that AoA effects in this group may not be the same for hearing L2 signers.

In this study we use the visual world paradigm to investigate the processing dynamics of sub-lexical parameters in speech (onset and rhyme) and in sign language (handshape and location) in hearing native signers and in hearing L2 signers of Spanish Sign Language (LSE). Specifically, participants' eye movements to pictures on the screen were monitored while listening to spoken words or watching signs. In critical trials, the images on the screen included images of words that shared onset or rhyme with the target word (Experiment 1.a), or signs that shared location or handshape with the target sign (Experiment 1.b). For example, in Spanish the target word **estrella** [star] will be accompanied by on-screen images of a sword (**espada** – onset competitor), a bottle

[2] The study presented in this chapter has been published in Villameriel, S., Costello, B., Dias, P., Giezen, M., & Carreiras, M. (2019). Language modality shapes the dynamics of word and sign recognition. *Cognition*, *191*, 103979. DOI: 10.1016/j.cognition.2019.05.016

(**botella** – rhyme competitor) and two images that bear no similarity with the target word (unrelated distractors). In LSE, as exemplified in Figure 2.1, the target sign **VENTANA** [window], articulated on the forearm with a closed fist, is presented together with images of a ruler (the sign **REGLA**, is articulated on the forearm – location competitor), a broom (the sign **ESCOBA** is articulated with a closed fist – handshape competitor) and two other images whose signs bear no similarity to the target sign (unrelated distractors).

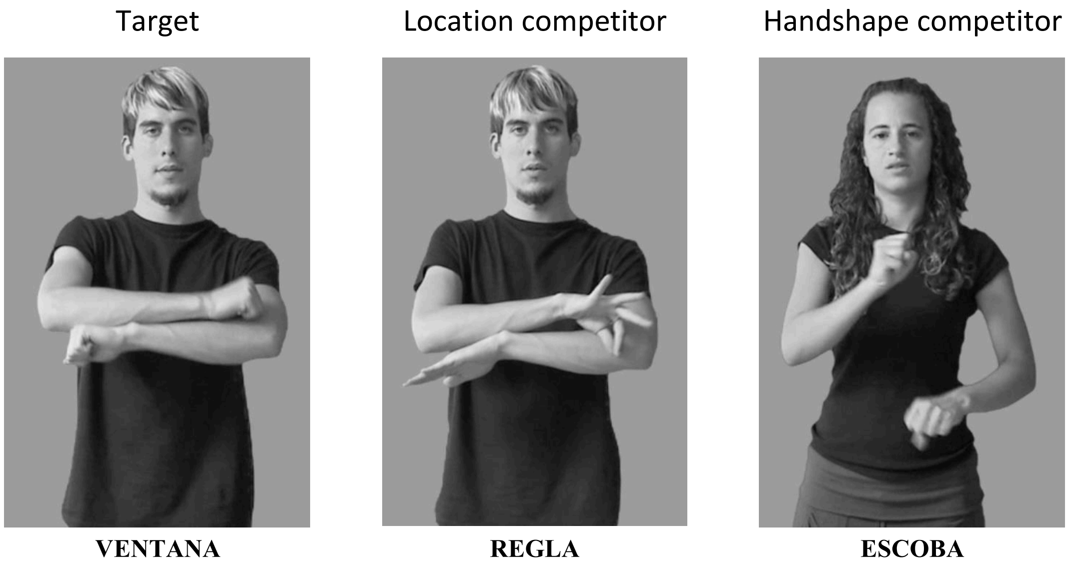


**Figure 2.1**. The target sign **VENTANA** shares location (forearm) with **REGLA** and handshape ( ) with **ESCOBA**.

To examine differences in the time course of gaze behaviour, we performed a time series analysis: Growth Curve Analysis (Mirman, 2017). This allows us to estimate the strength of the co-activation, indexed by the proportion of looks (intercept term), and the temporal development of co-activation, revealed by the changes in the looking behaviour over time (linear and quadratic term). In order to choose the polynomial order for each growth curve model we used a combination of a statistical and a theoretical approach (Mirman, 2017), including only orthogonal time terms that significantly improved model fit and that were included in our predictions. Orthogonal polynomials were used to reduce collinearity between the time terms (see section 2.2.1.4 for a detailed description).

For spoken Spanish (Experiment 1.a), in line with previous research (Allopenna et al., 1998), we hypothesize that participants will look more to onset and rhyme competitors compared to unrelated distractors (with no difference between native and L2 signers since for both groups Spanish is the dominant language); we expect significant differences in the intercept for onset and rhyme competitors compared to unrelated distractors. Furthermore, we anticipate that the sequential unfolding of the word across time would result in more and earlier activation of shared onsets than rhymes. For instance, the onset competitor **espada** [sword] for the target word **estrella** [star] will have more and earlier looks than the rhyme competitor **botella** [bottle] will. If this is the case, we expect significant differences between onset and rhyme competitors on the intercept term (reflecting more looks to the onset competitors) and on the time terms (reflecting a different time course for looking behaviour for each type of competitor).

For LSE (Experiment 1.b), we hypothesize that native signers will look more at handshape and location competitors compared to unrelated distractors. Thus, we expect differences in the intercept (and possibly also temporal terms) for each competitor relative to the unrelated distractors. With respect to the relative strength of each parameter, the mixed results of previous studies regarding facilitation and inhibition (see section 1.1.2) do not generate clear predictions about which effect is stronger. For the relative time course of handshape and location competitor effects, the existing literature suggests earlier and/or more sustained activation of location competitors (Emmorey & Corina, 1990; Gutiérrez et al., 2012). Thus, we primarily expect differences between the location and handshape competitors in the linear and quadratic terms (reflecting differences in the onset and duration of the effects, respectively). Regarding the AoA effect, for L2 signers of LSE, we envisage two possible outcomes. On the one hand, they may perform similarly to native signers, in which case the patterns in their results should be similar to those just described. On the other hand, they may perform more like deaf late learners, who experience difficulty in processing phonology (Emmorey et al., 1995; Mayberry & Eichen, 1991; Mayberry & Witcher, 2005) and revealed no early activation of phonology in a previous visual world paradigm study (Lieberman et al., 2015). In that case, we expect fewer and/or later fixations to one or both competitors for L2 signers, reflecting greater processing costs, compared to native signers. Since L2 signers struggle with handshape (Morford et al., 2008; Ortega & Morgan, 2015), it is reasonable to expect that processing of this parameter is especially affected. This would be supported by significant group differences on the intercept (fewer fixations) and/or linear term (later fixations) for either competitor, but especially handshape.

## 2.2 Experiment 1.a: spoken language

### 2.2.1 Methods

#### 2.2.1.1 Participants

A group of 56 native speakers of Spanish (28 hearing native signers and 28 hearing L2 signers) were included in the study. Both groups were highly proficient in LSE and Spanish. All participants used LSE on a daily basis for their work: most of them were working as sign language interpreters at the time they did the task. In contrast to the native signers, who had acquired LSE from birth, the L2 signers had all been exposed to the language as adults (mean age of exposure: 21.1; range 16-28). Participants were tested in different cities across the country where participants were recruited (Bilbao, Burgos, Madrid, Palencia, Pamplona, San Sebastián and Valladolid). Participants' characteristics are shown in Table 2.1.

**Table 2.1**
*Experiment 1.a Participant characteristics (standard deviations in brackets)*

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

#### 2.2.1.2 Materials

The experimental task consisted of 45 trials with four images in the corners of the screen and an auditory stimulus presented over headphones (Figure 2.2). In critical trials ($n$ = 30), the target picture was absent, a common practice in visual world paradigm experiments (see Huettig & Altmann, 2005; Huettig & McQueen, 2007) to increase the chances of observing competitor activation. In these trials, the spoken target was phonologically related to the corresponding word for two of the images: one word shared the onset with the target word, and the other competitor word rhymed with the target word. The remaining two pictures were unrelated distractors. (See Table A1 in Appendix A for a list of all stimuli in critical trials.) In filler trials ($n$ = 15), the target image was present, and the remaining three images were unrelated distractors.

All targets, competitors and distractors were nouns in Spanish. Phonological characteristics of the Spanish words were carefully controlled such that there was only phonological overlap in the onset or rhyme of targets and competitors. In each trial, the LSE translations of the words had no phonological similarity (i.e. signs were visually different). Two critical trials were excluded from the analysis because of visual competition between the target word and the distractor pictures, resulting in 28 analysed critical trials.

Semantic relations between targets and onset competitors ($M$ = 0.08, $SD$ = 0.1); targets and rhyme competitors ($M$ = 0.11, $SD$ = 0.1); and targets and distractors ($M$ = 0.07, $SD$ = 0.06) were controlled using scores (between 0 and 1) from the semantic analysis tool DISCO[3] (extracting DIstributionally related words using CO-occurrences, Kolb, 2008, 2009) on a large, 232 million (word) token corpus of Spanish texts. A one-way ANOVA showed that there were no significant differences in DISCO values across targets paired with each competitor and each distractor ($F(2,54) = 2.3$, $p$ = .1). We controlled for log frequency and number of phonemes, letters and syllables in competitors with EsPal, the Spanish Lexical Database (Duchon, Perea, Sebastián-Gallés, Martí, & Carreiras, 2013), using the Written and Web Tokens database (2012-11-06) and Castilian Spanish phonology. The properties of the word lists are shown in Table 2.2.

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

**Table 2.2**
*Characteristics of competitor words (means; standard deviations in brackets)*

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

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

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

2.2.1.3 Procedure

SR Research Experiment Builder software (v1.10.1630) was used to present the stimuli. Eye movements were recorded at a sampling rate of 1000Hz with the SR Research Eyelink 1000 system using a desk-mounted chin and forehead rest. Only the right eye was recorded. All participants sat in front of a screen (1044x768 pixels) at 60 cm from their eyes. Participants were instructed to push the appropriate key on a Cedrus RB-844 button box (with four large buttons in a two-by-two layout) when the corresponding picture matched the target word. When the target word did not have a corresponding image, participants were instructed to wait for the next trial to start. After reading the task instructions on the screen, a 9-point calibration procedure was performed. Before the experimental task, participants completed a practice block of six trials with feedback on accuracy. Drift correction was performed at the start of each trial. Subsequently, the four images appeared on the screen for 500 ms before the target word was presented over headphones. The images remained on the screen for another 2,500 ms after target word offset or until the participant pushed any of the buttons, followed by 100 ms of blank screen (Figure 2.2). We used two lists with different presentation sequences that were counterbalanced across participants. Competitors, distractors and target images appeared a similar number of times in each location on the screen.

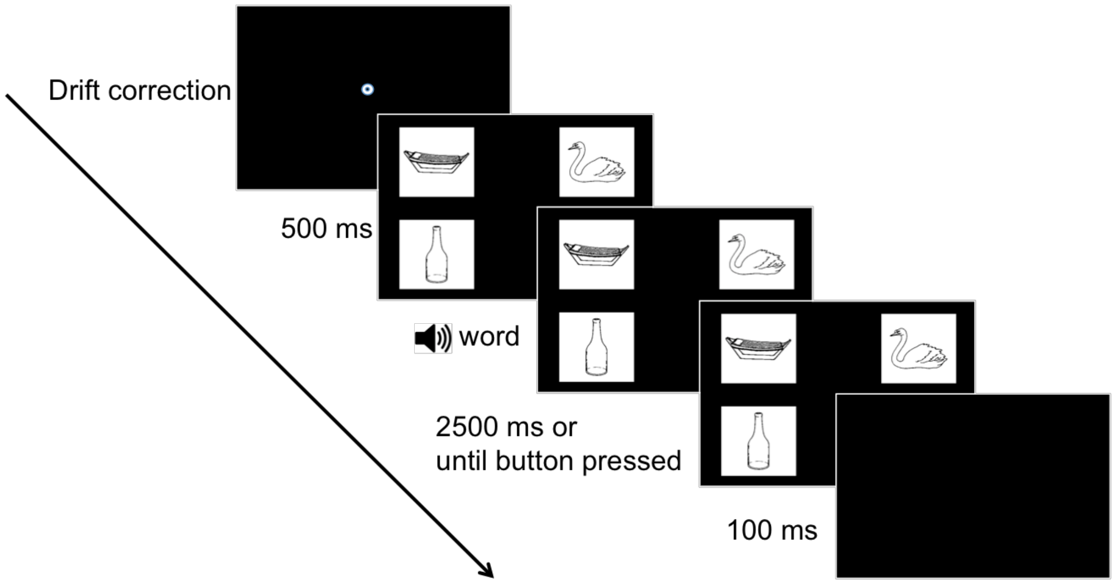


**Figure 2.2**. Trial sequence for Experiment 1.a: spoken words.

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

2.2.1.4 Analysis

For the analysis, we used R v4.0.3 (R Core Team, 2020) with the VWPre package v1.2.3 (Porretta, Kyröläinen, van Rij, & Järvikivi, 2018) for pre-processing and the lme4 package v1.1-25 (Bates, Mächler, Bolker, & Walker, 2015) for statistical analysis. Fixations to the four interest areas, corresponding to each picture presented, were grouped in 20 ms bins (20 samples) and averaged across trials. Furthermore, we averaged the proportion of looks to the two unrelated distractors to create a single unrelated baseline for the analyses.

For the statistical analysis, we defined the time windows for the competitors based on the temporal properties of the auditory stimuli for all target words in critical trials and allowing for approximately 200 ms needed to programme and launch an eye movement (Matin, Shao, & Boff, 1993) (see Figure 2.3). Thus, for the analysis of onset competitors, a time window (200-420 ms) was selected from 200 ms after the start of the word until 200 ms after the mean duration of the onset. For rhyme competition, a time window (440-820 ms) was selected from 200 ms after the mean point at which the rhyme starts until 200 ms after mean word offset. Individual trials with more than 25% track loss in the time window of interest were excluded from the analysis for the onset window ($n$ = 10, 0.6% of the data) and for the rhyme window ($n$ = 4, 0.3% of the data).

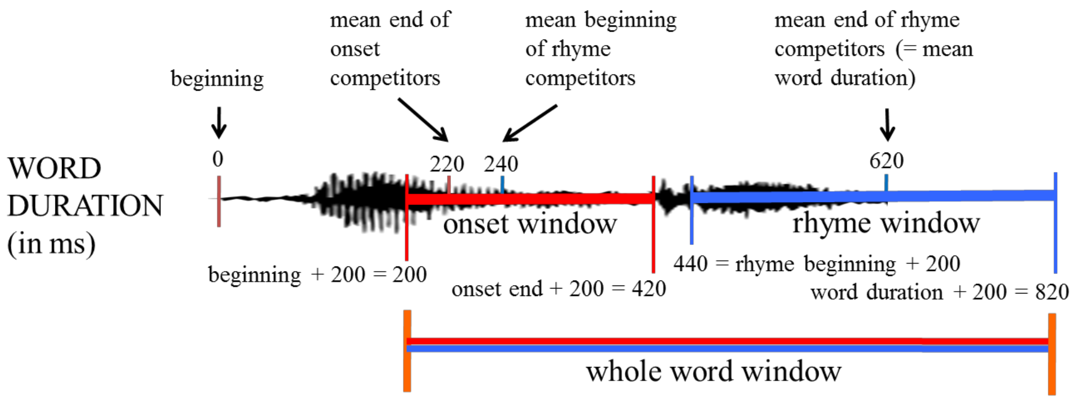


**Figure 2.3**. Illustration of word duration and the selected time windows for the analysis of onset and rhyme competition effects.

As explained earlier we used Growth Curve Analysis (Mirman, 2017) to estimate parameters of fixation curves that reflected the average height of the curve (intercept term), steepness of the slope (linear term) and the shape of the curve (quadratic and higher-order terms). The high temporal resolution of time series analysis presents an important advantage over approaches that average fixation proportions across windows of interest and do not retain detailed information about the time course. Unless indicated otherwise, treatment coding was used to code the contrasts for fixed effects in the growth curve models. In treatment coding, one level of the contrast is treated as the reference level and parameters are estimated for the other level of the contrast relative to this reference level.

To capture interindividual variation in the rate of lexical activation, the models also included random effects of Participants and Participant-by-Competitor. Since visual world paradigm studies typically involve a single trial per item per participant and data from a single visual world paradigm trial consist of a sequence of categorical fixations rather than a smooth fixation probability curve, it is not possible to use growth curve analysis on participant-by-item data (Mirman, Dixon, & Magnuson, 2008). For the model parameter estimates, normal approximation (z-distribution) was used to calculate p-values.

**Sub-lexical effects**. To evaluate the effect of the sub-lexical competitors, the overall time course of fixations was modelled with a first-order (linear) orthogonal polynomial and fixed effects of Competitor type (Onset vs. Unrelated Distractor, Rhyme vs. Unrelated Distractor) on the time term. For onset competition, the window of analysis was from 200 ms to 420 ms after word onset. For rhyme, the window was from 440 ms to 820 ms after word onset. The Unrelated distractor was treated as the reference level and parameters were estimated for the Onset and Rhyme competitors. The model also included participant and participant-by-competitor random effects on the temporal term.

**Comparison of sub-lexical effects**. To examine differences in the time course of onset and rhyme competitor effects, we performed growth curve analysis across a whole-word length window, that is, mean duration of the target words (620 ms) plus 200 ms to account for the planning of eye movements (i.e. 200-820 ms). The competitor curves were modelled with a second-order (quadratic) orthogonal polynomial and fixed effect of Competitor type (Onset vs. Rhyme), as well as participant and participant-by-competitor random effects on all temporal terms. Looks to the onset competitor were treated as the reference level and parameters were estimated for the rhyme competitor.

### 2.2.2 Results

Figure 2.4 shows the proportion of looks to onset and rhyme competitors and unrelated distractors in critical trials across all participants for 2000 ms after the onset of the target word.

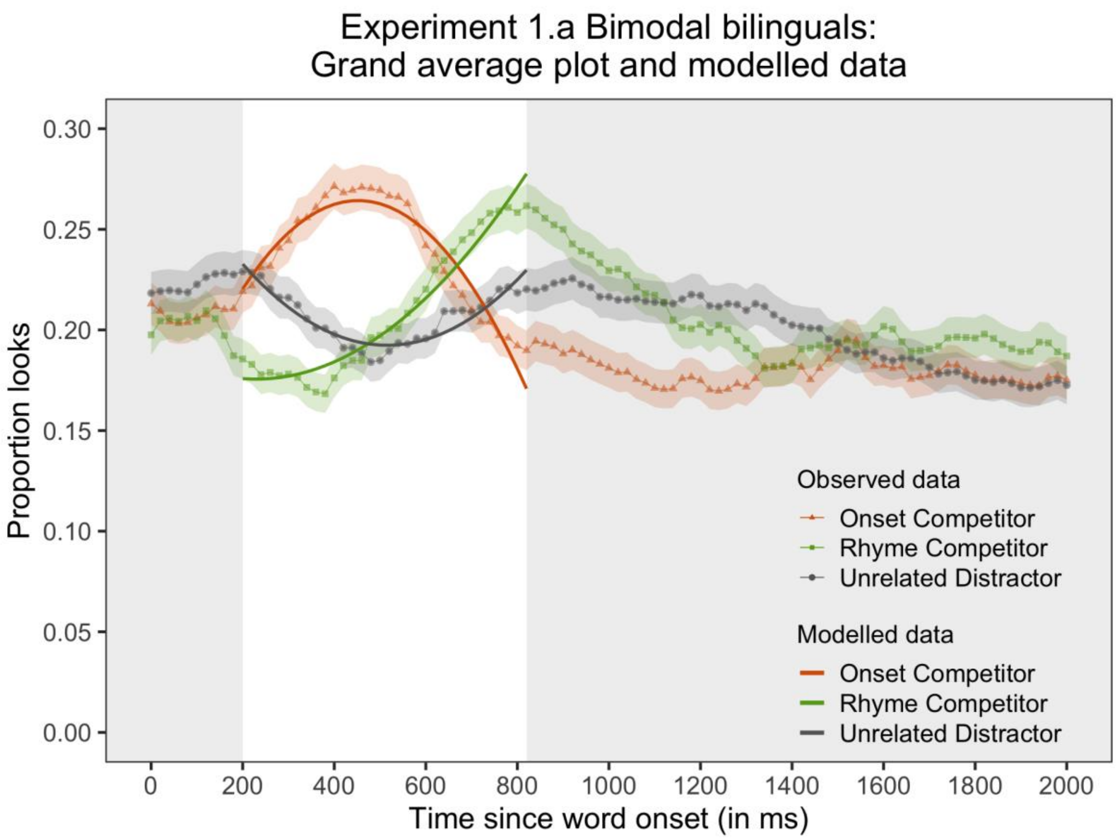


**Figure 2.4**. Proportion of looks and model fit for onset and rhyme competitors and unrelated distractors since word onset for native and L2 signers (all native speakers of Spanish) in Experiment 1.a: spoken words. Error bands show standard errors. Within the window of interest (200-840 ms), on a white background, bold lines show the fitted model.

2.2.2.1 Sub-lexical effects: onset and rhyme

***Onset competitors.*** There was a significant effect of competitor type on the intercept term (*Estimate* = 0.035, *SE* = 0.011, $p$= 0.001), indicating a higher overall proportion of looks to onset competitors than unrelated distractors. There was also a significant effect of Competitor type on the linear term (*Estimate* = 0.102, *SE* = 0.023, $p < 0.001$), indicating a steeper slope for looks to the onset competitor than for unrelated distractors (see the left panel in Figure 2.5 and Table 2.3).

**Table 2.3**
*Parameter estimates for growth curve analysis of onset competitor (200-420 ms time window) for native and L2 signers*

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

***Rhyme competitors***. The analysis showed a significant effect of Competitor type on the intercept term (*Estimate* = 0.025, *SE* = 0.007, $p < 0.001$), reflecting a higher overall proportion of looks to the rhyme competitors than to unrelated distractors. A significant effect of Competitor type on the linear term was also found (*Estimate* = 0.064, *SE* = 0.030, $p = 0.029$), indicating a steeper slope of looks to the Rhyme competitor relative to unrelated distractors (see the right panel in Figure 2.5 and Table 2.4).

**Table 2.4**

*Parameter estimates for growth curve analysis of rhyme competitor (440-820 ms time window) for native and L2 signers*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.203 | 0.006 | 35.863 | **<0.001** |
| Linear | 0.053 | 0.021 | 2.531 | **0.011** |
| Rhyme : Intercept | 0.025 | 0.007 | 3.375 | **<0.001** |
| Rhyme : Linear | 0.064 | 0.030 | 2.181 | **0.029** |

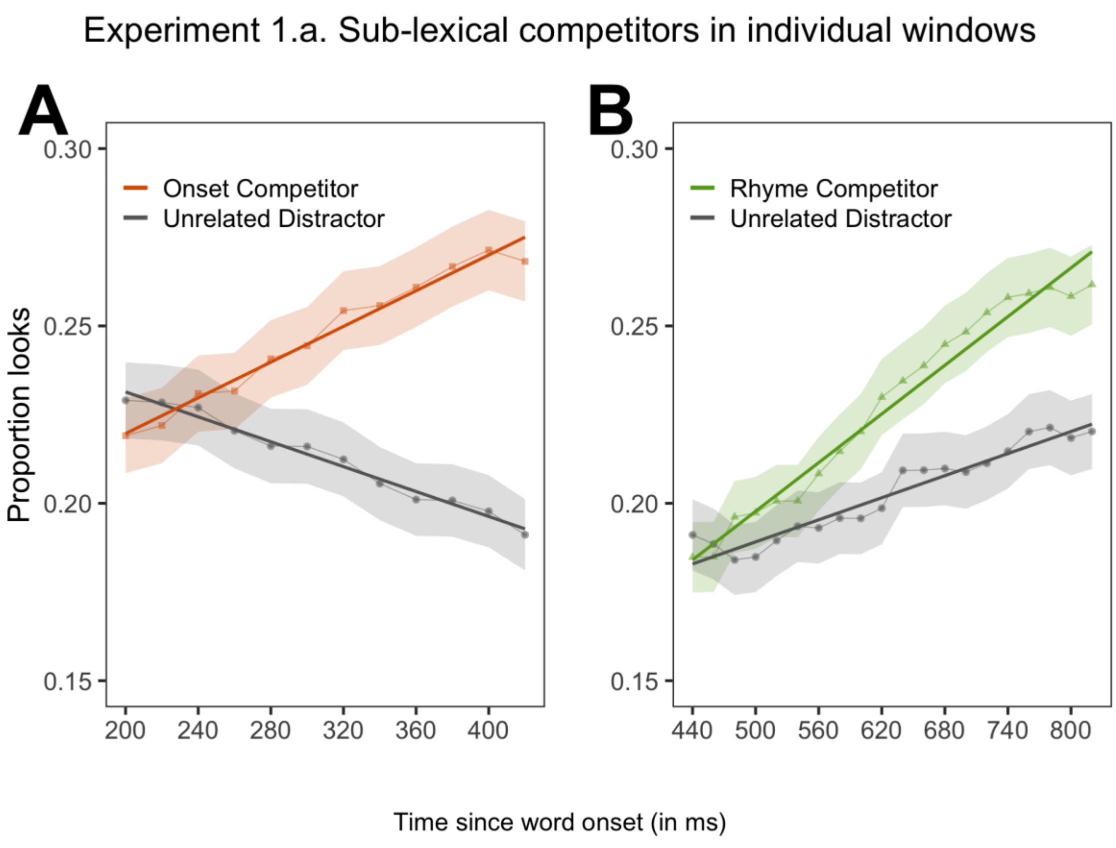


**Figure 2.5**. Model fit for onset (left) and rhyme (right) competitors and unrelated distractors across native and L2 signers (all native speakers of Spanish) in Experiment 1.a: spoken words. Error bands show standard errors.

***Comparison of onset and rhyme competitors***. This analysis yielded a significant effect of Competitor type on the intercept (*Estimate* = -0.030, *SE* = 0.007, $p < 0.001$), indicating a greater proportion of looks to the Onset competitor compared to the Rhyme competitor. Additionally, there were significant effects of Competitor type on the linear term (*Estimate* = 0.255, *SE* = 0.042, $p < 0.001$) and on the quadratic term (*Estimate* = 0.169, *SE* = 0.034, $p < 0.001$); these differences in the time terms indicate that the time course of the two competitors differed. Specifically, the more positive linear term and the change in polarity of the quadratic term for the Rhyme competitors with respect to the Onset competitors indicate that the Rhyme effect was later than the Onset effect, as can be seen in Figure 2.4 Together, these results indicate earlier and stronger effects from onset than rhyme competitors (see Table 2.5).

**Table 2.5**
*Parameter estimates for growth curve analysis (200-820 ms time window) to compare onset (reference) and rhyme competitors for all participants*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.238 | 0.006 | 42.244 | **<0.001** |
| Linear | -0.084 | 0.031 | -2.706 | **0.007** |
| Quadratic | -0.119 | 0.024 | -4.892 | **<0.001** |
| Rhyme : Intercept | -0.030 | 0.007 | -4.173 | **<0.001** |
| Rhyme : Linear | 0.255 | 0.042 | 6.108 | **<0.001** |
| Rhyme : Quadratic | 0.169 | 0.034 | 4.921 | **<0.001** |

## 2.3 Experiment 1.b: signed language

### 2.3.1 Methods

#### 2.3.1.1 Participants

The same participants that did Experiment 1.a (spoken language) performed Experiment 1.b (signed language).

#### 2.3.1.2 Materials

The experimental task with LSE signs consisted of 45 trials with four images in the corners of the screen and a centrally presented video of an LSE target sign (Figure 2.6). In critical trials ($n = 30$), the target sign in the video was phonologically related to two of the signs corresponding to the pictures: one sign had the same place of articulation as the target sign (location competitor), and the other sign had the same handshape as the target sign (handshape competitor). The other two pictures were unrelated to the target sign. In critical trials there was no image corresponding to the target sign (see Table A2 in Appendix A for an overview of all stimuli in critical trials). In filler trials (*n* = 15) the target image was present and the other three images were unrelated distractors.

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

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

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

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

2.3.1.3 Procedure

The procedure was the same as that used for experiment 1.a with two differences: instructions were shown in LSE; and a video with an LSE target sign was presented in the centre of the screen during each trial instead of a Spanish auditory target word. Figure 2.6 illustrates the trial sequence.

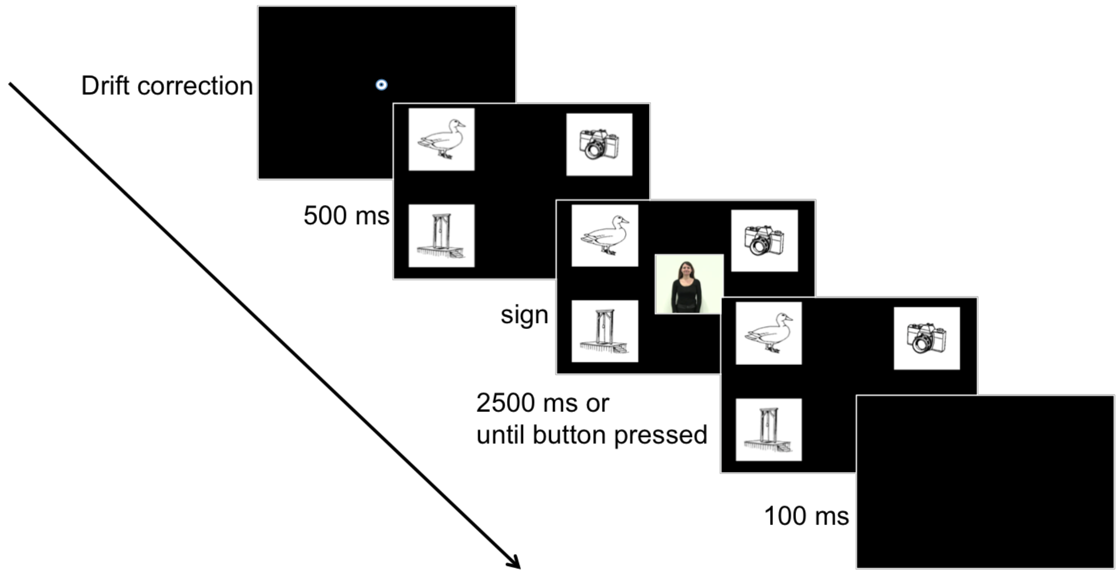


**Figure 2.6**. Trial sequence for Experiment 1.b: signs.

2.3.1.4 Analysis

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

As in Experiment 1.a, data were pre-processed and analysed using the VWPre package and the lme4 package on R v4.0.3. Fixations to each interest area were grouped in 20 ms bins (20 samples) and averaged across trials. Looks to the unrelated pictures were averaged together to create a single unrelated baseline condition for the analysis.

For the analysis of sign competitors, we selected a time window motivated by the properties of the sign stimuli (see Figure 2.7). In contrast to onset and rhyme competitors in experiment 1.a, the sub-lexical parameters of signs are present simultaneously when the sign is articulated. Therefore, we selected the same time window for the analyses of handshape and location competitors. The onset point for the window of analysis was adjusted to the sign onset of each individual target sign (defined as the moment when both handshape and location were visibly articulated). Mean sign duration was 740 ms (*SD* = 152), resulting in a 200-940 ms window for analysis after accounting for the ~200 ms required to programme an eye movement. Individual trials with more than 25% track loss in the time window of interest were excluded from the analysis (*n* = 1, 0.06% of the data).

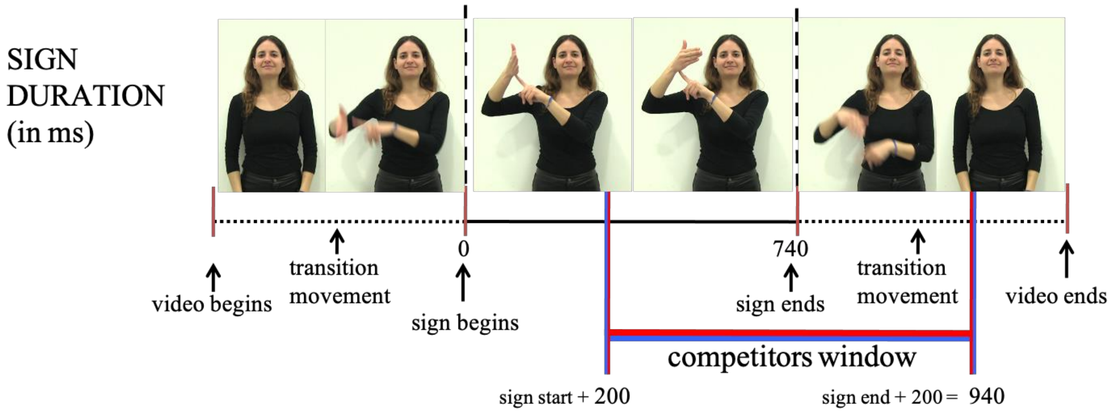


**Figure 2.7**. Illustration of video and sign duration (in ms) and the selected time windows for the analysis of location and handshape competition effects for the LSE sign BANDERA [flag].

**Group comparison**. To compare the time course of the co-activation between native and L2 signers we computed two difference curves by subtracting the proportion of looks to the unrelated distractors from the proportion of looks to the location and handshape competitors, respectively, in the time window of interest. We performed growth curve analysis including group (native signers vs. L2 signers) as a between-subjects factor. The overall time course of fixations was modelled with a second-order (quadratic) orthogonal polynomial and fixed effects of Competitor type and Group on all time terms. To estimate main effects of Group and Competitor type in the model, we used sum coding for these contrasts, which estimates simple effects (Mirman, 2017).

**Sub-lexical effects**. To check the effect of the sub-lexical competitors, the overall time course of fixations was modelled with a second-order (quadratic) orthogonal polynomial and fixed effects of Competitor type (Location vs. Unrelated Distractor, Handshape vs. Unrelated Distractor) on all time terms. Treatment coding was used to code the contrasts for fixed effects. The Unrelated distractor was treated as the reference level and parameters were estimated for the Location and Handshape competitors. The model also included participant and participant-by-competitor random effects on all temporal terms.

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

## 2.3.2 Results

Average response time for filler trials (target present) was 1,862 ms (*SD* = 214) for the native bimodal bilinguals, and 1,941 ms (*SD* = 212) for L2 signers; this difference between groups was not significant (two-tailed t-test: $t(54) = -1.38$, $p = .174$). The mean time to shift their gaze away from the stimulus video to the interest areas in critical trials was 1,157 ms (*SD* = 150) for native signers, and 1,185 ms (*SD* = 99) for L2 signers; this difference between groups was not significant (two-tailed Welch t-test: $t(46.7) = .84$, $p = .405$).

### 2.3.2.1 Group comparison: native and L2 signers

This analysis yielded a main effect of Competitor type on the linear term (*Estimate* = 0.043, *SE* = 0.015, $p = 0.006$). The interaction between Competitor type and Group was also significant on the linear term (*Estimate* = 0.055, *SE* = 0.015, $p < 0.001$) (see Table 2.6). Therefore, we performed follow-up growth curve analyses for each group and competitor separately.

**Table 2.6**
*Parameter estimates for growth curve analysis including Competitor type (location versus handshape) and Group (native signers versus L2 signers). This analysis uses sum coding to show main effects of each contrast.*

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

2.3.2.2 Native signers

Figure 2.8 shows the proportion of looks from sign onset to location and handshape competitors, unrelated distractors and stimulus video for native bimodal bilinguals.

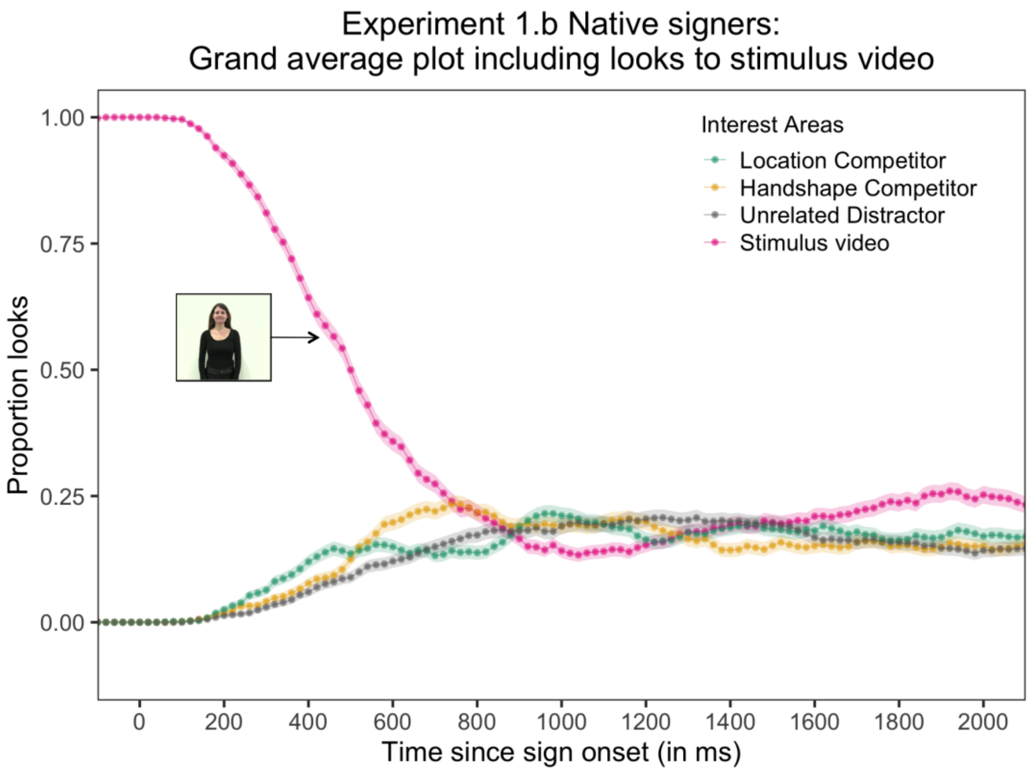


**Figure 2.8**. Proportion of looks to location and handshape competitors, unrelated distractors and stimulus video for native bimodal bilinguals from sign onset (0-2100 ms).

**Sub-lexical effects: location and handshape**

***Location competitors.*** There was a significant effect of Competitor type on the intercept term (*Estimate* = 0.019, *SE* = 0.006, *p* = 0.002), indicating a higher overall proportion of looks to location competitors than to unrelated distractors. There was also a significant effect of Competitor type on the linear term (*Estimate* = -0.115, *SE* = 0.045, *p* = 0.01) reflecting a more negative slope for the location competitors relative to unrelated distractors, likely driven by the relative decrease of looks to location competitors in the second half of the window. See Figure 2.9 for model fit and Table 2.7 for full results.

***Handshape competitors.*** The analysis showed a significant effect of Competitor type on the intercept (*Estimate* = 0.036, *SE* = 0.006, $p < 0.001$), reflecting a higher overall proportion of looks to handshape competitors than to unrelated distractors. There was also a significant effect of Competitor type on the quadratic term (*Estimate* = -0.100, *SE* = 0.039, *p* = 0.01); as the estimate for the quadratic term for the distractors was negative, this negative effect means that the (absolute) magnitude of the quadratic term for handshape competitors was greater, indicating a sharper peak for looks to handshape competitors compared to distractors. See Figure 2.9 for model fit and Table 2.7 for full results.

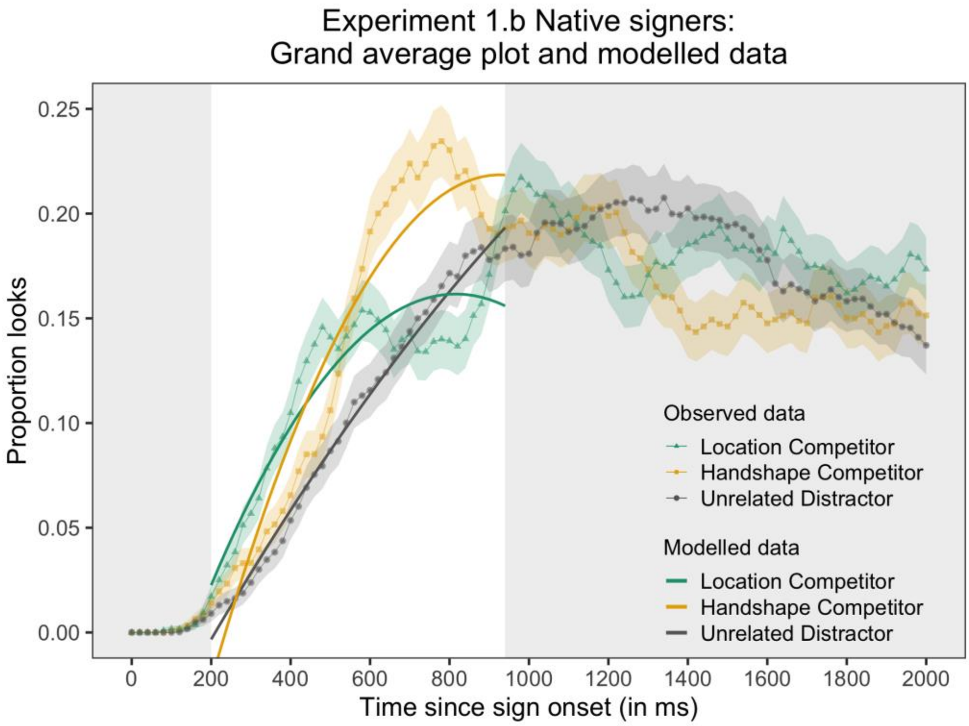


**Figure 2.9**. Proportion of looks to location and handshape competitors and unrelated distractors for native bimodal bilinguals (*n*=28) from sign onset to the end of the trial (0-2000 ms). Error bands show standard error. Within the window of interest (200-940 ms), on a white background, bold lines show the fitted model.

**Table 2.7**
*Parameter estimates for growth curve analysis of Location and Handshape Competitors (compared to unrelated distractors) for native bimodal bilinguals*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.102 | 0.007 | 14.438 | **<0.001** |
| Linear | 0.359 | 0.032 | 11.069 | **<0.001** |
| Quadratic | -0.020 | 0.029 | -0.715 | 0.474 |
| Location : Intercept | 0.019 | 0.006 | 3.007 | **0.002** |
| Handshape : Intercept | 0.036 | 0.006 | 5.503 | **<0.001** |
| Location : Linear | -0.115 | 0.045 | -2.556 | **0.010** |
| Handshape : Linear | 0.082 | 0.045 | 1.821 | 0.068 |
| Location : Quadratic | -0.076 | 0.039 | -1.941 | 0.052 |
| Handshape : Quadratic | -0.100 | 0.039 | -2.553 | **0.010** |

**Comparison of location and handshape competitors**

There was a significant effect of Competitor type on the intercept (*Estimate* = -0.0164, *SE* = 0.007, $p = 0.03$), indicating a higher proportion of looks towards handshape competitors compared to location competitors (see Figure 2.9). The analysis also showed a significant effect of Competitor type on the linear term (*Estimate* = -0.197, *SE* = 0.047, $p < 0.001$), indicating a more positive slope for looks to handshape competitors compared to location competitors. These results suggest that compared to location competition, handshape competition was stronger and occurred later (see Table 2.8 for full results).

**Table 2.8**
*Parameter estimates in growth curve analysis to compare competition from location and handshape (reference) for native bimodal bilinguals*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.138 | 0.007 | 18.249 | **<0.001** |
| Linear | 0.441 | 0.035 | 12.275 | **<0.001** |
| Quadratic | -0.121 | 0.034 | -3.528 | **<0.001** |
| Location : Intercept | -0.016 | 0.007 | -2.166 | **0.030** |
| Location: Linear | -0.197 | 0.047 | -4.174 | **<0.001** |
| Location : Quadratic | 0.024 | 0.046 | 0.512 | 0.608 |

2.3.2.3 L2 signers

Figure 2.10 shows the proportion of looks from sign onset to location and handshape competitors, unrelated distractors and stimulus video for L2 signers.

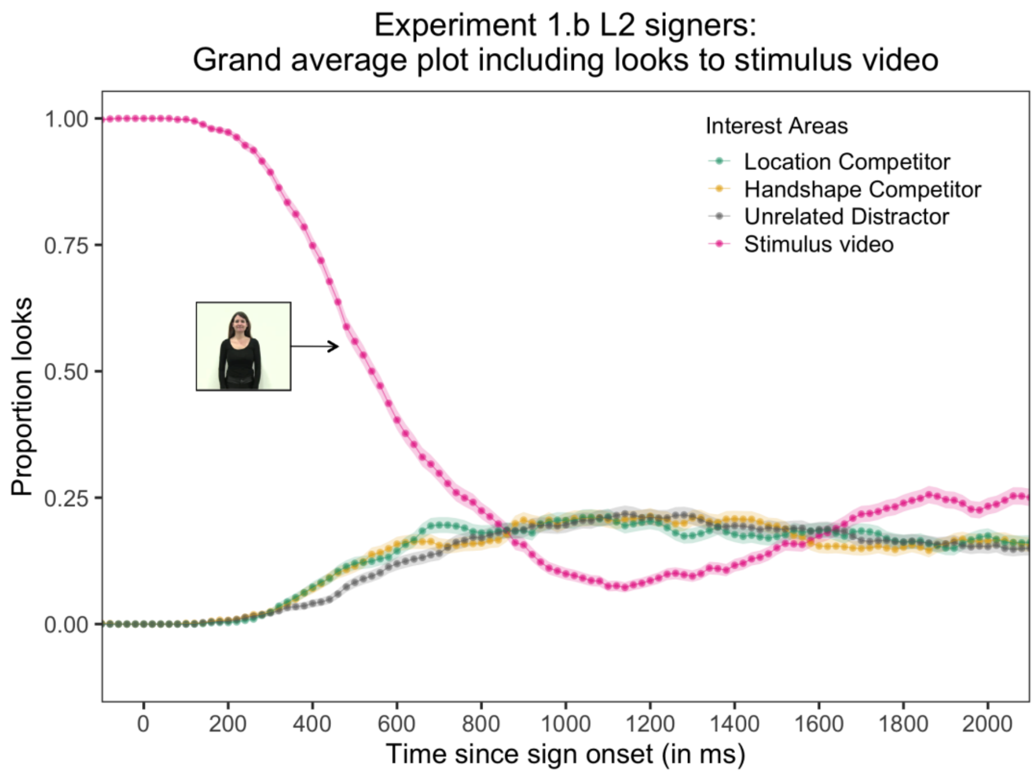


**Figure 2.10**. Proportion of looks to location and handshape competitors, unrelated distractors and stimulus video for L2 signers from sign onset (0-2100 ms).

### Sub-lexical effects: location and handshape

***Location competitors.*** A significant effect of Competitor type on the intercept term was found (*Estimate* = 0.020, *SE* = 0.007, *p* = 0.004), reflecting a higher overall proportion of looks to location competitors than to unrelated distractors. There was also a significant effect of Competitor type on the quadratic term (*Estimate* = -0.107, *SE* = 0.034, *p* = 0.001), indicating a sharper peak for looks to location competitors compared to unrelated distractors. See Figure 2.11 for model fit and Table 2.9 for full results.

***Handshape competitors.*** A significant effect of Competitor type was found on the intercept term (*Estimate* = 0.014, *SE* = 0.007, *p* = 0.036), indicating a higher overall proportion of looks to handshape competitors than to unrelated distractors. There was a significant effect of Competitor type on the quadratic term (*Estimate* = -0.074, *SE* = 0.034, *p* = 0.029), indicating a sharper peak for handshape competitors relative to unrelated distractors (see Figure 2.11 for model fit and Table 2.9 for full results).

**Table 2.9**
*Parameter estimates for growth curve analysis of Location and Handshape competitors (compared to unrelated distractors) for L2 signers*

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

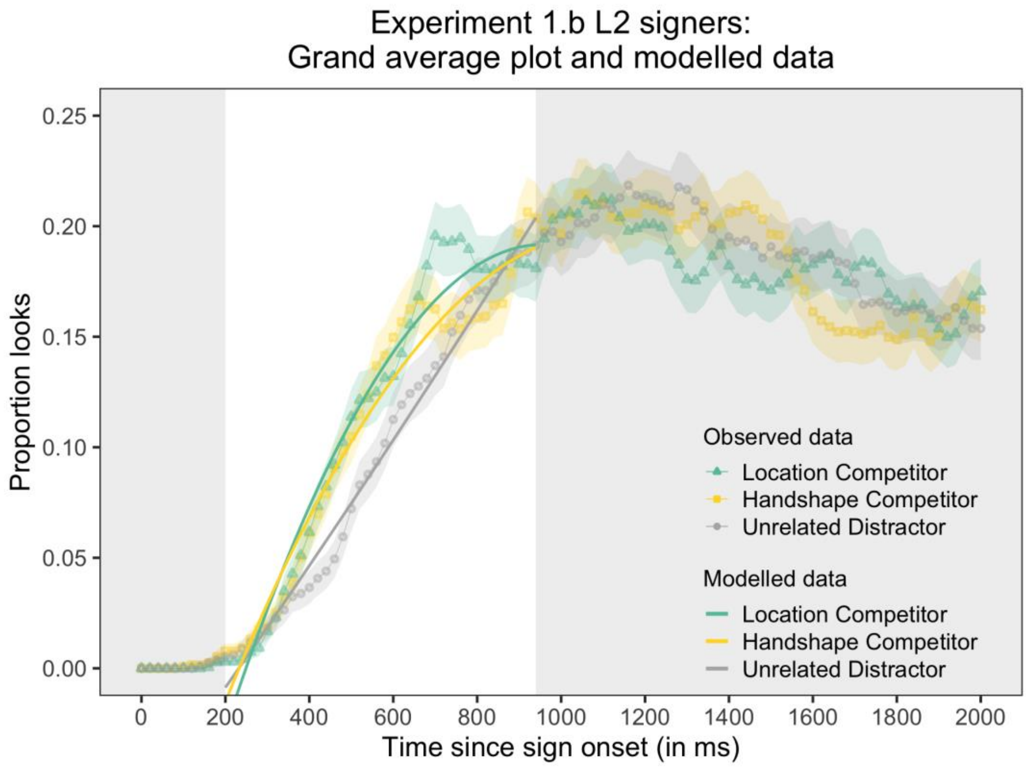


**Figure 2.11**. Proportion of looks to location and handshape competitors and unrelated distractors for L2 signers (*n*=28) from sign onset to the end of the trial (0-2000 ms). Error bands show standard error. Within the window of interest (200-940 ms), on a white background, bold lines show the fitted model.

### Comparison of location and handshape competitors

A growth curve analysis with looks to the handshape competitor as reference did not show any significant effects, indicating a similar effect with the same time course for both competitors (see Table 2.10 for full results).

**Table 2.10**
*Parameter estimates for growth curve analysis to compare location and handshape (reference) competitors for L2 signers*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.110 | 0.007 | 14.935 | **<0.001** |
| Linear | 0.375 | 0.028 | 13.260 | **<0.001** |
| Quadratic | -0.068 | 0.027 | -2.471 | **0.013** |
| Location : Intercept | 0.005 | 0.008 | 0.658 | 0.510 |
| Location : Linear | 0.024 | 0.038 | 0.637 | 0.524 |
| Location : Quadratic | -0.032 | 0.034 | -0.942 | 0.346 |

2.3.2.4 Comparison between native and L2 signers for each competitor.

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

***Location competitors.*** There was no effect of Group on the intercept, and thus no evidence of a difference in the overall proportion of looks to location competitors between native signers and L2 signers. However, there was a significant effect of Group on the linear term (*Estimate* = 0.127, *SE* = 0.061, $p$ = 0.038), indicating a more positive slope for looks to location competitors over distractors in L2 signers compared to native bimodal bilinguals, motivated by an earlier effect in the native bilinguals. See Figure 2.12 (left panel) and Table 2.11 for full results.

**Table 2.11**
*Parameter estimates for growth curve analysis of location competitor comparing native signers (reference level) and L2 signers*

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

***Handshape competitors.*** There was a significant effect on the intercept (*Estimate* = -0.021, *SE* = 0.008, $p$ =0.012), indicating an overall lower proportion of looks to handshape competitors by L2 signers compared to native bimodal bilinguals. There were no significant group differences on any of the time terms. See Figure 2.12 (right panel) and Table 2.12 for full results.

**Table 2.12**
*Parameter estimates for growth curve analysis of handshape competitors comparing native signers (reference level) and L2 signers*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.036 | 0.005 | 6.051 | **<0.001** |
| Linear | 0.082 | 0.038 | 2.125 | **0.033** |
| Quadratic | -0.100 | 0.033 | -3.001 | **0.002** |
| L2 signers : Intercept | -0.021 | 0.008 | -2.507 | **0.012** |
| L2 signers : Linear | -0.095 | 0.054 | -1.737 | 0.082 |
| L2 signers : Quadratic | 0.025 | 0.047 | 0.543 | 0.586 |

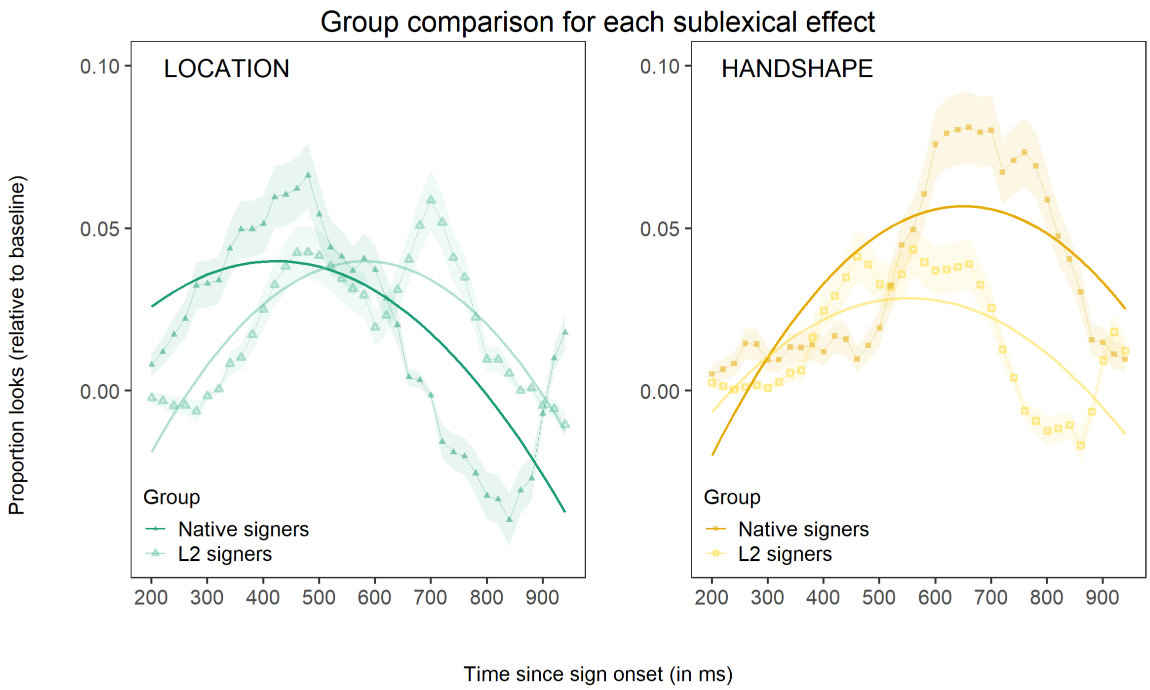


**Figure 2.12**. Model fit for location (left) and handshape (right) competitor effects in Experiment 1.b: signs. Error bands show standard errors.

## 2.4 Discussion

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

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

### 2.4.1 Impact of language modality on lexical access

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

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

The results also align with recent eye-tracking studies using the visual world paradigm that have further confirmed that deaf children and adults process signs incrementally and use partial information to constrain lexical recognition processes (Lieberman et al., 2014; MacDonald et al., 2018; Thompson et al., 2013), despite having to divide their visual attention between the sign (stimulus video in the experimental context) and the visual environment (objects on the screen in the experimental context). However, these studies relied on combinations of shared parameters between target and competitors, for example, signs sharing handshape *and* location, or location *plus* movement. The unique contribution of the current study, therefore, is that we independently manipulated handshape and location overlap to investigate sub-lexical co-activation during lexical processing in the signed modality; and onset and rhyme overlap in the spoken modality (cf. Allopenna et al., 1998; Magnuson et al., 2007). In addition, a particularly strong feature of our design is that we limited potential confounding stimulus and participant artefacts in the results by using the same experimental paradigm (visual world paradigm), group of participants (hearing bimodal bilinguals), and the same set of target items for within-modality phonological overlap (target-absent design with two competitors on the screen).

Despite the broadly simultaneous nature of the sign language signal, lexical processing appears to be incremental: location effects occurred earlier than handshape effects in hearing native bimodal bilinguals, in line with evidence from gating studies in which location is identified before handshape (Emmorey & Corina, 1990). In our stimuli, handshape, in fact, appeared slightly *before* location during the production of the signs (by around 80 ms on average – see section 2.3.1.2) and this subtle temporal precedence for handshape has been reported for other sign languages (Hosemann et al., 2013). This finding, therefore, suggests that the temporal course of sign processing does not follow the temporal order of the signal. In the remainder of the discussion, we will consider several other differences between the two phonological parameters that may account for this finding.

### 2.4.2 The role of different phonological parameters in sign recognition

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

A recent computational study by Caselli and Cohen-Goldberg (2014) examined the different impact of location and handshape by simulating the activation dynamics of sub-lexical units in a lexical network (see section 1.1.2 for more details). These simulations showed that earlier perception and a higher resting activation of location could both account for the often-reported combination of facilitatory effects of handshape overlap and inhibitory effects of location overlap in phonological priming studies. In line with this model, our results provide empirical support for earlier activation of location information than handshape information in native signers during sign recognition. Our results do not appear to provide support for higher resting activation of location; on the contrary, handshape competitors showed a stronger effect. However, it should be mentioned that their model aims to explain differential priming effects of location and handshape, and our data come from a very different task and reflect fixation patterns instead of reaction times. For example, greater looks to handshape competitors may reflect the facilitatory nature of handshape and could represent another instantiation of the facts that Caselli and Cohen-Goldberg attempt to explain rather than insight into the underlying mechanism. Reconciling and integrating findings from different paradigms is a goal for future research.

Higher resting activation for location information in signs could be due to higher sub-lexical frequency (in most sign languages there are fewer possible sign locations than hand configurations) or enhanced perceptual saliency of location information. As mentioned in section 1.1.3, perceptual saliency might explain differences between phonological parameters in the lexical processing of signs. Handshape is not very prominent perceptually, whereas location, especially in combination with movement, is perceptually more salient (Brentari, 2006; Corina & Hildebrandt, 2002; Dye & Shih, 2006; Hildebrandt & Corina, 2002; Thompson et al., 2013). A study in BSL using the visual world paradigm found evidence of effects only from competitors that shared both location and movement with the target sign, while competitors that shared location and handshape or handshape and movement did not yield reliable effects (Thompson et al., 2013). Since movement and location are the most salient parameters of the visual signal, the authors concluded that sign language processing is driven by saliency constraints and not by temporal factors relating to the order in which each parameter appears or is perceived in the signal. Although our results corroborate the conclusion that sign processing does not follow the temporal order of the signal, they do not fully align with the perceptual saliency account: hearing bimodal bilinguals (including the L2 signers) showed reliable competition effects from handshape competitors, contrary to the BSL findings. Nonetheless, there are differences between the two studies that might account for the divergent findings. Firstly, the competitors in the BSL study used combinations of shared sub-lexical units, while we examined the effect of each parameter separately. Furthermore, the two studies tested different groups of signers (deaf vs. hearing) and languages (BSL vs. LSE), which also makes a direct comparison of the findings difficult.

### 2.4.3 Age of acquisition effects in sign recognition

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

Native bimodal bilinguals showed significantly stronger handshape competitor effects compared to L2 signers. This may reflect differences in phonological processing conditioned by age of acquisition, in line with previous work that demonstrates that handshape is particularly problematic for L2 learners of the signed language (Carreiras et al., 2008; Orfanidou et al., 2009). This apparent complexity of handshape compared to location is also reflected in acquisition and learning studies. During infant acquisition, location is acquired before handshape, whether the child is deaf or hearing (Conlin, Mirus, Mauk, & Meier, 2000; Karnopp, 2002; Marentette & Mayberry, 2000; Meier, 2000; Morgan, Barrett-Jones, & Stoneham, 2007; Siedlecki & Bonvillian, 1993). In adult second language learning, a similar pattern appears, with handshape being more difficult to learn than location (Bochner, Christie, Hauser, & Searls, 2011; Ortega, 2013; Ortega & Morgan, 2015). Handshape is also the most affected parameter in sign language aphasia (Corina, 2000). All this evidence points to the fact that the acquisition and/or processing of handshape is more challenging than the processing of location, and that the processing of handshape benefits from native experience. The difficulty associated with handshape may be due to various reasons. Firstly, handshape is made up of more complex information: phonological models (such as Brentari, 1998) posit more features to specify handshape in comparison with location, and those features tend to have a larger set of possible values for handshape compared to location. This has a knock-on effect on other properties of these sub-lexical units that influence processing. The wider range of values for handshape features means that a larger number of handshapes exists in the phonological repertoire of a given language. As a result, handshapes tend to have lower sub-lexical frequencies than locations. Secondly, handshape involves smaller articulators, namely, the fingers and their joints, compared to location, which includes the head, the upper body and the non-dominant hand. This leads to greater articulatory complexity in production and reduced perceptual saliency during comprehension. This factor may account for the challenging nature of handshape during developmental acquisition. However, the finding that L2 signers discriminate more handshapes but have less categorical perception compared to native signers (Morford et al., 2008) suggests that their difficulty with handshape is related to mapping the visual signal onto phonological categories and not difficulties in perceiving the visual signal itself. Results from our study also point away from perceptual saliency as driving factor in L2 processing: one might expect L2 signers to make greater use of location as a perceptually more salient parameter, yet the L2 signers did not show any greater reliance on location (either with respect to handshape or compared to native signers).

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

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

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

## 2.5 Conclusions

Our results demonstrate that the dynamics of language modality impact lexical access. The sequential structure of spoken words is evident in the word recognition process, as onset effects precede rhyme effects, demonstrating that lexical access is conditioned by the auditory information as it becomes available. The availability of simultaneous sub-lexical information in signed languages influences sign recognition, but lexical access is also conditioned by other sub-lexical factors, namely, differences between location and handshape processing arising from the linguistic properties of these sub-lexical parameters and from affordances of the visual modality, in which transition movements can provide information about location before handshape information becomes available. Compared to native signers, late signers showed weaker effects from handshape competitors, which may reflect less robust phonological representations of this complex parameter, and later effects from location competitors, possibly due to reduced sensitivity to early location cues during the transition movements.

These results demonstrate that the experimental paradigm is valid for use with signed language stimuli and reveal the dynamics of sub-lexical activation when perceiving linguistic signals in different modalities. The next chapter investigates *cross-modal* co-activation by adapting the current experiments to examine the time course and nature of sub-lexical activation of words and signs when bimodal bilinguals perceive signs and spoken words, respectively.

# Chapter 3. Cross-Language Lexical Access

## 3.1 Introduction

From the previous experiments we know how bimodal bilinguals process sub-lexical units in spoken language, on the one hand, and in sign language, on the other. In this chapter we shift our attention to parallel activation between a signed and a spoken language, which is to say, to *cross-language*, *cross-modal* parallel activation, and we focus on three issues. Firstly, although we know that hearing bimodal bilinguals activate the signed language while hearing spoken words (Giezen et al., 2015; Shook & Marian, 2012; Villameriel et al., 2016), it is unclear whether cross-language activation in bimodal bilinguals is bidirectional, that is, whether the spoken language is also co-activated while processing signs. Secondly, we explore the role of sub-lexical units in spoken and signed parallel activation to build on the findings of the previous chapter, which revealed the impact of the sub-lexical structure of spoken and signed languages on lexical co-activation *within* the language. Here we look at what happens during lexical co-activation *across* two languages with very different sub-lexical units: auditory for the spoken language and visual in the case of the signed language. Finally, we look at the impact of modality: how does parallel activation compare between bimodal and unimodal bilinguals? In addition to the previous questions, we consider whether parallel activation and processing is modulated by the AoA of the signed language in bimodal bilinguals.

The previous experiments from chapter 2 revealed the mechanisms underlying lexical access for a given language while that language is perceived. Hearing **estrella** [star] facilitates the activation of the onset competitor **espada** [sword] and the rhyme competitor **botella** [bottle] because both words share certain sounds with the target. In this chapter, we report findings from experiments in which the perceived (explicit) signal comes from a modality or language different to that of the (implicit) parallel language. For example, when seeing the Spanish Sign Language (LSE) sign **ESTRELLA** instead of hearing the word **estrella**, are the Spanish words **espada** and **botella** still activated? In this case, since the word is not perceived, the temporal structure of the spoken word may no longer affect the order in which onset and rhyme competition occur. To this end, we again use the visual world paradigm, which allows us to examine the time course of this parallel activation. To test co-activation in cross-language setting we performed the following experiments. Experiment 2.a looks at co-activation of spoken Spanish in an LSE context, that is, a *cross-modal* context: participants see an LSE sign and the on-screen pictures include phonological competitors for the Spanish translation of the sign. Experiment 2.b examines co-activation of spoken Spanish while hearing spoken Basque, that is, in a *within-modal* context: Spanish-Basque bilinguals hear a Basque word and the on-screen images include phonological competitors for the Spanish translation of the Basque word. Experiment 2.c explores *cross-modal* parallel activation of LSE while hearing Spanish: bimodal bilinguals hear a Spanish word and the on-screen pictures include phonological competitors for the LSE translation of the word. Finally, Experiment 2.d replicates Experiment 2.c with sign language naïve individuals to ensure that any effects shown by the bimodal bilinguals are due to their knowledge of sign language and not our specific experimental design.

We used Growth Curve Analysis (Mirman, 2017), as in chapter 2, and we included predictions for the intercept and the time terms in our hypotheses. Given the robust evidence for bidirectional parallel activation in unimodal bilinguals (e.g. van Hell & Tanner, 2012) and given that the spoken language tends to be the dominant and, therefore, stronger language for hearing bimodal bilinguals (this was confirmed by the participants' self-ratings in the present study), we expect LSE signs to co-activate spoken Spanish in native bimodal bilinguals. Thus, in Experiment 2.a, native bimodal bilinguals will look more to word competitors compared to unrelated distractors. We expect significant differences in the intercept for onset and rhyme competitors compared to unrelated distractors. Furthermore, our within-language findings in Chapter 2 and previous research (e.g. Marslen-Wilson & Zwitserlood, 1989) show that onset competition is more robust than rhyme competition, so we predict a higher proportion of fixations towards onset competitors compared to rhyme competitors, that is, significant differences between onset and rhyme competitors on the intercept term (reflecting more looks to the onset competitors). Concerning the time course of activation, we foresee two possibilities. On the one hand, onset competition may continue to precede rhyme competition in line with the temporal course of the spoken signal. On the other hand, since the target Spanish word is not actually presented but only indirectly activated by the LSE sign, the time course of activation of onset and rhyme competitors may differ from the within-language setting.

In this sense, any possible differences in timing will be reflected by differences in the time terms. Concerning AoA of the signed language we can also envisage two possible outcomes. Given that both native and L2 signers have acquired Spanish as a native language from birth, the two groups might show similar co-activation patterns. Alternatively, the processing of the visual input may impact the time course of parallel activation. As shown in chapter 2, within-language co-activation in LSE was different between native and late signers, so native signers and L2 signers might show a different pattern of parallel Spanish activation due to differences in processing of the target signs.

In the case of Spanish-Basque bilinguals, we expect Basque words to co-activate Spanish words. Thus, in experiment 2.b Spanish-Basque bilinguals will look more to competitors than to distractors. This will be shown by significant differences in the intercept for onset and rhyme competitors relative to unrelated distractors. Furthermore, since a spoken signal is still perceived (even if it concerns a different language), we expect stronger activation from onset competitors compared to rhyme competitors in this cross-language context, similar to the within-language setting (see Chapter 2), through significant differences between onset and rhyme competitors on the intercept term. Concerning the time course of the parallel activation, we can again foresee two possibilities: onset competitors precede rhyme competitors, revealed by significant differences in the temporal terms (reflecting earlier looks to the onset competitors), in line with the temporal structure of the target word in the explicit language (Allopenna et al., 1998). Alternatively, cross-language activation may not be sensitive to the sequential structure of spoken words, since sub-lexical units in the implicit language are only indirectly activated by the linguistic signal. Importantly, although Spanish and Basque share the same modality, we are investigating *covert* co-activation in this experiment (cf. Shook & Marian, 2019, see section 1.3.2): target Basque words and Spanish competitors do not overlap in phonology (overt co-activation), but the Spanish translation of the target Basque word has the same onset and rhyme as the Spanish competitor (covert co-activation).

In Experiment 2.c on parallel LSE activation elicited by spoken words, we expect that native bimodal bilinguals will show co-activation of LSE, in line with previous work (Giezen et al., 2015; Shook & Marian, 2012; Villameriel et al., 2016), through significant differences on the intercept term for location and handshape competitors compared to unrelated distractors. If the pattern found in chapter 2 for within-language co-activation also holds in this cross-language context, we expect handshape effects to be stronger and occur later relative to location effects, revealed by significant differences between handshape and location competitors on the intercept term (reflecting more looks to handshape competitors) and significant differences on the time terms (reflecting earlier activation of location). Previous studies suggest that we should also expect parallel activation of LSE in L2 signers (Giezen et al., 2015; Villameriel et al., 2016). This co-activation may show a similar pattern as in the within-language context, with no differences between handshape and location effects. On the other hand, other forces might be at play: L2 representations of sign language may be weaker than those of native signers and, as a result, L2 signers may not inhibit their sign language to the same extent that native signers do. This could result in co-activation patterns that are more similar to that of the native group.

In Experiment 2.d we expect to find no co-activation of signs during processing of the spoken language in individuals with no knowledge of LSE.

In the following four sections we present the design and results of each experiment. The chapter continues with a discussion of the results in section 3.6 and ends with the conclusions (section 3.7).

## 3.2 Experiment 2.a: cross-modal. Parallel spoken lexical access in bimodal bilinguals

### 3.2.1 Methods

#### 3.2.1.1 Participants

We recruited two groups of participants: one group of 28 hearing native bimodal bilinguals and another group of 28 hearing late bimodal bilinguals. Most of the participants also participated in the experiments in chapter 2, but the experimental sessions were separated by at least 6 months. All participants were highly proficient in LSE and Spanish and used LSE on a daily basis for professional purposes (for the L2 signers, mean age of exposure: 21.1; range 16-26). We recruited participants and ran the experiment at various locations (Bilbao, Burgos, Madrid, Palencia, Pamplona, San Sebastián and Valladolid). Participants' characteristics are shown in Table 3.1.

**Table 3.1**
*Experiment 2.a Participant Characteristics (standard deviations in brackets)*

| Group | Number of participants | Gender | Mean Age | Mean years of LSE usage for professional purposes | Mean self-rated LSE competence (from 1 to 7) |
|---|---|---|---|---|---|
| Native signers | 28 | 22 women<br>6 men | 44<br>(7.3) | 20<br>(7.8) | 6.6<br>(0.6) |
| L2 signers | 28 | 21 women<br>7 men | 37<br>(6.1) | 10<br>(6.4) | 6.1<br>(0.5) |

3.2.1.2 Materials

We used the same materials from experiment 1.a with one modification: the target stimulus was presented as an LSE sign instead of as a spoken word. Therefore, in critical trials ($n$ = 30), the Spanish translation of the sign stimulus was phonologically related to the corresponding word for two of the images: one word shared the onset with the Spanish translation of the sign, and the other competitor word rhymed with the Spanish translation of the sign. In four of the critical trials there was visual overlap between the target sign and one or more of the corresponding signs for the on-screen pictures. These trials were excluded from the analysis, so the final number of critical trials was 26.

The video recordings for the target signs had the same characteristics as those of experiment 1.b: videos of a female deaf signer, cropped and scaled to 320x296 pixels and presented in the centre of the screen (25 fps). Each video started with the signer in resting position (hands by her sides) followed by a transition movement to articulate the sign and then finished back in the resting position. Average duration of the recorded video was 2,063 ms ($SD$ = 246 ms). The sign onset was defined as the frame in which the handshape was visibly articulated at the sign's location on the body. The end of the sign was defined as the last frame before the onset of the transition movement to the resting position. Average sign duration was 877 ms ($SD$ = 242); the average handshape onset was 387 ms after video onset and 420 ms for location onset.

3.2.1.3 Procedure

The procedure was the same as that used in Experiment 1.b in LSE (see Figure 3.1).

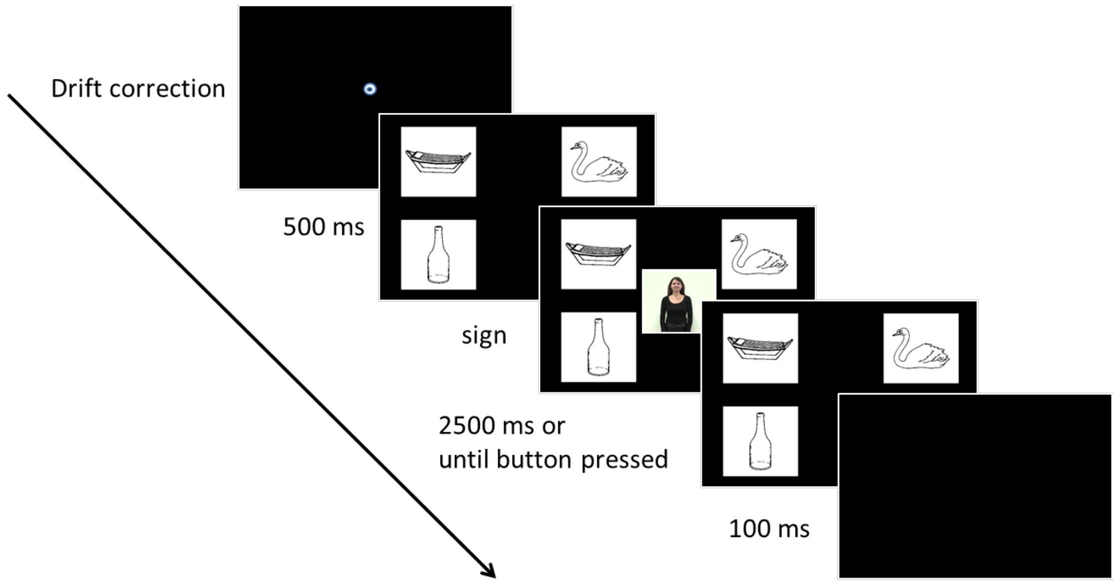


**Figure 3.1**. Trial sequence for Experiment 2.a: parallel activation of spoken Spanish.

3.2.1.4 Analysis

To account for dialectal variation of LSE, after the experiment the participants produced Spanish translations of the stimulus signs. When they did not produce the expected target Spanish word or they did not know the sign, the trial was eliminated from the analysis. In the case of native bimodal bilinguals 25.4% of the trials were discarded (range 3-12 per participant), and 25.1% for L2 signers (range 3-14 per participant). After removing these invalid trials, there were no critical trials with incorrect responses (i.e. false hits).

We analysed the data using R (R Core Team, 2020) v4.0.3 with the VWPre package (Porretta, Kyröläinen, van Rij, & Järvikivi, 2018) v1.2.3 for pre-processing and the lme4 package (Bates et al., 2015) v1.1-25 for statistical analysis. Fixations to each picture were clustered in 20 ms bins (20 samples) and averaged across trials. The proportion of looks to the two unrelated distractors was averaged together to generate a single unrelated baseline for the analysis.

For the analysis of onset and rhyme co-activation, we selected a time window based on the duration of the sign stimuli. We used the same time window for the analyses of both competitors. The onset point for the window of analysis was adjusted to the sign onset of each individual stimulus sign (defined as the moment when both handshape and location were visibly articulated). Average sign duration was 877 ms (*SD* = 242), resulting in a 200-1080 ms window for analysis after accounting for the ~200 ms involved to programme an eye movement (Matin et al., 1993) (see Figure 3.2). We excluded individual trials with more than 25% track loss in the analysis window (*n* = 4, 0.2% of the data).

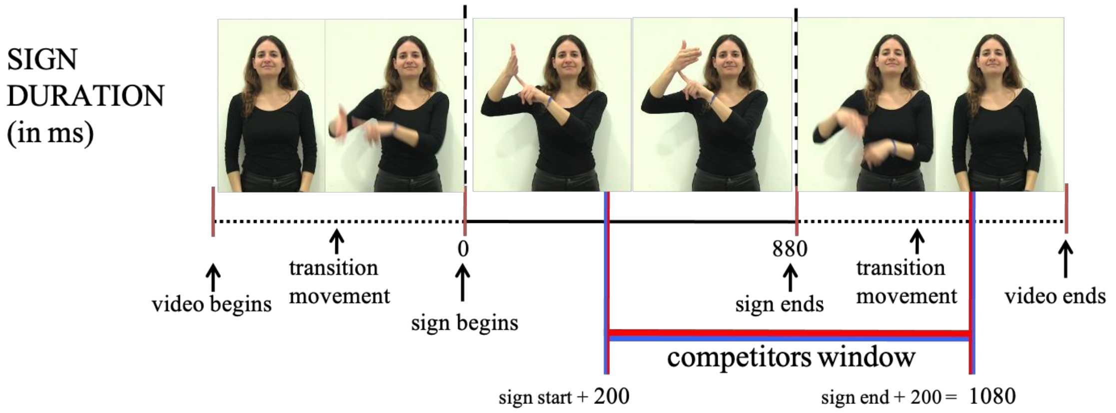


**Figure 3.2**. Illustration of sign duration (in ms) and the selected time window for the analysis of onset and rhyme competition effects.

To examine differences in the time course of gaze behaviour, we performed Growth Curve Analysis (Mirman, 2017), as in chapter 2.

**Group comparison**. To compare the time course of the co-activation between native and L2 signers we computed two difference curves by subtracting the proportion of looks to the unrelated distractors from the proportion of looks to the onset and rhyme competitors, respectively, in the time window of interest. We performed growth curve analysis including group (native signers vs. L2 signers) as a between-subjects factor. The overall time course of fixations was modelled with a second-order (quadratic) orthogonal polynomial and fixed effects of Competitor type and Group on all time terms. To estimate main effects of Group and Competitor type in the model, we used sum coding for these contrasts.

**Sub-lexical effects**. To assess the effect of the sub-lexical competitors, the overall time course of fixations was modelled with a second-order (quadratic) orthogonal polynomial and fixed effects of Competitor type (Onset vs. Unrelated Distractor, Rhyme vs. Unrelated Distractor) on all time terms. Treatment coding was used to code the contrasts for fixed effects. In treatment coding, one level of the contrast is treated as the reference level and parameters are estimated for the other level of the contrast relative to this reference level. The Unrelated Distractor was treated as the reference level and parameters were estimated for the Onset and Rhyme competitors. The model also included participant and participant-by-competitor random effects on all temporal terms.

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

## 3.2.2 Results

For filler trials (target present), the accuracy rate was 86.7% ($SD$ = 7.2) for the native signers and 88.1% ($SD$ = 6.9) for the L2 signers (no significant difference between groups: Mann-Whitney $U$ = 459, $p$ = .25). For these responses, the mean response time for the native bimodal bilinguals was 2,368 ms ($SD$ = 254), and 2,484 ms ($SD$ =281) for the L2 signers (no significant difference between groups: $t(54)$ = 1.60, $p$ = .114). For the experimental trials (target not present), the average time to shift gaze away from the stimulus video was 1,194 ms ($SD$ = 157) for native signers, and 1,268 ms ($SD$ = 124) for L2 signers (significant difference between groups: Mann-Whitney $U$ = 556.5, $p$ = .007); this group difference was confirmed by a two-sided paired t-test by items: $t(24)$ = 3.93, $p$ < .001, 95% CI [39.3, 126.1]).

Figure 3.3 shows the proportion of looks to onset and rhyme competitors, unrelated distractors and the stimulus video for bimodal bilinguals from sign onset (0-2100 ms).

Figure 3.4 shows the proportion of looks to onset and rhyme competitors and unrelated distractors for bimodal bilinguals (native and L2 signers), with the window of interest (200-1080 ms) based on the duration of the sign stimuli.

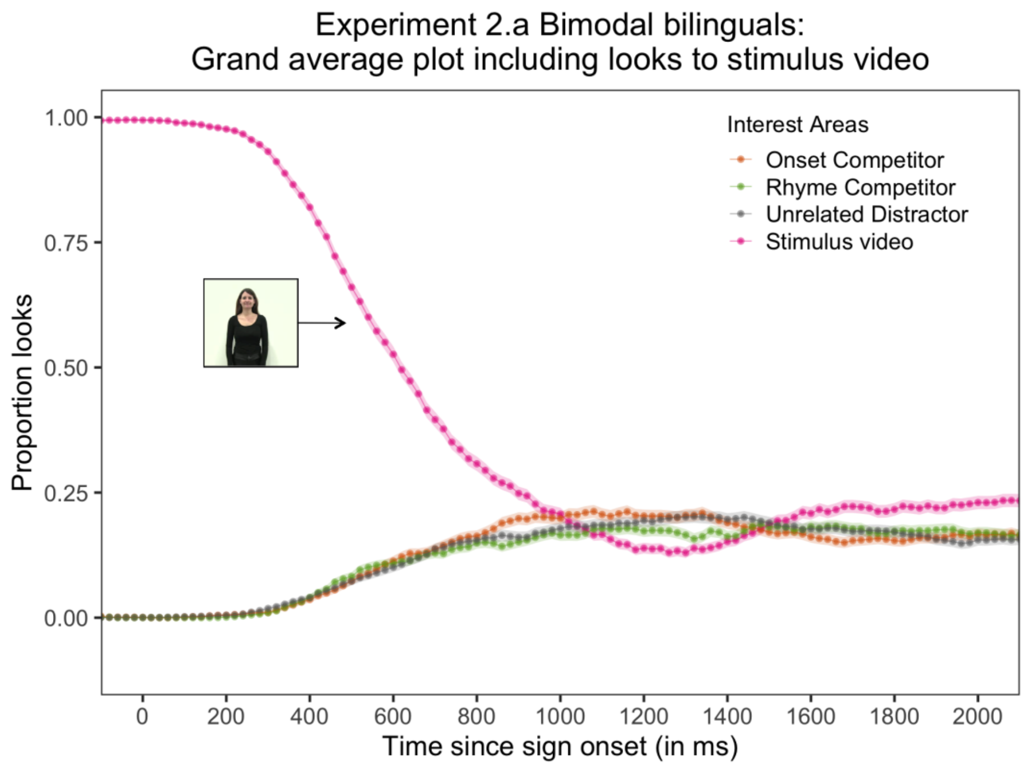


**Figure 3.3**. Proportion of looks to onset and rhyme competitors, unrelated distractors and stimulus video for all bimodal bilinguals (*n*=56) from sign onset (0-2100 ms). Error bands show standard error.

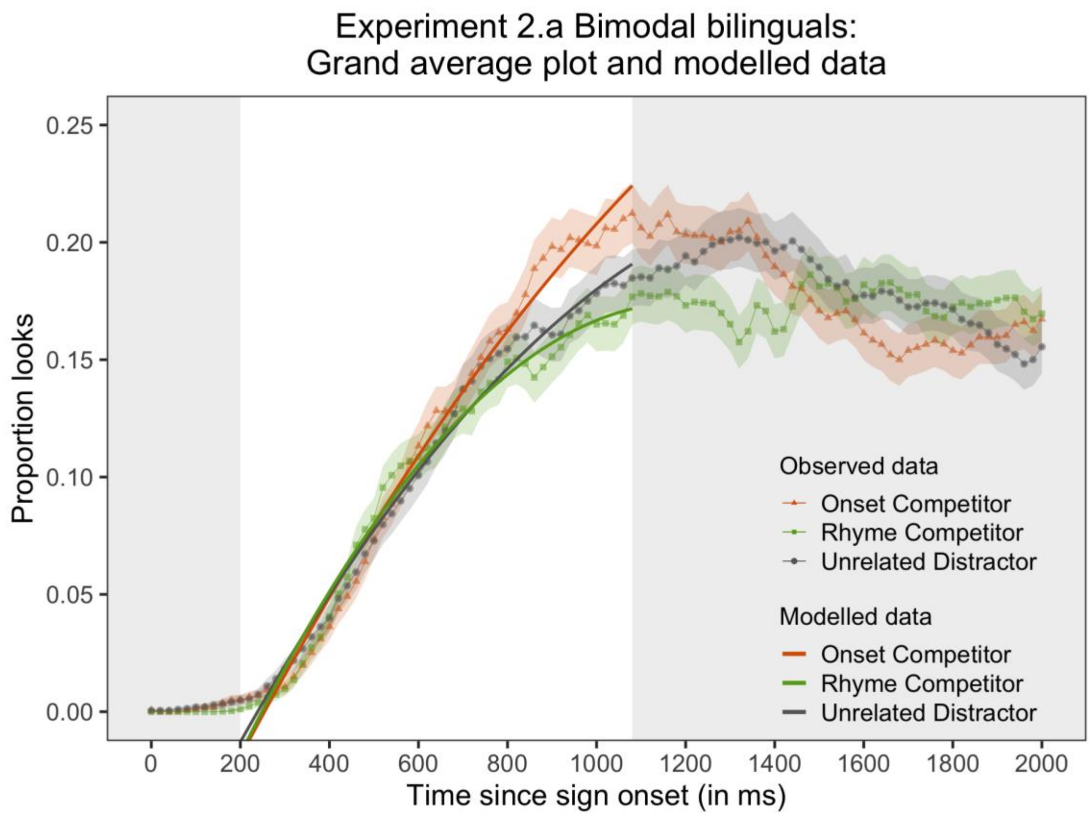


**Figure 3.4**. Proportion of looks to onset and rhyme competitors and unrelated distractors for all bimodal bilinguals (*n*=56) from sign onset to the end of the trial (0-2000 ms). Error bands show standard error. Within the window of interest (200-1080 ms), on a white background, bold lines show the fitted model.

3.2.2.1 Group comparison: native and L2 signers

The overall analysis considering both Competitor type and Group showed a main effect of Competitor type on the intercept (*Estimate* = 0.007, *SE* = 0.003, *p* = .017) and on the linear term (*Estimate* = 0.053, *SE* = 0.019, *p* = .006) but no effect of Group (see Table 3.2 for full results). As there was no main effect or interaction with Group, the analyses to examine the effect of each type of competitor were performed on the combined group of native and L2 signers.

**Table 3.2**
*Parameter estimates for growth curve analysis including Competitor type (onset versus rhyme) and Group (native signers versus L2 signers). This analysis uses sum coding to show main effects of each contrast.*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---:|---:|---:|---:|---:|
| Intercept | 0.003 | 0.004 | 0.894 | 0.371 |
| Linear | 0.026 | 0.025 | 1.039 | 0.299 |
| Quadratic | -0.009 | 0.028 | -0.314 | 0.753 |
| Competitor : Intercept | 0.007 | 0.003 | 2.378 | **0.017** |
| Group : Intercept | 0.005 | 0.004 | 1.363 | 0.173 |
| Competitor : Linear | 0.053 | 0.019 | 2.732 | **0.006** |
| Competitor : Quadratic | 0.020 | 0.020 | 1.021 | 0.307 |
| Group : Linear | 0.026 | 0.025 | 1.073 | 0.283 |
| Group : Quadratic | 0.012 | 0.028 | 0.418 | 0.676 |
| Competitor : Group : Intercept | 0.004 | 0.003 | 1.594 | 0.111 |
| Competitor : Group : Linear | 0.032 | 0.019 | 1.634 | 0.102 |
| Competitor : Group : Quadratic | 0.027 | 0.020 | 1.381 | 0.167 |

3.2.2.2 Sub-lexical effects: onset and rhyme

***Onset competitors.*** There was a significant effect of Competitor on the intercept term (*Estimate* = 0.010, *SE* = 0.005, *p* = .047), indicating a higher overall proportion of looks to onset competitors with respect to unrelated distractors, and on the linear term (*Estimate* = 0.079, *SE* = 0.032, *p* = .015), indicating a steeper slope for looks to onset competitors compared to unrelated distractors (see Figure 3.4 for model fit and Table 3.3 for full results).

***Rhyme competitors.*** The analysis showed no significant effect of Competitor on the intercept or on the temporal terms, indicating that overall there was no difference in proportion of looks or in the shape of the curve between rhyme competitors and distractors (see Figure 3.4 for model fit see and Table 3.3 for full results).

**Table 3.3**
*Parameter estimates for growth curve analysis of Onset and Rhyme Competition (compared to unrelated distractors) for native and L2 signers*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.104 | 0.005 | 22.141 | **<0.001** |
| Linear | 0.403 | 0.023 | 17.500 | **<0.001** |
| Quadratic | -0.049 | 0.023 | -2.118 | **0.034** |
| Onset : Intercept | 0.010 | 0.005 | 1.982 | **0.047** |
| Rhyme : Intercept | -0.003 | 0.005 | -0.610 | 0.542 |
| Onset: Linear | 0.079 | 0.032 | 2.435 | **0.015** |
| Rhyme: Linear | -0.027 | 0.032 | -0.845 | 0.398 |
| Onset: Quadratic | 0.012 | 0.032 | 0.365 | 0.715 |
| Rhyme: Quadratic | -0.029 | 0.032 | -0.918 | 0.359 |

3.2.2.3 Comparison of onset and rhyme competitors

The direct comparison of onset and rhyme competitor yielded a significant effect of Competitor type on the intercept term (*Estimate* = -0.013, *SE* = 0.005, *p* = .017) and on the linear term (*Estimate* = -0.106, *SE* = 0.035, *p* = .003), indicating a higher overall proportion and a steeper slope of looks to onset competitors compared to rhyme distractors (see Figure 3.4 for model fit and Table 3.4 for full results).

**Table 3.4**
*Parameter estimates for growth curve analysis of onset (reference) and rhyme competitors for native and L2 signers*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.114 | 0.005 | 22.928 | **<0.001** |
| Linear | 0.482 | 0.025 | 18.904 | **<0.001** |
| Quadratic | -0.037 | 0.025 | -1.493 | 0.135 |
| Rhyme : Intercept | -0.013 | 0.005 | -2.380 | **0.017** |
| Rhyme : Linear | -0.106 | 0.035 | -3.021 | **0.003** |
| Rhyme : Quadratic | -0.041 | 0.035 | -1.160 | 0.246 |

# 3.3 Experiment 2.b: within-modality. Parallel spoken lexical access in unimodal bilinguals

## 3.3.1 Methods

### 3.3.1.1 Participants

A group of 33 highly proficient Spanish-Basque balanced bilinguals (AoA of both languages before 6 years old) with no knowledge of LSE (mean age 38, *SD*: 6.6; 9 male) performed the experiment. In this version of the experiment, participants heard Basque words.

### 3.3.1.2 Materials

The competitor images were the same of experiments 1.a and 2.a (Spanish onset and rhyme competitors and unrelated distractors). Fourteen critical trials were excluded as the Basque target and the equivalent Spanish word were cognates (i.e. similar words in both languages due to a common origin or to a borrowing process between these languages). Thus, the final number of critical trials was 16.

A male Basque native speaker recorded the words. The average duration of the Basque targets was 660 ms. The window of analysis was consequently 200-860 ms after word onset (see Figure 3.5).

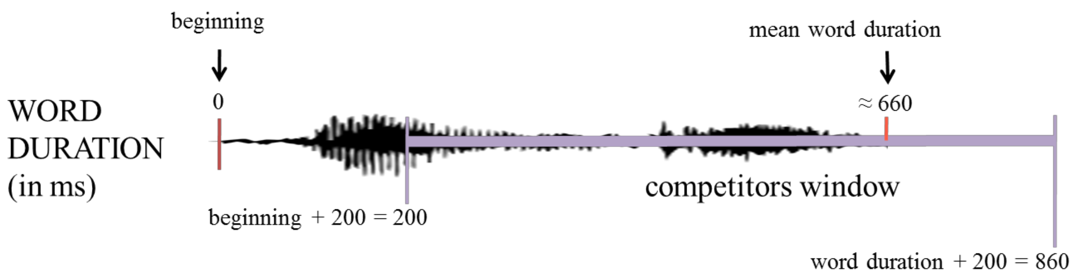


**Figure 3.5**. Illustration of Basque word duration (in ms) and the selected time window for the analysis of Spanish onset and rhyme competition effects.

### 3.3.1.3 Procedure

The procedure was the same as that used for experiment 2.a. However, in this version of the experiment, task instructions were shown in written Basque and, instead of seeing a sign, participants heard a Basque word on each trial. Figure 3.6 illustrates the trial sequence. The experiment lasted less than 10 minutes.

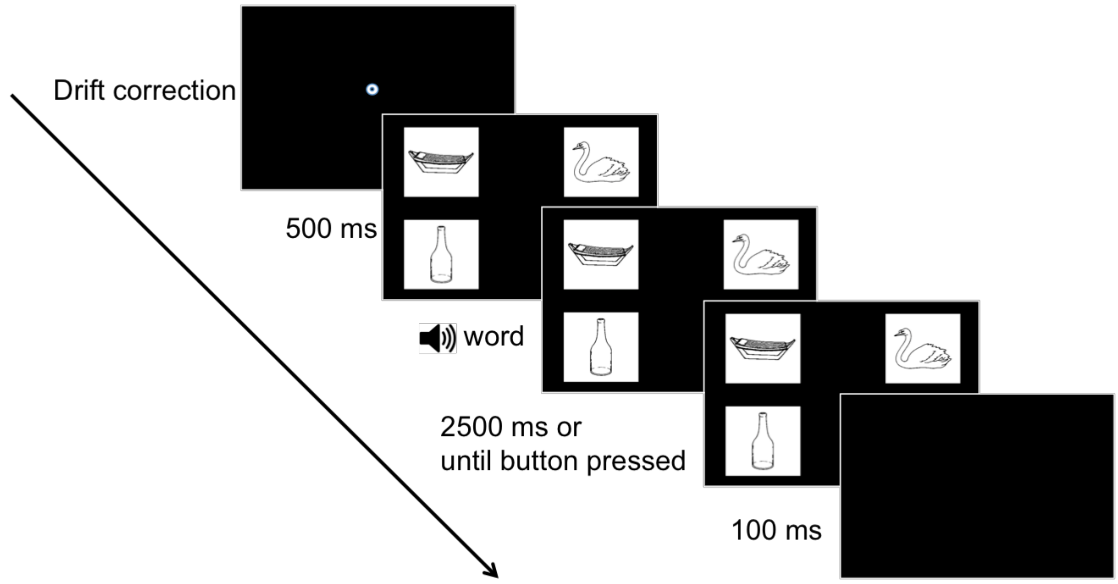


**Figure 3.6**. Trial sequence for Experiment 2.b words: parallel activation of spoken Spanish in unimodal bilinguals.

#### 3.3.1.4 Analysis

We performed the same analysis as described for Experiment 2.a, but with no between-group analysis. Experimental trials with false responses were removed from the analysis (*n*=7, 0.7% of the data), We excluded individual trials with more than 25% track loss in the analysis window (*n* = 1, 0.1% of the data).

### 3.3.2 Results

The accuracy rate for filler trials (target present) was 98.2% (*SD* = 3.0). The mean response time for the filler trials was 1,612 ms (*SD* = 171). Figure 3.7 shows the grand average plots for the eye gaze behaviour, with the window of interest (200-860 ms) based on the duration of the stimuli.

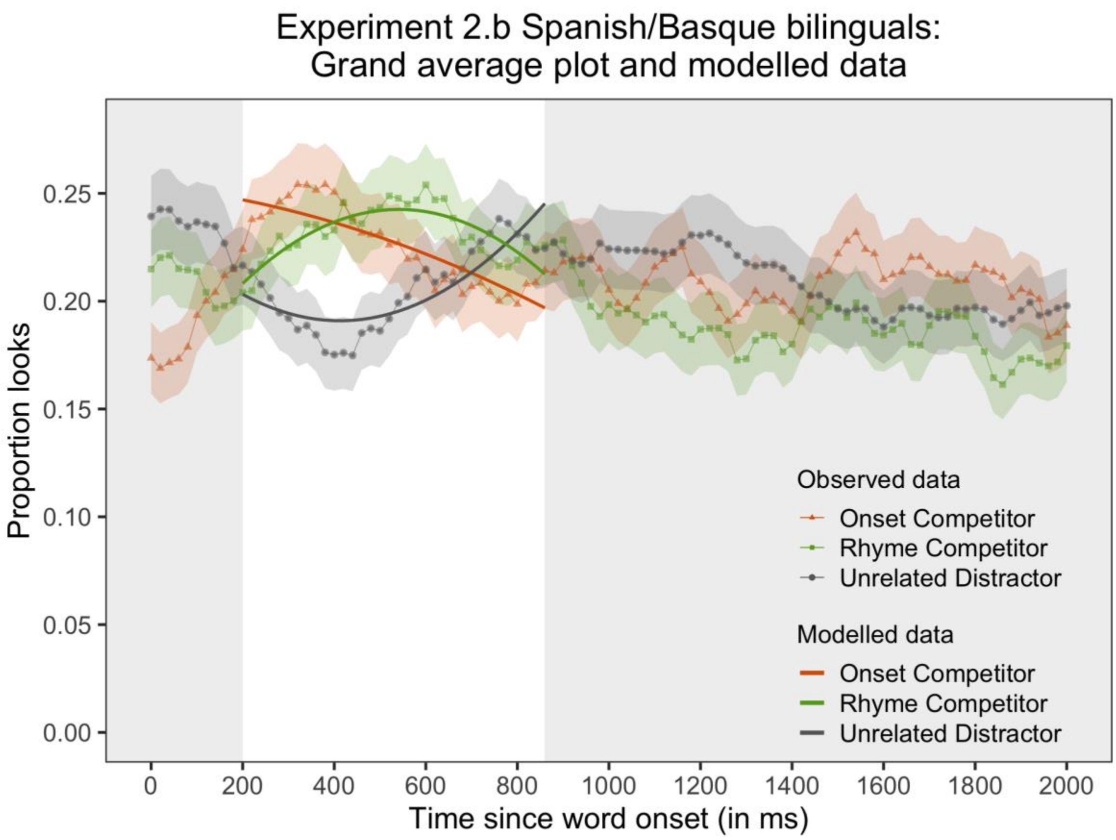


**Figure 3.7**. Proportion of looks to onset and rhyme competitors and unrelated distractors for Spanish-Basque unimodal bilinguals (*n*=33) from word onset to the end of the trial (0-2000 ms). Error bands show standard error. Within the window of interest (200-860 ms), on a white background, bold lines show the fitted model.

3.3.2.1 Sub-lexical effects: onset and rhyme

***Onset Competitors.*** There was a significant effect of Competitor on the intercept term (*Estimate* = 0.020, *SE* = 0.009, $p$ = .025), indicating a higher overall proportion of looks to onset competitors than to unrelated distractors, and on the linear term (*Estimate* = -0.160, *SE* = 0.67, $p$ = .017), indicating a different time course compared to unrelated distractors (see Figure 3.7 for model fit and Table 3.5 for full results).

***Rhyme Competitors.*** Significant effects of Competitor on the intercept (*Estimate* = 0.026, *SE* = 0.009, $p$ = .004) and on the quadratic term (*Estimate* = -0.114, *SE* = 0.053, $p$ = .031), indicated a higher proportion of looks to rhyme competitors and different time course compared to unrelated distractors (see Figure 3.7 for model fit and Table 3.5 for full results).

**Table 3.5**
*Parameter estimates for growth curve analysis of Onset and Rhyme Competitors (compared to unrelated distractors) for Spanish-Basque unimodal bilinguals*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---:|---:|---:|---:|---:|
| Intercept | 0.205 | 0.007 | 30.981 | **<0.001** |
| Linear | 0.073 | 0.047 | 1.539 | 0.124 |
| Quadratic | 0.054 | 0.037 | 1.458 | 0.145 |
| Onset : Intercept | 0.020 | 0.009 | 2.239 | **0.025** |
| Rhyme : Intercept | 0.026 | 0.009 | 2.864 | **0.004** |
| Onset: Linear | -0.160 | 0.067 | -2.384 | **0.017** |
| Rhyme: Linear | -0.066 | 0.067 | -0.978 | 0.328 |
| Onset: Quadratic | -0.065 | 0.053 | -1.223 | 0.221 |
| Rhyme: Quadratic | -0.114 | 0.053 | -2.154 | **0.031** |

3.3.2.2 Comparison of onset and rhyme competitors

The direct comparison between onset and rhyme competitor did not reveal any significant differences between looks to the onset and the rhyme competitors (see Table 3.6).

**Table 3.6**
*Parameter estimates for growth curve analysis (200-860 ms time window) to compare onset (reference) and rhyme competitors for Spanish-Basque bilinguals*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---:|---:|---:|---:|---:|
| Intercept | 0.225 | 0.008 | 29.234 | **<0.001** |
| Linear | -0.087 | 0.054 | -1.620 | 0.105 |
| Quadratic | -0.010 | 0.041 | -0.244 | 0.807 |
| Rhyme : Intercept | 0.006 | 0.010 | 0.561 | 0.575 |
| Rhyme : Linear | 0.094 | 0.076 | 1.244 | 0.213 |
| Rhyme : Quadratic | -0.049 | 0.058 | -0.840 | 0.401 |

## 3.4 Experiment 2.c: cross-modal. Parallel signed lexical access in bimodal bilinguals

### 3.4.1 Methods

3.4.1.1 Participants

The participants were the same as those in Experiment 2.a.

#### 3.4.1.2 Materials

The materials for this experiment were the same as those used in experiment 1.b with the only difference that an audio recording of a Spanish word was presented as target. Thus, in critical trials (*n* = 30), the signs corresponding to two of the pictures were phonologically related to the LSE translation of the Spanish word that was presented: one sign had the same location as the sign translation of the target word, and the other competitor shared the handshape with the sign translation of the word.

The same male Spanish native speaker used for the word recording in experiment 1.a in Spanish was used for the audio recordings of this experiment. Average duration of the words was 654 ms (*SD* =116). Two trials were found to have phonological competition from one of the distractor pictures, so they were excluded from the analysis. Therefore, the final number of critical trials was 28.

#### 3.4.1.3 Procedure

The procedure was the same as that used for Experiment 1.b with the following differences. Task instructions were shown in written Spanish and instead of seeing a sign, participants heard a Spanish word on each trial. Figure 3.6 illustrates the trial sequence. The experiment lasted less than 10 minutes.

#### 3.4.1.4 Analysis

We performed the same analysis described for Experiment 2.a.

To account for dialectal variation of LSE, after the experiment participants produced the signs they would normally use for the Spanish stimulus words and for the images that served as competitors. When they used a different sign to the one expected, the trial was eliminated from the analysis. Thus, 28.1% of the trials were eliminated for the native bimodal bilinguals (range per participant: 1-14), and 24.8% for the L2 signers (range per participant: 1-13). After removing these invalid trials, there were no critical trials with incorrect responses (i.e. false hits).

A time window based on the mean duration of the word stimuli (654 ms), shifted 200 ms to allow for the programming and launching of eye movements, was selected for the analyses of handshape and location co-activation. This resulted in a window of interest between 200 ms and 860 ms after word onset (see Figure 3.5). Individual trials with more than 25% track loss in the time window of interest were excluded from the analysis ($n$ = 8, 0.5% of the data).

In the growth curve analyses (group comparison, sub-lexical effects and comparison of sub-lexical effects), the random structure of the models was simplified to allow convergence. The models included participant random effects on all time terms and participant-by-competitor random effects on the linear term. This renders the results of the quadratic terms less reliable, but none were significant. In the analysis comparing handshape and location competitors, looks to the location competitor were treated as the reference level and parameters were estimated for the handshape competitor.

### 3.4.2 Results

The accuracy rate in filler trials (target present) was 99.8% ($SD$ = 1.3) for the native bimodal bilinguals and 99.0% ($SD$ = 2.4) for the late bimodal bilinguals (no significant difference between groups: Mann-Whitney $U$ = 350, $p$ = .169). The average response time in filler trials for the native signers was 1,580 ms ($SD$ = 175), and 1,527 ms ($SD$ =154) for the L2 signers (no significant difference between groups: Mann-Whitney $U$ = 298, $p$ = .126).

Figure 3.8 shows the proportion of looks to location and handshape competitors and unrelated distractors for bimodal bilinguals, showing the window of interest (200-860 ms) based on the duration of the stimuli.

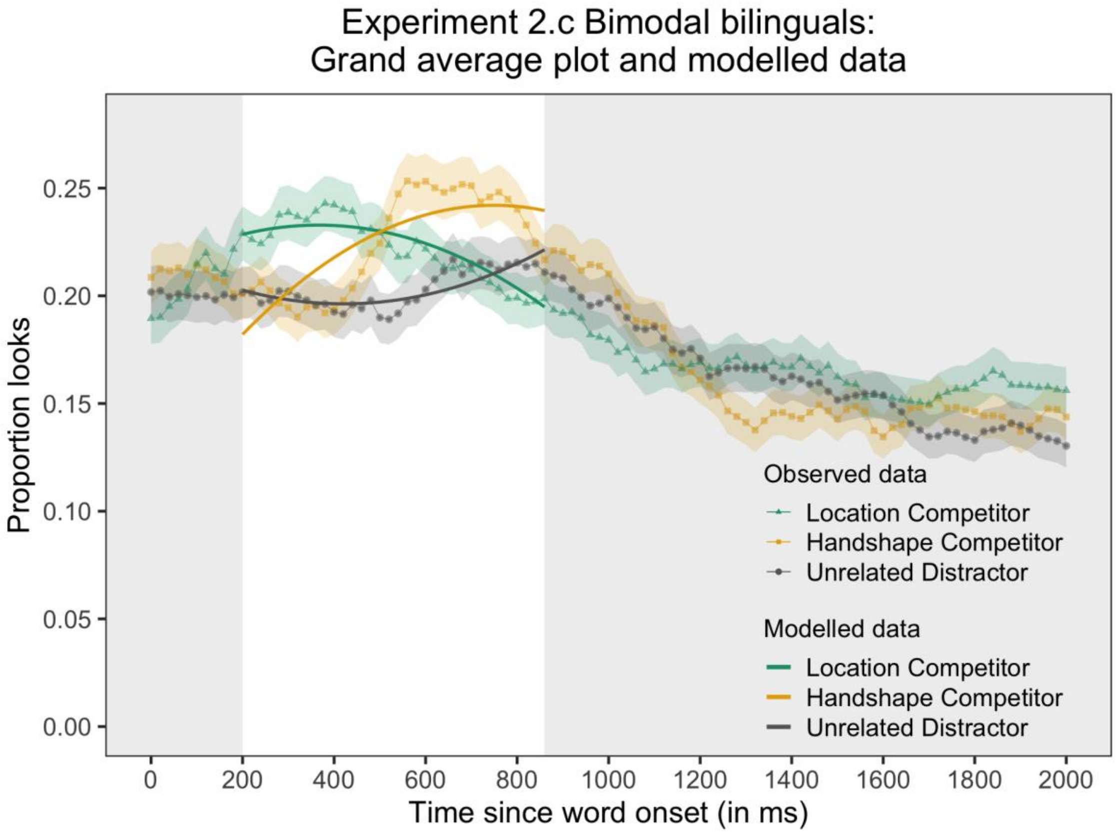


**Figure 3.8**. Proportion of looks to location and handshape competitors and unrelated distractors for all bimodal bilinguals (*n*=56) from word onset to the end of the trial (0-2000 ms). Error bands show standard error. Within the window of interest (200-860 ms), on a white background, bold lines show the fitted model.

### 3.4.2.1 Group comparison: native and L2 signers

This analysis yielded a main effect of Competitor type on the linear term (*Estimate* = -0.079, *SE* = 0.032, *p* = .015) and no significant main effect of Group or interaction between Group and Competitor type (see Table 3.7 for full results). Consequently, we performed subsequent analyses on the combined group of bimodal bilinguals (native and L2 signers).

**Table 3.7**

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

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.021 | 0.006 | 3.378 | **0.001** |
| Linear | -0.012 | 0.043 | -0.276 | 0.783 |
| Quadratic | -0.062 | 0.029 | -2.136 | **0.033** |
| Competitor : Intercept | -0.001 | 0.004 | -0.295 | 0.768 |
| Group : Intercept | -0.009 | 0.006 | -1.460 | 0.144 |
| Competitor : Linear | -0.079 | 0.032 | -2.439 | **0.015** |
| Competitor : Quadratic | 0.004 | 0.027 | 0.160 | 0.873 |
| Group : Linear | -0.029 | 0.043 | -0.680 | 0.497 |
| Group : Quadratic | -0.016 | 0.029 | -0.540 | 0.589 |
| Competitor : Group : Intercept | -0.003 | 0.004 | -0.849 | 0.396 |
| Competitor : Group : Linear | 0.029 | 0.032 | 0.880 | 0.379 |
| Competitor : Group : Quadratic | 0.042 | 0.027 | 1.552 | 0.121 |

3.4.2.2 Sub-lexical effects: location and handshape

***Location competitors.*** A significant effect of this competitor on the intercept term (*Estimate* = 0.020, *SE* = 0.007, $p$ = .005) indicated a higher overall proportion of looks to location competitors than to unrelated distractors (see Figure 3.8 for model fit and Table 3.8 for full results).

***Handshape competitors.*** The analysis showed a significant effect of Competitor on the intercept term (*Estimate* = 0.022, *SE* = 0.007, $p$ = .002), reflecting a higher overall proportion of looks to the handshape competitors than to unrelated distractors (see Figure 3.8 for model fit see and Table 3.8 for full results).

**Table 3.8**

*Parameter estimates for growth curve analysis of Location and Handshape Competitors (compared to unrelated distractors) for native and L2 signers*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.203 | 0.005 | 37.723 | **<0.001** |
| Linear | 0.033 | 0.036 | 0.907 | 0.364 |
| Quadratic | 0.026 | 0.028 | 0.942 | 0.346 |
| Location : Intercept | 0.020 | 0.007 | 2.793 | **0.005** |
| Handshape : Intercept | 0.022 | 0.007 | 3.099 | **0.002** |
| Location: Linear | -0.091 | 0.051 | -1.800 | 0.072 |
| Handshape : Linear | 0.067 | 0.051 | 1.328 | 0.184 |
| Location : Quadratic | -0.057 | 0.039 | -1.464 | 0.143 |
| Handshape : Quadratic | -0.066 | 0.039 | -1.684 | 0.092 |

#### 3.4.2.3 Comparison of location and handshape competitors

The effect of Competitor type on the intercept term was not significant, indicating no significant difference in the proportion of looks to location and handshape competitors. However, there was a significant effect of Competitor type on the linear term (*Estimate* = 0.158, *SE* = 0.057, $p$ = .006), indicating that looks to location competitors decreased in the time window, while looks to handshape competitors increased; this difference was driven by earlier looks to location competitors relative to handshape competitors (see Table 3.9 for full results).

**Table 3.9**
*Parameter estimates in growth curve analysis to compare competition from location and handshape (reference) for native and L2 signers*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.223 | 0.006 | 36.896 | **<0.001** |
| Linear | -0.058 | 0.041 | -1.435 | 0.151 |
| Quadratic | -0.031 | 0.032 | -0.987 | 0.324 |
| Location : Intercept | 0.002 | 0.007 | 0.300 | 0.764 |
| Location: Linear | 0.158 | 0.057 | 2.750 | **0.006** |
| Location : Quadratic | -0.009 | 0.045 | -0.192 | 0.848 |

## 3.5 Experiment 2.d: cross-modal. Parallel signed lexical access in sign-naïve bilinguals

### 3.5.1 Methods

#### 3.5.1.1 Participants

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

#### 3.5.1.2 Materials

The materials were the same as for Experiment 2.c.

#### 3.5.1.3 Procedure

The procedure was the same as for Experiment 2.c.

#### 3.5.1.4 Analysis

We performed the same analysis as described for Experiment 2.c, but with no between-group analysis. We excluded individual trials with more than 25% track loss in the analysis window (*n* = 2, 0.3% of the data). There were no incorrect responses in the experimental trials.

### 3.5.2 Results

The accuracy rate in filler trials (target present) was 99.7% (*SD* = 1.3). The mean response time for filler trials was 1,593 (*SD* = 163). Figure 3.9 shows the grand average plots for the eye gaze behaviour, with the window of interest (200-860 ms).

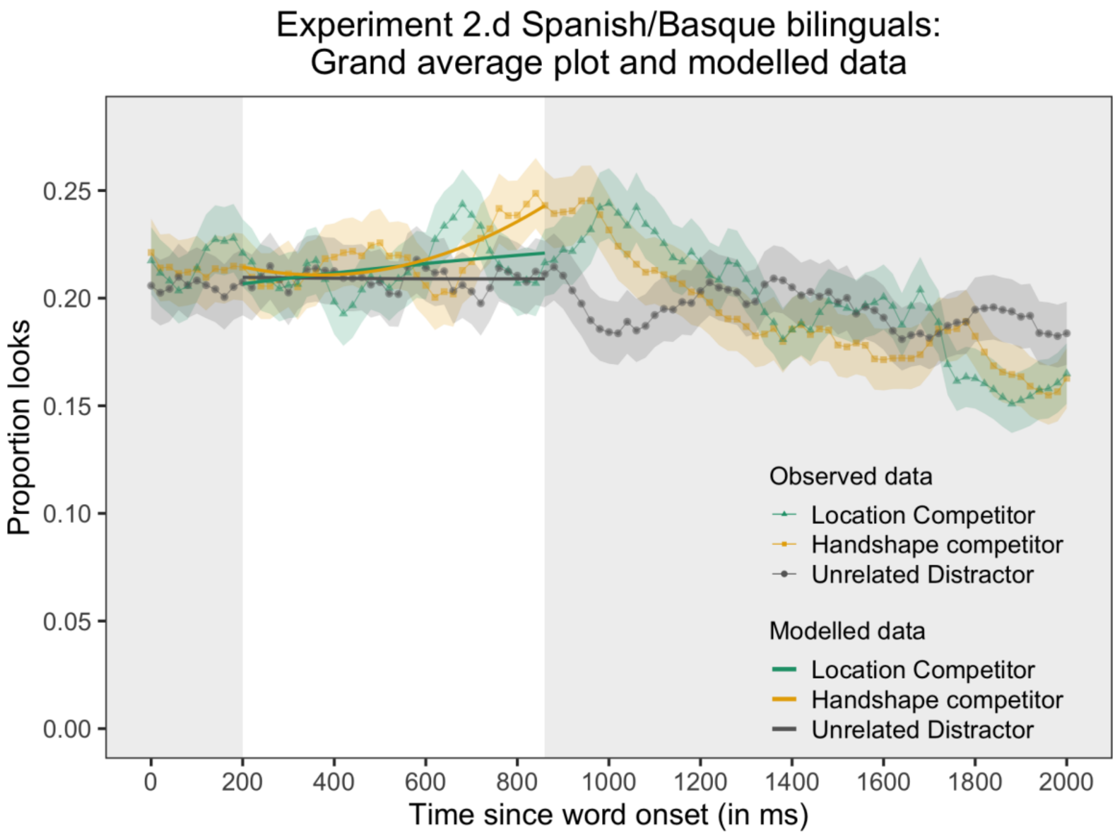


**Figure 3.9**. Proportion of looks to handshape and location competitors and unrelated distractors for Spanish-Basque unimodal bilinguals with no knowledge of LSE (*n*=25) from word onset to the end of the trial (0-2000 ms). Error bands show standard error. Within the window of interest (200-860 ms), on a white background, bold lines show the fitted model.

3.5.2.1 Sub-lexical effects: location and handshape

The analysis did not show a significant effect of Competitor type on the intercept or on any of the temporal terms for either competitor, indicating that there were no differences in proportion of looks or in curve shapes between competitors and distractors (see Figure 3.9 for model fit and Table 3.10 for full results).

**Table 3.10**
*Parameter estimates for growth curve analysis of Location and Handshape Competition for Spanish-Basque unimodal bilinguals*

| | *Estimate* | *Std. Error* | *t* | *p* |
|---|---|---|---|---|
| Intercept | 0.209 | 0.008 | 26.723 | **<0.001** |
| Linear | -0.001 | 0.039 | -0.029 | 0.977 |
| Quadratic | 0.001 | 0.031 | 0.017 | 0.986 |
| Location : Intercept | 0.005 | 0.007 | 0.763 | 0.445 |
| Handshape : Intercept | 0.010 | 0.007 | 1.508 | 0.132 |
| Location : Linear | 0.026 | 0.053 | 0.489 | 0.625 |
| Handshape : Linear | 0.050 | 0.053 | 0.955 | 0.340 |
| Location : Quadratic | -0.002 | 0.043 | -0.047 | 0.963 |
| Handshape : Quadratic | 0.026 | 0.043 | 0.604 | 0.546 |

## 3.6 Discussion

The experiments reported in this chapter investigated lexical cross-language access in different contexts. Two experiments looked at *cross-modal* co-activation in hearing native bimodal bilinguals and late bimodal bilinguals: Experiment 2.a examined parallel activation of Spanish while viewing LSE signs, and Experiment 2.c inspected parallel activation of LSE while hearing Spanish words. Experiment 2.b examined *within-modal* covert cross-language co-activation in spoken unimodal bilinguals (Spanish-Basque), while Experiment 2.d confirmed that these same unimodal bilinguals showed no co-activation of LSE. As we predicted, bimodal bilinguals showed cross-modal and cross-language activation in both directions (Experiments 2.a and 2.c). Unimodal bilinguals also showed cross-language activation of Spanish while hearing Basque words (Experiment 2.b), but not of LSE signs while hearing Spanish words (Experiment 2.d).

This parallel activation of one language by another is indirect (covert co-activation), and it is worth pointing out the steps that are involved to have a better appreciation of what these results mean. In the first step, the bilingual perceives a lexical item in one language; this item then activates its translation equivalent (cross-language activation). In turn, the translation equivalent activates phonologically similar items in the same language (within-language activation). Thus, the sign **ESTRELLA** activates the Spanish word **estrella**, which can activate **espada** (shared onset) and **botella** (shared rhyme) (Figure 3.10). Importantly, in our experimental design, the signs **ESTRELLA**, **ESPADA** and **BOTELLA** (as well as the distractor signs) are not phonologically similar in LSE (i.e. there was no visual overlap between the signs). In these experiments, our goal was to look at cross-modal activation: therefore, the first step of the process involved an item from a sign language activating the translation equivalent in a spoken language (or vice versa). Since signed and spoken languages have no shared phonemes (and even use different phonological systems), cross-modal co-activation (e.g. between **ESTRELLA** and **botella**), in contrast to co-activation between two spoken languages, cannot be driven by phonological overlap.

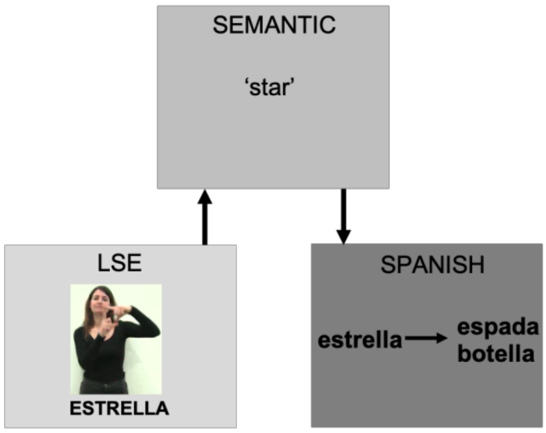


**Figure 3.10**. Expected route for parallel activation of Spanish onset and rhyme when viewing LSE sign meaning star. Light and dark grey areas represent different languages/modalities; medium grey denotes shared language representation at the semantic level.

Additionally, we were interested in the role of the sub-lexical units of the co-activated language and the time course of cross-modal co-activation. Hearing bimodal bilinguals (both native and L2 signers) showed onset competition, but no rhyme competition, while seeing signs. In contrast, unimodal bilinguals co-activated both onset and rhyme competitors of the other language, with no significant difference in the strength or time course between the two competitor types. Finally, while hearing Spanish words, the bimodal bilinguals co-activated both location and handshape competitors to the same extent but with location competition occurring earlier than handshape competition. In this section, we consider what these findings tell us about how modality affects cross-language activation.

## 3.6.1 Parallel spoken language activation

In contrast to the within-language setting (Chapter 2), we did not find evidence for co-activation of rhyme competitors in cross-modal and cross-language activation of Spanish by LSE. Since rhyme competition is typically weaker than onset competition (as shown in chapter 2), activation of the rhyme competitors may have failed to reach the threshold for significance. This could be explained by the fact that cross-modal cross-language activation involves (at least) two separate steps (translation of the target sign into Spanish and activation spreading to phonologically similar Spanish words), which could weaken the spreading activation (Figure 3.11-right). The lack of a rhyme effect could be due to the cross-language or the cross-modal setting of this co-activation. Comparing the results of experiment 2.a (cross-modal, cross-language) with those of experiment 2.b (within-modal, cross-language) allows us to tease these two factors apart. The Spanish-Basque bilinguals showed clear co-activation of both the onset and the rhyme competitors (Figure 3.11-left), suggesting that the cross-modal context is responsible for the lack of rhyme competition in bimodal bilinguals. This difference may be due to a lack of shared phonologies between the two languages: in the case of within-modal co-activation, the entire process involves a single type of phonological representation (e.g. auditory); for cross-modal activation, a visual-manual phonological system is activated as well as an auditory system. The increased demands of computing relations in two non-overlapping phonologies may supress certain co-activation effects, in this case rhyme competition.

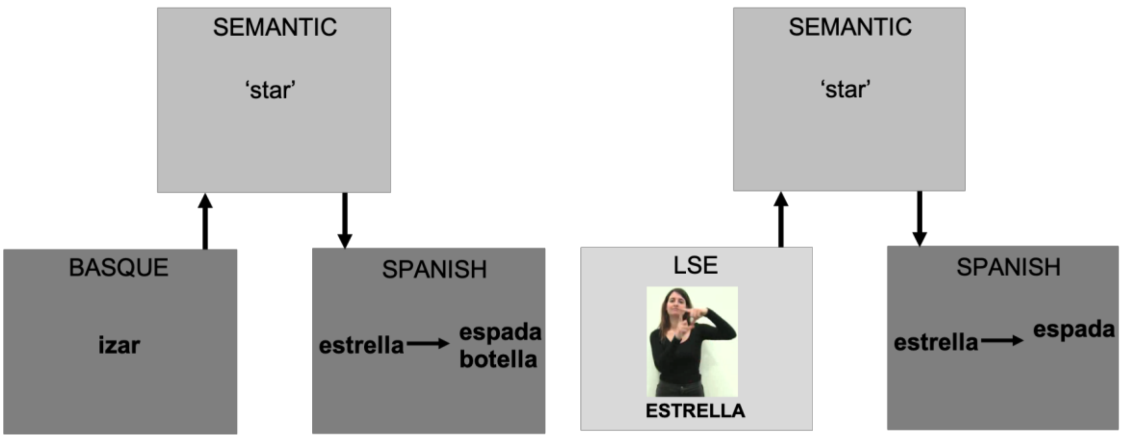


**Figure 3.11**. Route for parallel activation of Spanish onset and rhyme when listening to Basque word (left) and when viewing LSE sign (right) meaning star. Light and dark grey areas represent different languages/modalities; medium grey denotes shared language representation at the semantic level.

The different results for the bimodal and the unimodal bilinguals in our study may also be due to differences between the two groups. Firstly, the unimodal bilinguals may be more balanced bilinguals since they have grown up in a bilingual environment in which both languages are used in the wider community and have gone through formal education in both languages; for the bimodal bilinguals, one of their languages is only used in restricted settings and it is not part of the formal education system. Furthermore, some research suggests that bilinguals in spoken languages have enhanced cognitive mechanisms for language control (Green, 1998; Kroll, Dussias, Bogulski, & Valdes Kroff, 2012); because spoken and signed languages do not compete for the same articulatory and perceptual resources, these cognitive control mechanisms could be different for unimodal and bimodal bilinguals (Emmorey, Luk, Pyers, & Bialystok, 2008).

Despite these potential differences between the two samples of bilinguals, the idea that cross-modal co-activation is less extensive than within-modal co-activation finds support in studies comparing the written and the spoken modality of a single language. For example, priming between the written and the spoken form showed an effect for shared onsets but no effect for rhymes (Connine, Blasko, & Titone, 1993; W. Marslen-Wilson & Zwitserlood, 1989).

The results of the unimodal bilinguals in experiment 2.b serve as an interesting contrast for the bimodal case and also provide insight into cross-language co-activation. Specifically, they showed onset and rhyme co-activation and no differences in strength or time course of the two effects. To the best of our knowledge, there are no previous studies of parallel activation in spoken languages that have used the visual world paradigm with both onset and rhyme competitors. Therefore, this is the first study in unimodal bilinguals showing, on one hand, parallel activation of onset and rhyme in the non-target language and, on the other, a similar time-course of both effects. Based on previous work on within-language co-activation (Allopenna et al., 1998) and the results of experiment 1.a (chapter 2), we had hypothesized stronger and earlier co-activation for onset compared to rhyme competitors. However, the results suggest that *within-language* co-activation (earlier and stronger onset effects relative to rhyme effect) differs from *cross-language* co-activation (simultaneous and equally strong onset and rhyme effects). In other words, the way in which the lexical item of one language (**estrella**) is activated by input in another language (**izar**) is not the same as when getting the input directly in that language (i.e. hearing **estrella**). In the cross-language setting, the temporal structure of the lexical item's form is not as relevant and, as a result, the spreading co-activation no longer reflects how the word itself would unfold in time.

A note of caution is necessary concerning the results of the unimodal bilinguals. When concluding that there is no difference between the strength or relative timing of the onset and rhyme effects, we are relying on null effects: the analysis provides no evidence to show a difference in either dimension. Visual inspection of Figure 3.6 confirms that the two effects indeed look similar in magnitude, but the time courses appear to differ: onset co-activation peaks a bit earlier than that of rhyme. This does not seem to be an issue of insufficient power: the sample size of this study is comparable to that of experiment 1.a, which did find differences in relative strength and timing of these effects (in a within-language setting). As such, the results of this study suggest that the differences between the onset and rhyme effect are (at least) attenuated by the cross-language setting.

To summarize the findings of experiments 2.a and 2.b, cross-language co-activation occurs, but the temporal structure of the activated translation seems to be much less relevant for the subsequent within-language co-activation. When a Spanish-Basque bilingual hears the Basque word **izar** [star], the onset and rhyme competitors of **estrella** [star] in Spanish are both co-activated at approximately the same time. Furthermore, when the co-activation is cross-modal, this impacts the subsequent within-language co-activation, giving rise to fewer effects. When a bimodal bilingual sees the LSE sign meaning 'star', she only activates onset competitors of **estrella** [star] in Spanish. To the best of our knowledge, only three previous studies, one of which is unpublished, have shown parallel activation of the spoken or written code in deaf and/or hearing signers using different paradigms. A study on German Signed Language with deaf signers using ERPs showed parallel activation of German while seeing signed sentences (Hosemann et al., 2020). Another study with hearing late signers of NGT (*Nederlandse Gebarentaal*, Sign Language of the Netherlands) performing a sign-picture verification task showed co-activation of Dutch while processing NGT signs (van Hell, Ormel, van der Loop, & Hermans, 2009). Curiously, in that study co-activation occurred for words that shared rhymes, but not onsets. The reasons for these divergent findings could be related to the use of a different paradigm, language combination or participant profile. For example, the task in the NGT study involved presenting signs and images at the same time, so stimulus timing might play a crucial role for allowing onset and rhyme effects. The third study used ERPs in deaf and hearing English-ASL bilinguals who judged the sematic relation between two signs (Lee et al., 2019). Both groups showed parallel activation of English in the ERP results, but not in the behavioural measures. Experiment 2.a provides the first direct behavioural evidence that signs co-activate words of the spoken language in bimodal bilinguals. Additionally, our study shows, on one hand, that parallel activation of the spoken language elicited by signs occurs in both native and L2 signers; and, on the other hand, that non-selective activation of the spoken language is triggered not only by signed sentences or pairs of signs, but also by single signs.

### 3.6.2 Parallel signed language activation

In Experiment 2.c, hearing bimodal bilinguals showed competition from the location and handshape of co-activated signs while hearing words, with location competition preceding handshape competition.

All previous studies on parallel activation of the signed language, whether with deaf or hearing bilinguals and whether the explicit language was written or spoken, included sign competitors that were highly similar to the target. In these studies, signs shared more than one sub-lexical unit and, in many cases, differed in only one unit. This increases the likelihood of co-activation but makes it difficult to assess the role of different sub-lexical units. This is the first study showing cross-language activation of signs via a single shared sub-lexical unit: either handshape or location.

Cross-language and cross-modal parallel activation in this direction shows effects from both parameters (Figure 3.12). In contrast, when the explicit language was LSE (experiment 2.a), only onset competition was observed, not rhyme competition. The impact of the cross-modal context, therefore, appears to be different for the two directions of co-activation (sign to speech vs. speech to sign). In parallel activation of Spanish, cross-modality resulted in qualitatively less co-activation compared to a within-modality context (experiment 2.b). However, in the other direction, cross-modality does not seem to attenuate parallel activation of the signed language. One possible explanation for this cross-modal asymmetry could be language dominance. Spanish is the dominant language for both groups of hearing bimodal bilinguals, while LSE is their non-dominant language. Accordingly, LSE might be subject to less inhibition than Spanish, accounting for competition from both sub-lexical parameters. Another possibility is that co-activation of sub-lexical units in sign language is stronger than in spoken languages. Thus, even in a cross-language and cross-modal context, their co-activation is robust enough to show competition effects. Handshape and location have a special status in models of sign language phonology as inherent features (Brentari, 1998). This raises the question of the equivalence of the sub-lexical units between language modalities. How comparable are location and handshape in signs to onset and rhyme in spoken words? Although these are sub-lexical units in both languages, the only thing they have in common is that they are smaller parts of lexical items: beyond that, they may have very little in common. More research is needed to contrast phonological models for both modalities. For example, the sign parameters of handshape and location are not exactly phonemes or syllables (and, in many instances, carry some meaning). Onset and rhyme include phonemes and syllables (or part of syllables), that might or might not correspond with morphemes. Our cross-modal results provide evidence for bidirectional co-activation of the sub-lexical units across-modalities. However, this should not be taken as evidence for the interlanguage equivalence of spoken and signed sub-lexical units.

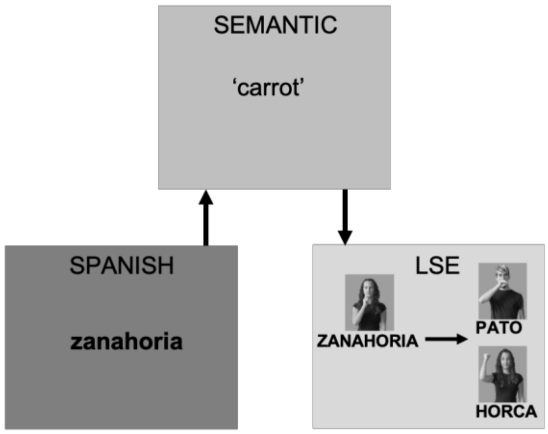


**Figure 3.12**. Route for parallel activation of LSE location (PATO) and handshape (HORCA) when listening to Spanish word (**zanahoria**) meaning carrot. Light and dark grey areas represent different languages/modalities; medium grey denotes shared language representation at the semantic level.

In parallel activation of the signed language, both native and late bimodal bilinguals co-activated location before handshape (Experiment 2.c). In the discussion chapter we will compare this result with the outcome of the within-language LSE experiment (1.b).

### 3.6.3 Age of acquisition

In the current study, we were also interested in examining whether parallel activation is modulated by the age of acquisition (AoA) of the signed language. In experiment 2.a, both native and late bimodal bilinguals showed equivalent parallel activation of Spanish when viewing signs, in line with our expectations given that Spanish was the dominant language for both groups. In experiment 2.c, both groups showed equivalent parallel activation of LSE when perceiving Spanish words. This outcome is in line with a previous study using a semantic relatedness paradigm that also showed no difference between hearing native and L2 signers in parallel activation of LSE in a Spanish context with (Villameriel et al., 2016). The lack of AoA effects may be explained by the fact that our group of L2 signers was also highly proficient in LSE, as the natives are, and this is a caveat to take into consideration. It would be interesting to test a group of less proficient L2 signers to break down if there are any differences between groups concerning AoA and signing proficiency.

## 3.7 Conclusions

Spanish-LSE cross-language activation is bidirectional in hearing bimodal bilinguals. Our results demonstrate that when using one of their languages, hearing bimodal bilinguals activate in parallel the other language, regardless of the direction of co-activation (LSE to Spanish or Spanish to LSE). In the case of cross-modal and cross-language activation of the spoken language, this is evidenced by word onset competition. For parallel activation of the signed language, bimodal bilinguals show co-activation of two types of competitors: first location and then handshape. Additionally, we did not find any effect of AoA of the signed language on cross-language activation in either direction.

Finally, taking all experiments from this chapter into account, we have shown that co-activation of the non-target language in bilinguals also occurs across linguistically disparate contexts. Cross-language activation in unimodal bilinguals has been demonstrated when there is no overt relation between the target and non-target languages, as in experiment 2.b in Spanish-Basque bilinguals. The effect has been shown even when languages use different writing systems, as in experiments with English and Chinese (Thierry & Wu, 2007; Wu & Thierry, 2010; Zhang et al., 2011) or English and Hindi (Mishra & Singh, 2014). Nevertheless, for hearing unimodal bilinguals, both languages have phonological representations of the same kind. Furthermore, studies in parallel activation have frequently used linguistic input that may trigger non-selective access to the languages of the bilinguals due to cross-language phonological overlap (such as cognates or homophones). Therefore, our results contribute to a growing body of evidence that, in addition to co-activation driven by phonological overlap, there is also extensive *covert* co-activation in bilingual processing, as there was no possibility of overlap between the phonological systems of the two languages of the bimodal bilinguals. This is in line with previous studies with deaf and hearing bimodal bilinguals that have shown non-selective activation between spoken/written languages and signed languages (Giezen et al., 2015; Lee et al., 2019; Meade et al., 2017; Morford et al., 2011; Shook & Marian, 2012; van Hell et al., 2009; Villameriel et al., 2016). The next chapter compares these findings to those of the within-modality experiments from chapter 2 and discusses the consequences of these results for current models of bilingual language processing.

# Chapter 4. General Discussion

This study aimed to investigate how modality-specific characteristics of sub-lexical structure impact language processing in bilinguals who are proficient in a spoken language and a signed language and whether this processing is modulated by the age of acquisition (AoA) of the signed language. This chapter starts with a summary of the main findings of the study (section 4.1). Section 4.2 contrasts the results from the within- and cross-modal experiments (from chapters 2 and 3, respectively) and describes, on the one hand, the impact that modality has on co-activation of the spoken language (section 4.2.1) and, on the other hand, the temporal consistency of LSE co-activation and differences between native and L2 signers (section 4.2.2). We then consider how the results of this study can contribute to models of bilingual language processing, focusing on the BLINCS model (section 4.3), and to models of signed language phonology (section 4.4). Finally, section 4.5 describes the limitations of the study and proposes future directions for this line of work.

## 4.1 Summary of the study

Our study reveals the impact of modality on accessing the mental lexicon through overt and covert co-activation of sub-lexical units in both spoken and signed languages in hearing bilinguals whose languages have no phonological overlap. We investigated the time course of lexical access using the visual world paradigm to examine co-activation at the sub-lexical level. Table 4.1 shows a summary of the main results. In chapter 2, we tested lexical access in a within-language context for both Spanish (looking at the role of onset and rhyme) and Spanish Sign Language (LSE) (looking at handshape and location). Our study is the first to use the visual world paradigm with overt single-parameter competitors for the signed language: each competitor shared only one sub-lexical parameter with the signed targets. These experiments also served to confirm that the paradigm worked for the sub-lexical manipulation, especially in the signed language case. The results of the within-language experiments showed, as expected, sequential activation from onset and rhyme for spoken Spanish in all bimodal bilinguals. This outcome reflects the dynamics of the spoken signal, which is sequentially produced and perceived as the phonemes unfold in time.

For the signed language, hearing signers experienced competition from both location and handshape, and these results were modulated by the AoA of the signed language. Hearing native signers showed earlier competition from location compared to handshape competition, which was, in turn, stronger. For hearing L2 signers, competition from location and handshape was similar in strength and timing. Relative to native bimodal bilinguals, for L2 signers location competition occurred later and handshape competition was weaker. Taking the native signers as our reference group, in line with gating studies, location is perceived before handshape (Emmorey & Corina, 1990). Native signers might have developed predictive abilities for the location parameter through the information available in the transition movement at the beginning of the sign. The weaker effect for handshape in L2 signers is in line with previous studies showing difficulties with handshape processing in L2 signers.

In chapter 3, using the same paradigm, we investigated cross-modal and cross-language covert co-activation. We found bidirectional parallel access for both groups of bimodal bilinguals: LSE co-activation while hearing Spanish words; and co-activation of Spanish while seeing LSE signs. Interestingly, lexical access in the cross-modal and cross-language context was not modulated by the AoA of LSE, as the results did not show significant differences between native and L2 signers.

Co-activation of spoken Spanish while seeing signs was evidenced by onset competition, with no evidence of rhyme co-activation. Concerning parallel activation of LSE, different from parallel activation of Spanish, both sub-lexical parameters were co-activated. This suggests that sub-lexical co-activation effects are robust in sign language and we speculate that this reflects the relevance of these sub-lexical units for sign language processing. Furthermore, location competitors were co-activated before handshape competitors. We will discuss this temporal ordering later in section 4.2.2.1, as it resembles the co-activation pattern observed for native signers in the within-language setting.

**Table 4.1**
*Summary of results (grey background represents within-language experiments, white background represents cross-language experiments; Loc = Location, Hs = Handshape)*

| Experiment | Group | Co-activation of competitors | | Temporal order | Magnitude of effects | AoA modulation of effects |
|---|---|---|---|---|---|---|
| | | Onset | Rhyme | | | |
| 1.a **Spanish** (within-language, within-modality) | Bimodal bilinguals (native and L2 signers) | ✓ | ✓ | Onset before Rhyme | Onset > Rhyme | **X** |
| 2.a Parallel activation of **Spanish** by LSE signs (cross-language, cross-modal) | Bimodal bilinguals (native and L2 signers) | ✓ | **X** | - | - | **X** |
| 2.b Parallel activation of **Spanish** by Basque words (cross-language, within-modality) | Spanish-Basque bilinguals | ✓ | ✓ | Onset = Rhyme | Onset = Rhyme | - |
| | | **Location** | **Handshape** | | | |
| 1.b **LSE** (within-language, within-modality) | Bimodal bilinguals (native signers) | ✓ | ✓ | Loc before Hs | Loc < Hs | Later Loc effect and weaker Hs effect for L2 signers relative to native signers |
| | Bimodal bilinguals (L2 signers) | ✓ | ✓ | Loc = Hs | Loc = Hs | |
| 2.c Parallel activation of **LSE** by Spanish words (cross-language, cross-modal) | Bimodal bilinguals (native and L2 signers) | ✓ | ✓ | Loc before Hs | Loc = Hs | **X** |
| 2.d Parallel activation of **LSE** by Spanish words (cross-language, cross-modal) | Spanish-Basque bilinguals | **X** | **X** | - | - | - |

## 4.2 Within-language activation vs. cross-language and cross-modal activation

Chapter 2 explored co-activation in within-language and within-modal contexts, while chapter 3 examined co-activation in cross-language and cross-modal contexts. In this section we discuss the differences between within- and cross-modal settings for sub-lexical co-activation of each language.

### 4.2.1 Spoken language activation: modality impacts parallel activation

In a within-language and within-modal setting (experiment 1.a), with overt activation, both groups of bimodal bilinguals (native and L2 signers) co-activated onset competitors before rhyme competitors, an outcome in keeping with the dynamics of the unfolding spoken signal. In contrast, in a cross-language and cross-modal setting with covert parallel activation of spoken Spanish while seeing signs (experiment 2.a), both groups showed onset co-activation but no rhyme co-activation. Here, we consider two possible explanations for the disparate results between parallel activation in bimodal and unimodal bilinguals: the cross-modal context and language dominance.

Co-activation of the parallel language in a cross-language setting implies indirect co-activation of the sub-lexical competitors (via a translation equivalent), while in the within-language context competitors are directly activated by the perceived stimulus. When you hear the Spanish word **cama** [bed], onset competitors (e.g. **caja** [box]) and rhyme competitors (e.g. **rama** [branch]) are directly co-activated through overt phonological overlap (Figure 4.1-left). In contrast, when you see the LSE sign **CAMA** [bed], then the equivalent word in Spanish (**cama**) is activated. This word in turn co-activates sub-lexical competitors which, in this case, were only the onset competitors, such as **caja** (Figure 4.1-right). Thus, the cross-language, cross-modal step appears to impact subsequent within-language co-activation, as rhyme competitors were no longer co-activated.

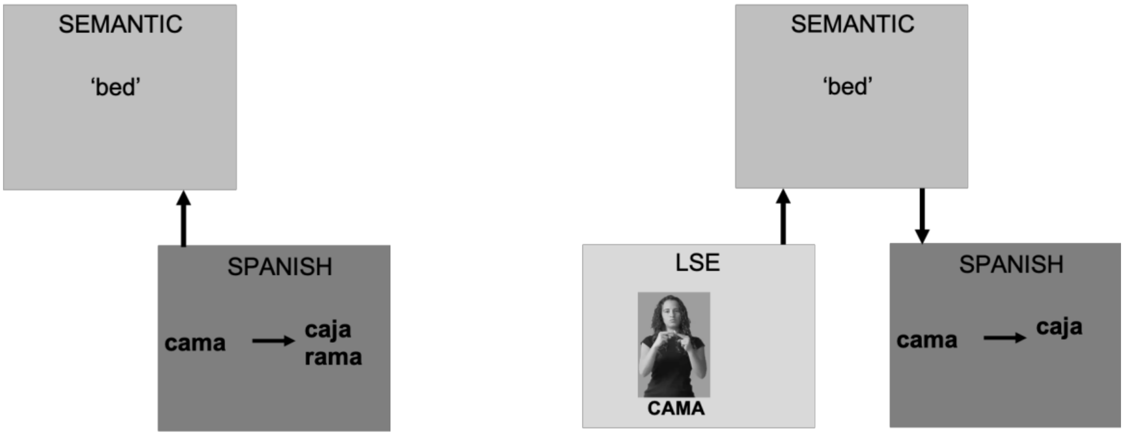


**Figure 4.1**. Route for activation of Spanish competitors when listening to Spanish words (left) and when viewing LSE signs (right). Light and dark grey areas represent different languages/modalities; medium grey denotes semantic representations.

In the case of unimodal bilinguals, the cross-language step impacted the temporal order of the effects (rhyme co-activation no longer followed, but coincided with onset co-activation) and the relative magnitude of the effects (no difference in strength between onset and rhyme co-activation), but both effects were maintained (Figure 3.11-left). In the spoken unimodal scenario, the phonological input from one language co-activates the same kind of phonological representations in the other language. This shared phonological system between different spoken languages (in this case, Spanish and Basque) might explain why the rhyme effect is present in the cross-language, within-modality setting. In section 4.3.2.1 below we will account for co-activation between two spoken languages in the framework of the BLINCS model.

The second reason that might account for the lack of a rhyme effect in the bimodal bilingual group is language dominance. Spanish is the dominant language for hearing bimodal bilinguals; when viewing signs, they might have inhibited Spanish to such a degree that rhyme competitors are no longer co-activated. In contrast, the unimodal group were balanced bilinguals of Spanish and Basque and live in a bilingual setting in which both languages are used. Previous research using, for instance, switching tasks in spoken unimodal bilinguals (Costa & Santesteban, 2004; Meuter & Allport, 1999) and hearing bimodal bilinguals (Dias, Villameriel, Giezen, Costello, & Carreiras, 2017) has shown slower processing in dominant bilinguals when they have to switch into their dominant language. This asymmetrical switch cost has been attributed to active inhibition of the more proficient language. Thus, when the bimodal bilinguals were performing an LSE task, their non-target dominant Spanish might have experienced strong inhibition that suppressed the co-activation of rhyme competitors.

The results of the unimodal cross-language co-activation also speak to the time course of co-activation in the presence or absence of a perceived stimulus in the same language. Hearing a word as it temporally unfolds (experiment 1.a) gives rise to effects related to what it is being heard at that moment in time: sequential co-activation of onset and rhyme competitors in the same language. However, in the cross-language context, this changes. When a spoken word is accessed indirectly via another spoken language, both competitor effects are still present, but the temporal order is lost. That is, in cross-language co-activation, the word does not seem to be activated as an unfolding ordered sequence; we do not "hear" the co-activated word in our head. In this context, the co-activation of sub-lexical competitors, follows – and is dependent on – intermediate activation of the translation equivalent of the stimulus sign. Our results suggest that such covert co-activation is independent from the properties of the overt signal.

### 4.2.2. Signed language activation

Bimodal bilinguals showed effects of location and handshape co-activation in both within- and cross-language contexts. In the within-language context, the effects were modulated by the AoA of the signed language. However, in the cross-language context, there was no significant difference between both groups of bimodal bilinguals. In this section we compare the results between the within- and the cross-language contexts, highlighting similarities (section 4.2.2.1) and differences (section 4.2.2.2).

#### 4.2.2.1 Temporal processing of signed parameters

In the cross-modal, cross-language context – when implicit LSE was elicited by explicit Spanish – co-activation of location occurred earlier than co-activation of handshape competitors for both groups of bimodal bilinguals (experiment 2.c). This outcome was similar to the results for native bimodal bilinguals in the within-language context (experiment 1.b) as location preceded handshape effects. There was a difference in the relative size of the effects between the within- and cross-language settings and we discuss this in section 4.2.2.2.

The results for our reference group of native bimodal bilinguals in within- and cross-language contexts reveal that location competition occurs earlier than handshape competition in signed lexical access, regardless of whether the linguistic stimulus comes explicitly from the same language (chapter 2) or whether it is activated in parallel via another language in a different modality (chapter 3). The results for L2 signers in the cross-language context also support this temporal pattern for location and handshape co-activation; however, when the sign is physically present the L2 signers' processing deviates from this 'location before handshape' pattern (see section 4.2.2.2).

When discussing the results in the within-language context (chapter 2), we proposed that hearing native signers may use cues in the transition movement of signs to predict location before that information is actually available in the signal. However, this cannot be the case for the cross-language setting as no transition movement could be seen: the explicit signal consisted of spoken words, not signs. The motivation for this temporal pattern, therefore, may be connected to other factors.

In the first place, the difference between location and handshape might be a mere question of relative complexity. Thus, even though both parameters are processed at the same time, location is a simpler sub-lexical component to deal with, so it is processed faster. In models of sign language phonology, compared to location, handshape is a more complex parameter with more phonological features (e.g. selected fingers, flexion, joints), each of which has multiple possible values (Brentari, 1998; Sandler & Lillo-Martin, 2006). As a result, location is less taxing to perceive (and articulate) than handshape. This is supported by several processing studies. Firstly, a sign-spotting study showed that deaf signers committed significantly more errors with handshape than location (Orfanidou et al., 2009). Secondly, a gating study showed that location is identified earlier than handshape (Emmorey & Corina, 1990), even though handshape is normally fully formed before the location of the sign is articulated. Thirdly, this time course of location and handshape aligns with ERP results on a form-based priming experiment where handshape overlap yielded later effects than location overlap (Gutiérrez et al., 2012) Our cross-language results show that this 'location before handshape' even holds in the absence of a visual signed signal. Therefore, this suggests easier and thus faster *processing* for location compared to handshape, not only easier *perception*.

Alternatively, this sequential time course might reflect hierarchical processing: the processing of location has to be resolved before handshape information can be processed. Most models of sign language phonology rest upon a hierarchical organization of different sub-lexical features (Brentari, 1998; Sandler, 1989), although they do not specify a hierarchical relation between location and handshape. Future research could investigate whether the temporal precedence of location over handshape is because the former is processed more efficiently, or because it has to be processed before the latter can be.

The consistent pattern of location co-activation preceding that of handshape in both within- and cross-language settings, together with the fact that this order does not reflect the temporal structure of signs themselves, suggests that this is a property of lexical activation in LSE; future work should confirm whether this finding also holds true for other signed languages.

#### 4.2.2.2 The impact of the explicit visual signal is modulated by AoA

Despite the similarity in timing of handshape and location co-activation in native bimodal bilinguals, overt and covert phonological co-activation yielded quantitative differences in the relative strength of handshape and location co-activation effects. In the within-language context, the handshape effect was significantly stronger than the location effect, while in the cross-language context there was no difference between the two effects. Why is the handshape effect more marked for native bimodal bilinguals when the sign is present in the input?

Handshape may play a greater role in the perception of signs by native signers due to their sign language experience. When acquiring a sign language in infancy, handshape is mastered later compared to location (in deaf children: Conlin et al., 2000; Meier, 2000; Morgan et al., 2007; in a hearing child: Karnopp, 2002; Marentette & Mayberry, 2000; in hearing and deaf children: Siedlecki & Bonvillian, 1993). This implies a greater effort to compute handshape. Mastering it early in life might lead to stronger handshape activation when perceiving signs than at a later age. When the visual signed input is not present, however, native bimodal bilinguals engaged a similar proportion of looks to both sub-lexical competitors, suggesting that stronger handshape activation is only associated with *overt* processing of signs. In our study, the absence of the visual signed input is a consequence of the cross-language, cross-modal setting. Therefore, it is challenging to disentangle whether the cross-language or the cross-modal context alone could explain the change in the size of the handshape effect. This could be done by running a similar cross-language experiment within the visual modality, that is, with bilinguals of two signed languages.

For L2 signers, the cross-modal, cross-linguistic context impacted the time course of co-activation of handshape and location. Consistent with the processing of hearing native signers, in the cross-language context L2 signers co-activated location before handshape. In contrast, in the within-language context, native signers showed a stronger handshape effect than L2 signers, while L2 signers had a later location effect compared to native signers. This could be due to the demands of processing the signed input for late L2 signers. Late learners struggle more with signed phonology (Dye & Shih, 2006; Emmorey & Corina, 1990; Emmorey et al., 1995; Lieberman et al., 2015; Mayberry & Eichen, 1991; Mayberry & Witcher, 2005). Neuroimaging studies have also revealed differences in phonological processing of the signed language for late learners compared to native signers (MacSweeney, Waters, et al., 2008; Newman et al., 2002). Our results suggest that the presence of the signed input slows down the processing of location for L2 signers. Late signers certainly make use of the sub-lexical structure of signs (Hall, Ferreira, & Mayberry, 2012), but especially handshape appears sensitive to AoA effects. For example, native signers are better at identifying (Corina & Hildebrandt, 2002), categorizing (Best et al., 2010; Morford et al., 2008) and perceiving handshapes (Orfanidou et al., 2009). In LSE, Carreiras et al. (2008) showed that late learners were slower and less accurate than native signers in a lexical decision task when signs had a handshape with a dense lexical neighbourhood.

In summary, in the cross-modal, cross-language setting native and late bimodal bilinguals showed the same pattern of processing (co-activation of location before handshape, and no differences in the strength of co-activation). In contrast, in the within-language setting, the presence of the sign impacted each group of bimodal bilinguals differently: the physical sign reinforced the handshape effect for native signers, while for L2 signers, the overt presence of the handshape delayed the co-activation of location so that it coincided with the handshape effect.

Overall, the differences between native and L2 signers in the within-language setting suggest that overt sign processing is more strongly impacted by AoA of the sign language than covert processing. The absence of such differences in the cross-modal, cross-language setting points towards common mechanisms underlying lexical processing in native and L2 signers.

## 4.3 Contributions on models of bilingual language processing

In the Introduction (section 1.3.1), we reviewed the most well-known models of language processing in bilinguals. One of them, the BIA+ (Dijkstra & van Heuven, 2002), has been adapted for deaf sign-print bilinguals (Hermans et al., 2008; Morford et al., 2017) and links the lexical orthography of the spoken language with the lexical phonology of the signed language. However, the input of this model is the written word and here we are interested in the processing of the primary form of the languages, that is, speech and sign.

Despite being originally proposed for spoken language bilingualism, the BLINCS model (Shook & Marian, 2013) features certain properties that align with the language setting that we are investigating. Firstly, the input for the model is spoken language, which is one of the languages of the bimodal bilinguals. Additionally, the model accommodates visual input (not only visual speech information but also visual information from the context/scene), which is important for integrating sign language into the model architecture. In fact, the model has been recently adapted for deaf sign-print bilinguals (Hosemann et al., 2020) to describe parallel activation of the written form of the spoken language elicited by visual signed input (L1). Finally, the model is dynamic and can be adjusted to new settings. For these reasons, BLINCS is a better candidate for adaptation to the bimodal bilingual scenario than other models of bilingual processing.

### 4.3.1 BLINCS model for spoken unimodal bilinguals

Before fitting the model to the bimodal context, in this section we first apply the model to our results from unimodal Spanish-Basque bilinguals (experiment 2.b). Cross-language parallel activation of Spanish elicited by Basque words showed effects of onset and rhyme competitors in Spanish. The BLINCS model, as it currently stands, accounts for cross-language co-activation, which deals with one major step in the parallel activation in our experiment: the translation. Translation equivalents are represented at the semantic and at the phono-lexical level. BLINCS considers the semantic system as a shared level across languages: translation equivalents from Spanish and Basque are mapped together in a single semantic node (on a self-organizing map: see section 1.3.1.3 for details). At the phono-lexical level, lexical nodes that are accessed by the same semantic node, namely translation equivalents, have strong lateral connections. These connections may be reinforced by conscious translation, which forms links between equivalent lexical nodes. In the presentation of the BLINCS model, Shook and Marian (2013) provide various examples of co-activated words, although none are about the activation of onset or rhyme competitors of the translated target, as tested in our study. However, this co-activation route can still be accommodated by the model. In what follows, we exemplify Spanish co-activation elicited by Basque with the Basque input word **ohea** [bed] (Figure 4.2).

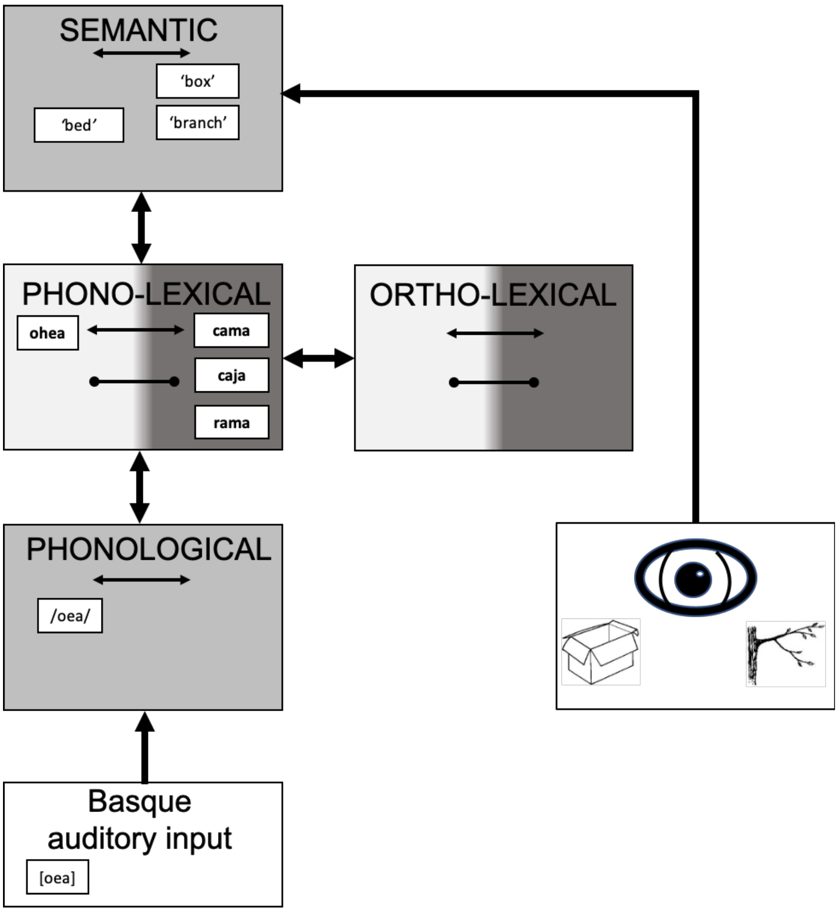


**Figure 4.2**. A schematic illustration of how a Basque word (**ohea** [bed]) gives rise to co-activation of the Spanish translation equivalent (**cama**) and to onset (**caja** [box]) and rhyme (**rama** [branch]) co-activation. Pointed endings represent the existence of excitatory connections at that level; round endings the existence of inhibitory connections. Light and dark grey areas represent different languages; medium grey denotes shared language representations. (The ortho-lexical level contains orthographic representations of the words, but these are not shown here as they are not relevant to the specific setting under consideration.)

Basque auditory input gives rise to activation at the shared phonological level (/oea/): the phonemes included in the input are activated. (The BLINCS model also allows visual input directly to the phonological level to account for the perception of lip movements. We do not consider that input here as our participants only heard the words and did not see mouth movements, but the model also accommodates audiovisual speech perception.) This phonological activation feeds forward to the phono-lexical level through excitatory connections. At this level, any lexical node (either Basque or Spanish) sharing phonemes with the activated node (**ohea**) will also experience some activation (Basque: **ohekide**, etc., Spanish: **oeste**, etc.). Translation equivalents are also activated due to lateral connections between them (Basque **ohea** activates Spanish **cama**). From the phono-lexical level, activation spreads to the semantic level (and to the ortho-lexical level) through excitatory connections. At the semantic level, the node for the concept 'bed' is directly activated. The activation of the semantic node feeds back through excitatory connections to the phono-lexical level, providing additional activation for the lexical item in the other language (Spanish **cama**). Once **cama** is activated at the phono-lexical level through these two routes (via lateral connections from **ohea** and via the semantic level from the 'bed' node), the spreading activation due to phonological overlap results in the activation of the onset and rhyme competitors (**caja**, **rama**), giving rise to the looking behaviour in our results. The lexical items corresponding to all four on-screen images (the two competitors and the two unrelated distractors) are activated to a certain extent via top-down excitation from the semantic level through the visual information available on the screen (i.e. the images); the additional activation of the competitors via the linguistic input results in greater activation and more looks to these items relative to the two unrelated distractors.

### 4.3.2 BLINCS model for hearing bimodal bilinguals

In this section we apply the BLINCS model to the bimodal setting. We start by adjusting the model to our cross-modal experimental scenarios: parallel activation of Spanish (section 4.3.2.1) and parallel activation of LSE (section 4.3.2.2). Then we go through the challenges that the BLINCS model faces to accommodate a bimodal configuration (section 4.3.2.3).

The first consideration to adjust the model to the bimodal setting pertains to the phonological level. In the original model, the phonological level is shared between both (spoken) languages: a given phoneme may belong to either or both languages. The bimodal bilinguals' languages do not share modality and the two phonologies do not overlap: the sub-lexical units of a spoken language and a signed language do not look or sound like each other. Thus, we must include two distinct phonological areas at this level.

At the phono-lexical level, the model needs to reflect the difference in modality inherent in bimodal bilingualism. The original BLINCS architecture maintains that there is some overlap at this level: as can be seen in Figure 4.2, the central area is shown in grey to depict lexical items that belong to both languages, mainly cognates and false-cognates (i.e. words that are similar due to a shared origin, and words that have a similar form but do not have a shared origin). In the case of bimodal bilinguals, lexical items are language-specific representations that belong to either one language or the other, although there might be some room for overlap due to mouthing. Mouthings are mouth movements based on the equivalent spoken word for a sign. Note that in our experiments we presented the target signs without mouthing to avoid any cues coming from the spoken language, even visually. We return to the topic of mouthing and its impact on the model in section 4.3.2.3., but, for now, we illustrate lexical items as language-specific representations at the phono-lexical level. We will discuss in section 4.3.2.3 whether such different language representations should be organised in a single self-organising map or in separate self-organising maps for each modality.

Finally, the ortho-lexical level is language-unique. Signs have no orthographic representation, so the ortho-lexical level is occupied only by Spanish written forms. For bimodal bilinguals, there might be a relation between the sign and the written form of the equivalent word, as that is the means they would use to represent the sign in writing. The relation between signs and the written form is further complicated by the use of fingerspelling while signing. Fingerspelled words are frequently inserted in signed utterances for different purposes (words with no established signed equivalent, proper nouns, etc.). Moreover, fingerspelling integrates into the sign language lexicon in the shape of lexicalized signs (fingerspelled words that have undergone a process of lexicalization, typically involving phonological reduction) or initialized signs (lexical items with a generic meaning that incorporate a handshape associated with a particular letter to denote a more specific meaning). Consequently, the connection between signs and written words is quite complex and we leave it for future research to investigate how signs and written words are related in bimodal bilinguals.

In the resulting architecture of the model, there are no between-language connections at the phonological level or at any stage before the phono-lexical level, as was the case for two spoken languages: /oea/ in Basque could activate /oeste/ in Spanish. Any cross-language activation in the bimodal bilingual context of our experiments takes place at the semantic level and the phono-lexical level thanks to the connections between translation equivalents (e.g. the Spanish word **cama** [bed] activates the LSE sign **CAMA**). The following sections provide a detailed description of the process of cross-modal, cross-language co-activation between a signed and a spoken language in each direction.

#### 4.3.2.1 BLINCS model for parallel activation of the spoken language

Our results showed evidence of parallel activation of Spanish words when bimodal bilinguals saw LSE signs (evidenced through covert co-activation of Spanish onset competitors). This section describes how the BLINCS model can account for that co-activation, following the example of the sign **CAMA** [bed] activating the Spanish word **caja** [box].

As explained in the previous section, the BLINCS model was originally designed for speech comprehension whilst allowing for visual input: we take advantage of this to accommodate visual linguistic input through sign language. As can be seen in Figure 4.3, the signed input gives rise to activation in one of the language-specific areas at the phonological level, in this case, the signed phonology. This phonological activation then feeds forward to the phono-lexical level (**CAMA**). This bottom-up route, therefore, only allows for activation associated with one modality/language until the phono-lexical level. At the phono-lexical level, phonologically similar signed items are activated (such as **CONTACTO**, which differs from **CAMA** only in handshape). Here, activation also spreads via lateral connections to the spoken language translation equivalents (**cama**) and through excitatory vertical connections to the semantic level. At the semantic level, representations are no longer language-specific but shared, and the activated node (‘bed’) feeds back to phono-lexical signed and spoken items corresponding to ‘bed’ (and to semantically related items). Thus, the translation equivalent (**cama**) is activated via two routes: via lateral phono-lexical connections and via the shared semantic node. This activation of the translation equivalent spreads to overlapping phono-lexical nodes through lateral excitation (**caja**), as **cama** and **caja** overlap partially. This activation results in more looks to the image associated with the onset competitors of the translated target.

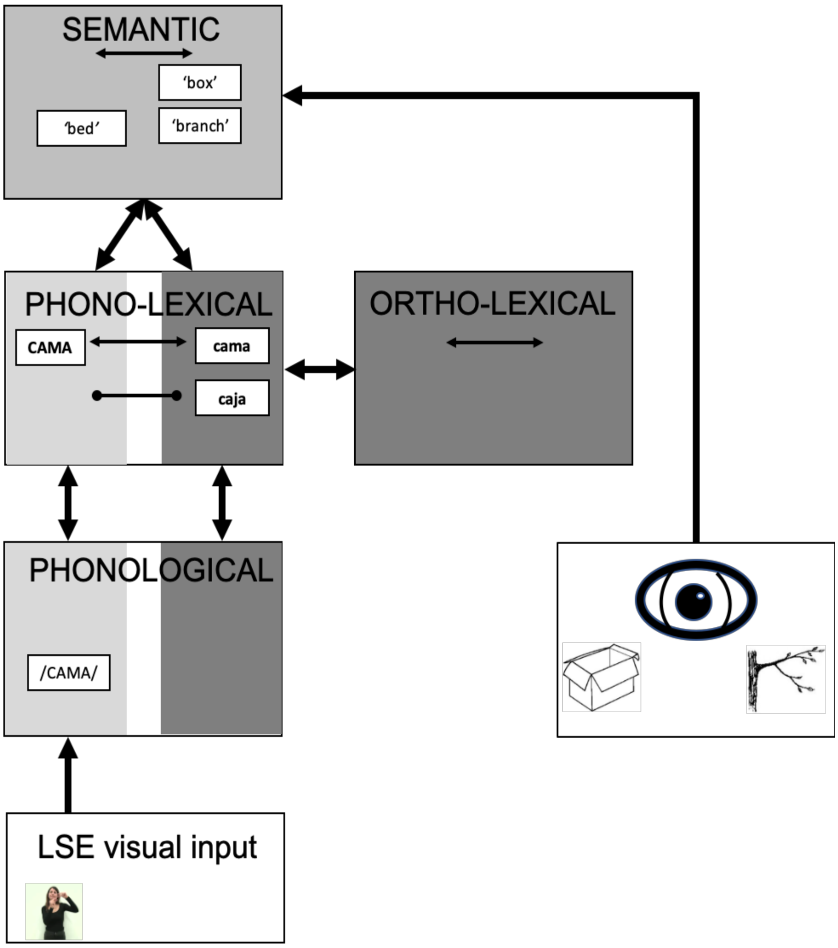


**Figure 4.3**. A schematic illustration of how an LSE sign (**CAMA** [bed]) gives rise to co-activation of the Spanish translation equivalent (**cama**) and to onset (**caja** [box]) co-activation. Pointed endings represent the existence of excitatory connections at that level; round endings the existence of inhibitory connections. Light and dark grey areas represent different languages; medium grey denotes shared language representations. (The ortho-lexical level contains orthographic representations of the words, but these are not shown here as they are not relevant to the specific language co-activation setting under consideration.)

Bimodal bilinguals showed parallel activation of Spanish words and the adaptation of the BLINCS model (Figure 4.3) can describe the architecture involved. However, the model does not account for the full details of our results: activation of onset and lack of activation of rhyme. We return to this issue in section 4.3.2.3.

### 4.3.2.2 BLINCS model for parallel activation of the signed language

When the input consisted of spoken Spanish words, bimodal bilinguals showed evidence of parallel activation of the signed language through location and handshape co-activation. Figure 4.4 depicts this process using the example of the Spanish word **zanahoria** [carrot] activating the LSE signs **PATO** [duck] and **HORCA** [noose]. The activation route in this case starts with the acoustic input that gives rise to activation at the phonological level of the spoken language. The phonological level is a space with modality-specific representations, so at this point the sign phonology is not activated. The activation at the phonological level feeds up to the phono-lexical level, where the corresponding Spanish lexical items (such as **zanahoria** or **zapato**) are activated, which, in turn, activate the signed translation-equivalents (**ZANAHORIA**). Activation then spreads to the corresponding nodes at the semantic and ortho-lexical levels. From the semantic node 'carrot', activation cascades back down to nodes at the phono-lexical level, adding further activation to the Spanish item (**zanahoria**) and the LSE item (**ZANAHORIA**). At the phono-lexical level, lateral connections enable activation of sign items that overlap with the activated node (**PATO** and **HORCA**). This activation of the location (**PATO**) and handshape (**HORCA**) competitors results in greater looks to the corresponding images in the visual world paradigm compared to unrelated distractors.

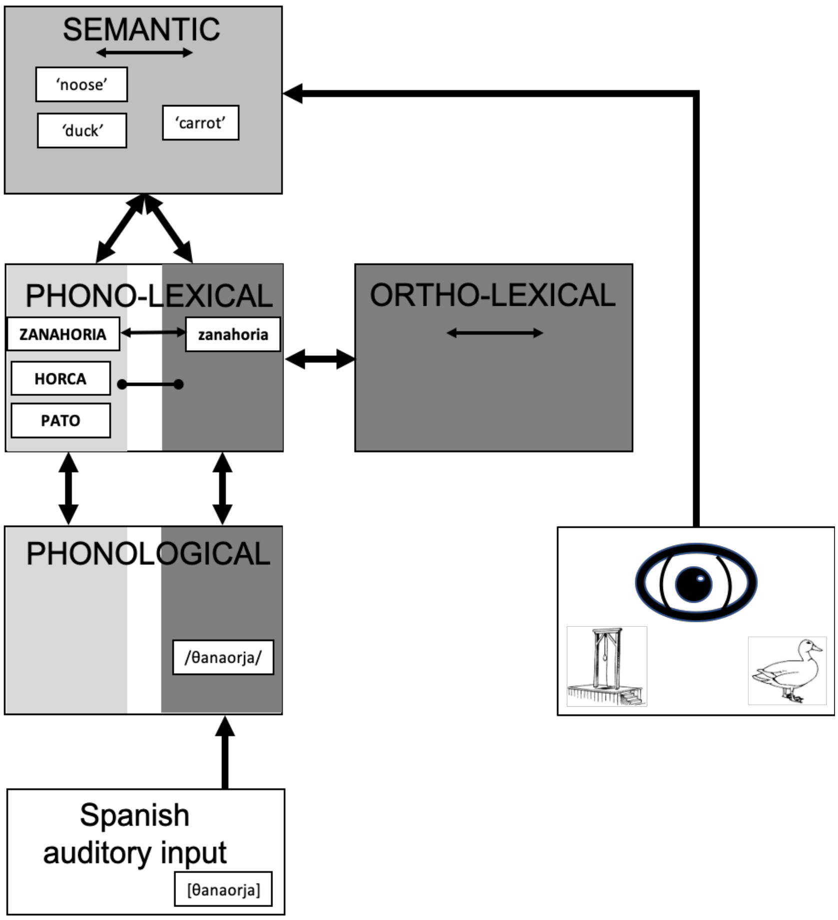


**Figure 4.4**. A schematic illustration of how a Spanish word (**zanahoria** [carrot]) gives rise to co-activation of the LSE translation equivalent (**ZANAHORIA**) and to location (**PATO** [duck]) and handshape (**HORCA** [noose]) co-activation. Pointed endings represent the existence of excitatory connections at that level; round endings the existence of inhibitory connections. Light and dark grey areas represent different languages; medium grey denotes shared language representations. (The ortho-lexical level contains orthographic representations of the words, but these are not shown here as they are not relevant to the specific language co-activation setting under consideration.)

#### 4.3.2.3 Challenges for a bimodal BLINCS model

We now turn to the challenges that bimodal bilingualism presents for the BLINCS model. The original model allows for visual input that can influence language processing, and thus requires little adaptation to allow for visual linguistic input, including signs. The presence of two modalities in the same bilingual network raises the question of whether single self-organising maps can represent such different inputs at the different levels in the model. This boils down to the question of whether the rules that organise items in a given map are different in each modality. For instance, at the phonological level, the principles that dictate the distribution of acoustic phonemic items of a spoken language are likely different from the rules that establish relations between visual signed sub-lexical units. Distinct self-organising maps, however, may build links between each other – relations between the items of the two different languages – because the development of lateral connections between languages is crucial for the adequate functioning of the model. Lexical items from different languages, such as a sign and word with the same meaning, will be connected at the phono-lexical level, even though they are part of different self-organising maps. These lateral connections in bimodal settings may be quite different from those that hold in unimodal settings between languages of the same type. We argued above that there are no cross-modal connections at the phonological level, but that there are such connections at the phono-lexical level. The lack of articulatory or perceptual competition between spoken words and visual signs could lead to stronger connections between languages than those in a unimodal bilingual context. Hearing bimodal bilinguals can mix their languages in ways that are not possible for unimodal bilinguals due to the availability of the two modalities: words and signs can be articulated simultaneously. Indeed, in language mixing, bimodal bilinguals mostly produce (simultaneous) code-blends instead of the typical (sequential) code-switches that characterize language mixing by unimodal bilinguals (for a review on code-blending, see Emmorey et al., 2016). Interestingly, most code-blends occur with the spoken code as the matrix language (i.e. the language providing the syntactic structure of the utterance) and the signed language as the accompanying code (Emmorey, Borinstein, Thompson, & Gollan, 2008). In contrast, when the sign language is the matrix language, the spoken language (being the dominant language) is suppressed and thus appears less frequently in signed utterances. This suggests that signs are readily available when using the spoken language but not the other way around, as the dominant spoken language is more inhibited. This asymmetry could partly explain why the co-activation of spoken words showed less effects (onset only) than that of signs (location and handshape) in our study, and highlights another consideration that could be incorporated into the model: language dominance.

The model should be able to represent the different modules in such a way that it can account for language dominance. In our study, spoken language was the dominant language for the hearing bimodal bilingual participants. This unbalanced status of the languages could be used to represent unbalanced unimodal bilinguals who are more proficient in one of their languages than the other. In Figure 4.4, this could be shown by altering the area occupied by the language modules in each level. Language dominance may furthermore impact the within-level excitatory and inhibitory lateral connections between the two languages. The dynamic nature of the BLINCS architecture could thus take into account such differences between the languages being represented in terms of modality and dominance.

Apart from the connections *between* languages, we must also ask whether the connections between items *within* a given language need to be reassessed to accommodate input from two different modalities. In the current model, the phonological level is made up of a self-organizing map that reflects the specific characteristics of spoken language phonology, such as the distinction between vowels and consonants, and the relation between phonemes is governed by features such as voicedness or manner and place of articulation. What would a self-organizing map for a signed phonology look like? Instead of vowel and consonants, we expect to find signed sub-lexical units, such as handshape and location, but how do the values of these features relate to one another? This will determine how activation spreads within this level. This brings back the question of the number of self-organising maps at certain levels. If different principles are at play in each modality, the model might require a different self-organising map for each language modality at the phonological level. In this way, language items can be distributed according to their modality-specific properties, while the dynamic nature of the model allows for the development of connections between languages.

Representation of different modalities at the phono-lexical level is also a challenge for the model. The self-organizing map at this level is defined by phonological overlap, which connects different items (and thus identifies lexical neighbourhoods), and phonotactics, which may identify items as belonging to one language or another. At this stage, we do not have a sufficient in-depth understanding of sign language phonology to provide an adequate characterization of phonological overlap. Contrary to spoken languages, where neighbours share all but one phoneme, in signed languages neighbours are frequently defined as signs that share only one sub-lexical unit, and the organization of the sign lexicon requires different ways of measuring similarity between items (for a discussion on this topic, see Caselli & Cohen-Goldberg, 2014). Moreover, previous research has shown that signs overlapping in just one sub-lexical unit are processed differently depending on which sub-lexical unit is shared (Baus et al., 2008; Carreiras et al., 2008; Corina & Emmorey, 1993; Corina & Hildebrandt, 2002).

A recent adaptation of the BLINCS model for deaf sign-print bilinguals accounted for activation of written words by a sign language (Hosemann et al., 2020). This adaptation included overlap in the phonologies of both languages due to mouthings, which consist of silently producing the equivalent word of the spoken language (or part of it) while articulating a particular sign (for a review on mouth patterns in sign language, see Boyes Braem & Sutton-Spence, 2001). Mouthings may be considered a code-mixing phenomenon, similar to code-blending, although they are more integrated in the lexicon as, in many instances, mouthings are considered an essential part of the sign. As a code-mixing phenomenon, mouthings give rise to simultaneous activation at the phono-lexical level: a word (or part of it) and a sign are simultaneously produced. At the phonological level, even if we accept that there are some items that may belong to both languages, there is no systematic correspondence between mouthings and the rest of the sign language phonology. For instance, the mouthing associated with the phoneme /p/ may occur with the LSE signs PATATA [potato] and POLICÍA [police] but this phoneme does not relate to the LSE phonological map in the same way that /p/ relates to /b/ or /f/ in spoken phonology. Future research on signed phonological models and on the relation between spoken and signed phonologies will hopefully shed some light on this matter.

Finally, it remains an open question whether a bimodal adaptation of BLINCS requires specific mechanisms to account for cross-modal connections between languages of different modalities, or whether it is sufficient to have modality-specific self-organizing maps. These maps might have different rules that depend on general (amodal) principles, or it may be the case that the organization of sign language phonology and lexicon necessitates a different type of mapping. The mental lexicon for each modality might be built differently. Previous research on models for lexical access in recognition showed that universal (non-modality-specific) activation rules could explain the effects for handshape and location (Caselli & Cohen-Goldberg, 2014). We propose, therefore, for future research, to develop studies on universal co-activation principles that could be applied to the BLINCS model with unimodal and bimodal data. For example, Caselli and Cohen-Goldberg (2014) found that an existing computational model of word processing in spoken languages could match the findings from sign language experiments by modifying just a couple of peripheral facts (namely, the timing of the perception and the sub-lexical frequency of locations vs. handshapes). Comparable adjustments in the BLINCS model, such as the sub-lexical frequency and/or the different weight in connections if they are related by location or by handshape, could reproduce, for instance, the sequential parallel activation pattern we found for co-activation of location and handshape. The BLINCS architecture, with its self-organizing maps and the possibility of visual input, offers a dynamic network to test effects of these and other factors, such as language dominance, on language co-activation in different bilingual populations.

### 4.3.3 The BLINCSS model

Although the model requires greater elaboration to overcome the issues expounded in the previous section, the basic mechanisms proposed by the BLINCS model serve to account for the interaction between the spoken and the signed lexicon. Consequently, we can extract a general adaptation of the model, called the BLINCSS model: Bilingual Language Interaction Network for Comprehension of Speech and Sign (Figure 4.5).

As Figure 4.5 shows, the shape of the language representations has been modified to show that these areas can have different structures as a function of modality. The lateral connections have also been modified to show that they might differ in strength and also in kind, so they can adjust to the relation between the languages to account for considerations such as modality or language dominance.

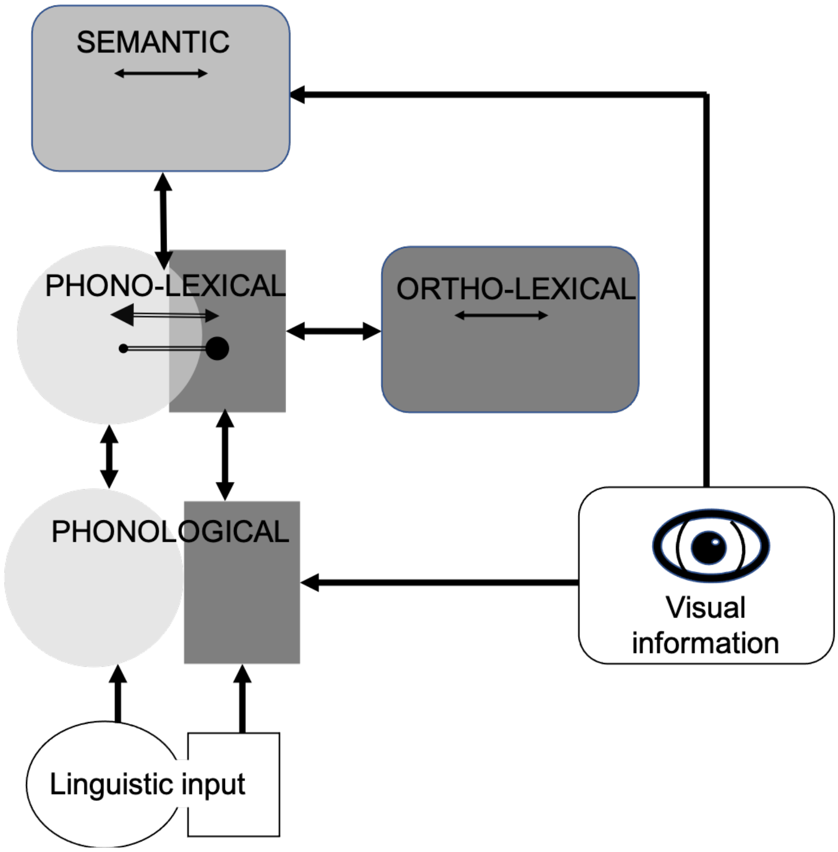


**Figure 4.5**. The BLINCSS model. Vertical connections reflect the modality-specific route up to the phono-lexical level in a bimodal scenario. Lateral connections may have different polarities (pointed endings represent excitatory connections; round endings inhibitory connections) and be of different strengths (represented by the different line thicknesses). Lateral connection between the visual information and the phonological level can feed into phonological levels of both modalities (i.e. speech and sign). Lateral connections between the ortho-lexical and phono-lexical levels can also relate to phono-lexical representations of both modalities. Light and dark grey areas represent different languages; medium grey denotes shared language representations.

The semantic level in BLINCSS is a language-shared representation for both languages, in accordance with the original BLINCS model. The phono-lexical level is occupied by language-specific representations that may partially overlap: in the bimodal case, this overlap is occupied by mouthings; in the unimodal case, by cognates. For the bimodal case, there is an ortho-lexical level for just one of the languages, but this level has connections with both languages at the phono-lexical level. The links between the written language and the sign forms are developed through gloss transcriptions, fingerspelling and other phenomena discussed in section 4.3.2. In the unimodal bilingual case, there are representations for both languages at the ortho-lexical level, as the original BLINCS model establishes. At the phonological level, for bimodal bilinguals, language-specific representations are autonomous as there is no overlap between their sub-lexical systems. For unimodal bilinguals, the phonological level would be shared between the languages, which allows for cross-language activation between the phonological and the phono-lexical level. Visual input can feed into the phonological and the semantic levels. (Obviously the ortho-lexical level also has visual input, but this is not shown in the figures for the sake of simplicity.)

Importantly, the dynamic construction of the self-organizing maps for each level will define whether a level is shared between languages or language-specific, the area that each language occupies and may also be able to account for the strength and nature of the lateral connections within levels. In this sense, the BLINCSS model is general enough to accommodate different types of linguistic input. Furthermore, there might be two self-organising maps at some levels, if the input from the two languages is not subject to common principles for its organisation and distribution. This proposal is for a basic framework that could account for the interaction between languages of different modalities. We leave it to future research to provide a more precise characterization of these details.

## 4.4 Contributions on models of sign language phonology

In chapter 1 we reviewed the most relevant models of signed language phonology. These models motivated the selection of handshape and location as the sub-lexical units manipulated in the experimental design of the current study. The temporal structure of signs provides a fundamental challenge for phonological models of signs: are sub-lexical elements, such as handshape and location, simultaneously or sequentially organized? Simultaneity and sequentiality are a question of degree, and spoken and signed languages have both simultaneous and sequential characteristics. However, simultaneity is more pervasive in signed languages than in spoken languages.

Models of sign language phonology coincide in considering location and handshape as sub-lexical with a simultaneous temporal structure (Brentari, 1998; Liddell & Johnson, 1989; Sandler, 1989; Stokoe, 1960; van der Kooij, 2002). However, our results reveal a clear ordering of location and handshape effects when signs are accessed in the mental lexicon. Reconciling the results of the experiments with phonological models is challenging, but also provides a holistic view of the sub-lexical operations involved in phonological processing.

The issue of temporal order in the processing of sub-lexical units is not limited to signed languages. In section 4.2.1, concerning co-activation of spoken language, we examined the time course of co-activation in the presence or absence of the target spoken word. Hearing a word unfolding in time gives rise to sequential effects: onset competition occurs earlier than rhyme competition. However, in the cross-language setting this pattern changes: effects of onset and rhyme competitors are concurrent and the co-activation of the word does not reflect an unfolding ordered sequence; when a target spoken word is co-activated via its translation equivalent, we do not "hear" the target word in our heads.

In the signed language case, the same temporal sequence of sub-lexical effects was maintained in the within- and the cross-language conditions (based on the results of the native bimodal bilinguals): whether or not the sign was seen, location precedes handshape co-activation. For the within-language setting, this result is surprising since handshape typically appears slightly before location (and this was also the case for our sign stimuli: in experiment 1.b, handshape appeared on average 78 ms earlier than location). This order of sub-lexical effects also appears in the cross-language setting, suggesting that the pattern reflects a characteristic of lexical access in sign language independent of the processing of an explicit visual signal.

The sequential order fits well with one of the most influential phonological models: the Hand Tier Model (Sandler, 1989). In this model, the major phonological categories are hand configuration and place of articulation. Hand configuration consists of handshape and hand orientation. Place of articulation consists of a major body area (e.g. the head), each of which is made up of various minor body areas or locations (e.g. the mouth, the nose). The Hand Tier Model defines location as the point of the body that the dominant hand obligatorily reaches in the course of executing the sign (Sandler, 1989). To account for the temporal organization of signs, the model proposes the structure shown in Figure 4.6: the sign is made up of a sequence of a location, a movement and another location.

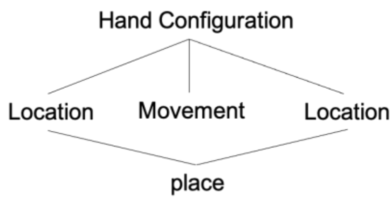


**Figure 4.6**. Canonical form of a monomorphemic sign in the Hand Tier Model (adapted from Sandler and Lillo-Martin, 2006, p. 132). The hand configuration is constant across the location-movement-location sequence. Both locations are normally within the same major body area, known as the place of articulation.

As can be seen in Figure 4.6, the major phonological categories of hand configuration and place of articulation span across the entire sign. This is the case for monomorphemic signs; we do not enter into the details for more complex signs since all signs used in this study were monomorphemic. Hand configuration is constant across the entire sign; handshape may undergo changes during the sign, but these modifications involve predictable internal movement of the finger position (Mandel, 1981). Thus, handshape is relatively stable across the articulation of the sign. In contrast, the place of articulation involves a sequence of two locations separated by a movement: each sign has an initial and final location. The initial and final location may be identical; if they are different, the only restriction is that they belong to the same major body area. As a result, the location of a sign is more transient than the handshape, and changes in location are not predictable. Furthermore, location serves various morphosyntactic and discursive functions (Uyechi, 1994).

These properties of location – temporal mutability plus multiple linguistic functions – fit well with our results: location competition is resolved earlier than handshape competition because location represents important information that may not be available in the signal for as long as handshape. In section 4.2.2.1, we suggested that location might be processed earlier than handshape because location is a less complex sub-lexical unit; the phonological model provides an additional explanation based on the transience of this sub-lexical unit.

The Hand Tier Model was designed to explain how signs are articulated, and is thus, like most other phonological models, a production-based account of sign structure. Our findings are based on lexical access during sign perception, but still appear to be compatible with this model for sign production. Various models of language processing propose a strong link between production and perception; these results provide further support for the idea that perception and production may rely on common underlying mechanisms.

Summing up this section, our results align with models that give handshape and location a prominent status as signed sub-lexical units, such as the Hand Tier Model (Sandler, 1989), the Dependency Phonology Model (van der Hulst, 1995), the Visual Phonology Model (Uyechi, 1994) and the Prosodic Model (Brentari, 1998). The Hand Tier Model provides an adequate framework for our results as it characterizes locations as a sequence of segments that the (unchanging) handshape traverses.

## 4.5 Limitations and future directions

The main goal of this thesis was to study the time-course of Spanish and LSE sub-lexical co-activation in a within-language, within-modality setting and in a cross-language, cross-modality setting, in two groups of hearing bimodal bilinguals: native and L2 signers. This study has provided several new insights, but some new challenges and unanswered questions have also emerged during the development of the thesis. This section identifies these issues and proposes new research directions to address them.

This study has identified some of the factors that impact sub-lexical co-activation of a spoken language. In the cross-language, cross-modal setting, only word onset competitors were co-activated, in contrast to other settings (i.e. within-language and cross-language, both within-modality) where both onset and rhyme competitors were co-activated. This leaves open the question of whether the lack of the rhyme effect was due to the cross-modality setting, or to some other factor. We noted that all hearing bimodal bilinguals had the spoken language as their dominant language and suggested that this might be a contributing or alternative factor driving the effect. Disentangling these possible explanations would require a study with sign-dominant hearing bimodal bilinguals. However, this profile is very rare because of the sociolinguistic setting of spoken and signed languages: all the hearing bimodal bilinguals of our study, whether native o L2 signers, reported the spoken language as their dominant language and this is generally representative of hearing sign-speech bilinguals.

Turning to signed language processing, the consistent time course of sequential activation in both within- and cross-language (and cross-modal) scenarios for hearing native signers, and for L2 signers in the cross-language and cross-modal setting, leaves little doubt about the order of location and handshape co-activation: first location, then handshape. Nevertheless, future research could further expand on this work by examining the underlying explanation for this pattern. We speculated that one contributing factor could be the relative complexity of handshape compared to location, which makes location faster to compute. Additionally, there might be an internal hierarchical structure that conditions how sub-lexical units are processed, such that location has to be accessed before handshape can be accessed. Therefore, our study could be extended with future theoretical developments informed by phonological models that give rise to specific predictions about the hierarchical relations among sub-lexical units.

The sequential time course of the co-activation of location and handshape is a novel finding of this study, but from a typological point of view, it is a result based on a sample of one language, LSE. Future research with single parameter manipulations on other signed languages could confirm whether this is a regular pattern for all signed languages or whether it reflects something about the phono-lexical properties of Spanish Sign Language.

Another question that this study raises concerns the precise role of modality. Hearing native signers showed a quantitative difference in the relative strength of co-activation of handshape between the within- and the cross-language setting. Specifically, handshape showed a stronger effect compared to location in the within-language context, while in the cross-language context there was no difference between the two effects. For bimodal bilinguals, the cross-language setting was also cross-modal. Studies with bilinguals in two sign languages could help to disentangle which findings can be attributed to the cross-language setting and which findings to the cross-modal setting. In spite of being an infrequent language profile, for a variety of reasons (e.g. studying abroad, travelling, being children of signing parents with different origins) more and more signers are becoming proficient in more than one signed language, so performing experiments with unimodal sign bilinguals might become feasible in the future.

All the bimodal bilinguals that participated in our study were highly proficient signers. Most of them were, in fact, working as sign language interpreters. This might influence the relation between the two languages. Thus, it is an open question whether our results will also hold true for other bimodal bilingual populations. Unfortunately, this is a naturally occurring confound in the population of hearing sign language users: highly proficient signers tend to be interpreters and it is difficult to find signers matched in proficiency who are not interpreters. Nevertheless, future research ought to examine the relative role of proficiency by looking at native or L2 signers who do not use both languages regularly.

Recruiting participants with an uncommon linguistic profile, such as hearing bimodal bilinguals, is a challenging task. While we were fortunately able to recruit individuals from different regions in Spain, this brings up the inherent issue of the regional variation of LSE, as occurs in most signed languages. For this reason, although the signed stimuli for the experiments were taken from the Standardized LSE Dictionary (*Diccionario Normativo de la Lengua de Signos Española*, 2011), many trials were removed as signers did not used the expected sign due to this geographical disparity. This is a challenge facing researchers of any non-standardized language, and will only improve as standard forms emerge, and more language resources and documentation become available.

Concerning models of bilingual language processing, BLINCS represents a fitting starting point to accommodate the bimodal context for a bilingual architecture and we have made certain suggestions in this direction based on our results (see section 4.3.2). However, the extension to bimodal bilingual processing also opens new challenges for the model. For example, the ortho-lexical level, which we have treated only in passing (as there was no written input in our experiments), is a key element in providing a full picture of the relations within and between both languages. Signed languages do not have written forms so hearing signers make use of the equivalent written word as a gloss for a sign when they need to write it. Fingerspelling and initialised signs (see section 4.3.2) represent other interactions between signed and written language. Future research on the ortho-lexical level of the model and on the sign-script link could shed light on the impact of this relation on the functioning of the bimodal bilingual network.

Another outstanding question related to the BLINCS model is the nature of the self-organizing maps in the signed modality, and this issue also requires support from models of sign phonology. The relation between signed representations at the phonological level of BLINCS must be informed by theory-driven hypotheses concerning the relations between sub-lexical units, such as location and handshape. How is a neighbourhood defined at the phono-lexical level? What makes two signs similar? Beyond the sign lexicon, how are the relations between languages determined? What, if anything, can be considered language overlap when modalities are different? We have already mentioned the possible role of mouthings at the phono-lexical level. We discussed these as a form of language mixing, but mouthings may also connect spoken and signed sub-lexical units, providing overlap at the phonological level of the model. For all these outstanding questions, future investigation has to combine findings from computational modelling of BLINCS with bimodal (or amodal) data and from signed phonological research.

The final chapter of this thesis provides an overview of the main findings of this study by revisiting the research questions set out in the Introduction. The concluding chapter also offers an evaluation of the contributions and possible applications of this research.

# Chapter 5. Conclusions

This doctoral thesis explored the effect of modality on language processing. Specifically, these experiments looked at the dynamics of lexical access in a spoken and a signed language and the role that the sub-lexical units of each language play in this process. The study focused on language processing in bimodal bilinguals of Spanish and Spanish Sign Language (LSE), and this made it possible to examine the interaction between the two languages.

This chapter opens with a review of the main findings in relation to our research questions (section 5.1) and then takes a step back by discussing the contributions of this study to various broader topics that it relates to, including signed language processing and bilingualism (section 5.2).

## 5.1 Summary of main findings: revisiting the research questions

1. **Does a language's modality influence the temporal dynamics of sub-lexical co-activation of that language?**

Yes. The current study demonstrates that the nature of the linguistic input signal influences lexical access. In the spoken modality, the auditory signal is processed in a sequential fashion as it unfolds in time: as the input becomes available, onset co-activation precedes (and is stronger than) rhyme co-activation (Experiment 1.a). For LSE, the visual modality impacts sign recognition by allowing the presence of concurrent sub-lexical information that is co-activated at the same time (Experiment 1.b). However, native signers showed slightly earlier processing of location compare to handshape, indicating that, in addition to the simultaneous sub-lexical information available in the input, other factors should be considered, such as the linguistic properties of the sub-lexical units or the age of acquisition (AoA) of the signed language. The following research questions address the influence of these factors.

- Do the sub-lexical units of handshape and location play a role in lexical co-activation and, if so, how is this organised temporally?

Yes. For native signers, signed lexical co-activation develops incrementally: location precedes handshape effects (Experiment 1.b). This pattern does not mirror the simultaneous nature of the sub-lexical information in the input. A careful analysis of the signed stimuli revealed that the actual temporal order of the articulation is handshape slightly preceding location, as has been found in other descriptions of sign structure (Hosemann et al., 2013). As such, the temporal organization of lexical processing is the reverse of the temporal structure of sign.

- If such co-activation does occur, is this processing modulated by AoA of the signed language?

Yes. Age of acquisition of the signed language modulates lexical processing (Experiment 1.b). Compared to native signers, L2 signers showed a weaker handshape effect. Handshape is the most complex phonological parameter (Brentari, 1998), is mastered later than location (Bochner et al., 2011; Conlin et al., 2000; Karnopp, 2002; Marentette & Mayberry, 2000; Meier, 2000; Morgan et al., 2007; Ortega, 2013; Ortega & Morgan, 2015; Siedlecki & Bonvillian, 1993) and is particularly challenging for L2 signers (Carreiras et al., 2008; Orfanidou et al., 2009). The early signing experience of native signers allows for a greater role for handshape in processing signs as adults. Native signers also exhibited earlier effects from location relative to late signers. This very likely reflects more general difficulties of late signers in processing signed phonology. Their less robust phonological representations of these sub-lexical units impact lexical processing; they show weaker handshape co-activation and later location co-activation relative to native signers.

2. **Is there cross-language, cross-modal parallel activation between a spoken and a signed language?**

Yes. This study shows bidirectional parallel activation between a spoken and a signed language in the same groups of bimodal bilinguals (Experiments 2.a and 2.c).

- Do bimodal bilinguals activate Spanish in parallel while seeing LSE signs? If so, is this parallel activation modulated by the AoA of the signed language?

Yes, but with no modulation of AoA. Bimodal bilinguals do show parallel activation of Spanish through onset competition while viewing LSE signs (Experiment 2.a). This co-activation is not modulated by the AoA of the LSE, as both groups of bimodal bilinguals showed equivalent effects. Spanish was the native language for all the bimodal bilinguals that participated in this study, so this result was expected. This is the first behavioural study showing implicit activation of spoken words elicited by signs.

- Do bimodal bilinguals activate LSE in parallel while hearing Spanish words? If so, is this parallel activation modulated by the AoA of the signed language?

Yes, but with no modulation of AoA. Bimodal bilinguals co-activate LSE while hearing Spanish words (Experiment 2.c), with no significant differences between native and late signers. This cross-language activation is evidenced by location and handshape effects. The lack of any effect of AoA is very likely related to the high proficiency in LSE of all participants in our study, as they all used LSE on an everyday basis. The relative strength of the cross-language co-activation of LSE (which showed both handshape and location effects) compared to that of Spanish (which showed only onset effects) may be related to language dominance. All participants reported the spoken language as their dominant language. Thus, the robust co-activation of the signed language could also be related to weaker inhibition of the signed language as the less dominant language.

**3. Does modality impact cross-language co-activation?**

Yes. Bimodal Spanish-LSE bilinguals and unimodal Spanish-Basque bilinguals showed parallel activation of Spanish while, respectively, seeing LSE signs (Experiment 2.a) and hearing Basque words (Experiment 2.b). However, the nature of Spanish co-activation differed between both groups of bilinguals, suggesting that modality influenced cross-language co-activation. The details of this difference are drawn out by the following more specific question.

- How are spoken sub-lexical units temporally processed in cross-language co-activation when bimodal bilinguals view signs compared to when unimodal bilinguals hear words in their other language?

Bimodal bilinguals (both native and L2 signers) showed only an onset effect and no rhyme effect while seeing signs (Experiment 2.a). In contrast, unimodal bilinguals showed both onset and rhyme effects with no significant difference in the strength or relative timing of the two effects (Experiment 2.b). This implies that changing modality, as occurs in bimodal bilinguals, results in reduced co-activation of the other language. In this case, the rhyme effect is lost. For the unimodal bilinguals, even with non-overlapping stimuli, sharing the auditory modality and the same type of phonological representation between the two languages may have result in more co-activation of the implicit language.

**4. Is sub-lexical co-activation different when it is overt (within-language) and covert (cross-language)?**

Yes. Overt and covert sub-lexical co-activation of Spanish and LSE differ quantitatively and qualitatively (Experiments 1.a, 1.b, 2.a, 2.b and 2.c). Generally, in a cross-language setting co-activation is attenuated compared to a within-language setting. Specifically, we can now provide answers for the co-activation process in each direction:

- Is the time course of sub-lexical spoken co-activation equivalent in within- and cross-language settings?

No. In within-language co-activation, onset effects precede and are stronger than rhyme effects. When co-activation takes place across languages, the time course and strength of the effects are altered relative to the within-language setting: the differences in timing and in strength between the two effects are lost (for the within-modal case) or one of the effects is lost (for the cross-modal case).

Co-activation of words of the same spoken language reproduces the time course of the auditory signal and shows a stronger onset effect. When a cross-language step is introduced in the process, but still within the same modality, the time course is different but both effects are still present, without a difference in relative strength of the effects. Finally, when a cross-modal step is also involved in the co-activation process, the rhyme effect disappears and only onset competitors show an effect.

- Is the time course of sub-lexical signed co-activation equivalent in within- and cross-language settings?

Yes. The temporal ordering of sub-lexical effects was equivalent for native bimodal bilinguals in within- and cross-language settings: location precedes handshape effects. However, the relative magnitude of the effects changes: in the cross-language setting, the handshape effect is no longer stronger than the location effect. The pattern of effects was different for late signers. When the visual signal is present, L2 signers processed location and handshape concurrently; in the cross-language setting, the location effect preceded that of handshape (in line with the native signers). This suggests that the overt processing of the sign delays co-activation in L2 signers relative to native signers, so that the location effect appears later.

In sum, the overt presence of the visual signal in the within-language context impacts each group of bimodal bilinguals differently. In contrast, in the cross-language context, the signed language is co-activated without the demands of processing any visual linguistic input, providing a consistent time course pattern in which location co-activation occurs earlier than handshape co-activation.

## 5.2 Contributions

### 5.2.1 What does this thesis tell us about language processing?

This thesis has looked at language processing at the lexical level in very different contexts: spoken words and manual signs. Looking at languages across different modalities allows us to identify what aspects of language processing are driven by a particular type of signal (an auditory word versus a visual sign) and what is intrinsic to language *per se*.

For both speech and sign, we have seen that the processing of sub-lexical units varies in relative strength and time course. This confirms that language representations are subject to a common set of mechanisms and structural principles: the hierarchy of sub-lexical units postulated by phonology theories is reflected in how the cognitive system handles linguistic information.

In addition to these commonalities across languages of different modalities, we have also seen important differences, particularly related to the physical properties of the linguistic signal. For speech, the co-activation of sub-lexical units mirrors the time course of the present unfolding auditory signal when the word is heard. However, when co-activation occurs without actually hearing the word, the temporal properties of the word no longer condition the processing (as we saw with the spoken language bilinguals). This suggests that temporal considerations are predominant during the processing of speech, but not necessarily of spoken language. Turning to signed language, the sub-lexical co-activation does not follow the temporal structure of the sign, regardless of whether or not the sign is actually seen. This confirms that signed language relies less on temporal structure, and the time course of sub-lexical processing of signs is determined by other factors, such as the computational complexity of each sub-lexical unit. While the temporal order of sign processing is unaffected by whether or not the sign is seen, the presence of the signal does impact processing: seeing the sign gives rise to a stronger handshape effect than when the sign is co-activated covertly.

For both spoken and sign language, the presence of the linguistic signal modulates the associated cognitive representation of that word or sign. This means that the mental lexicon consists of representations that do not correspond exactly with words as we hear them. The covert activation of a lexical item is not the same as the experience of overtly perceiving that item. This calls to mind the scientific debate on embodiment, and the extent to which our cognitive representations are shaped by our perceptual apparatus (Fischer & Zwaan, 2008; Jirak, Menz, Buccino, Borghi, & Binkofski, 2010). According to embodied semantics, the meaning of a word is tied to the sensory motor processing associated with the word meaning. Applying this logic to our results, we could expect the mental representation of a word to be tied to the sensory motor processing associated with that word. Thus, in the same way that comprehending verbal descriptions of actions relies on an internal simulation of the described action (Fischer & Zwaan, 2008), activating a word should involve an internal simulation of perceiving that word. If that were the case, cross-language processing should show the same pattern of co-activation as within-language processing. However, this study shows this is not the case: the representation of covertly co-activated words abstracts away from the perceptual properties of the word itself.

A more specific contribution of this thesis concerns our understanding of signed language processing at the sub-lexical level. Up to now, most studies looking at sign language processing have clustered sub-lexical units together, often to ensure that signs are sufficiently (phonologically) similar to obtain an effect. This study teases apart the contribution of location and handshape, and the time-course of each: generally, location is activated earlier than handshape even for cross-language co-activation (for specific details, see section 4.2.2). These sub-lexical units can be broken down into more specific features, such as major and minor location, or selected fingers and joint extension for handshape; future research could further characterize the sub-lexical processing by looking at the role of these features.

### 5.2.2 What does this thesis tell us about bilingualism?

This study investigated language processing in the spoken and signed modalities by examining individuals proficient in both languages: bimodal bilinguals. By looking at bilinguals of this type, we can gain a better understanding of how the brain handles more than one type of language system. In this section, I highlight what the findings of this study tell us about bimodal bilingualism and, by extension, about bilingualism in general.

Work on spoken language bilinguals has established that their two languages are interconnected: when one is in use, the other is – to some degree – activated (e.g. Canseco-Gonzalez et al., 2010; Ju & Luce, 2004; Marian et al., 2008; Weber & Cutler, 2004). Given that words of the same language that sound alike co-activate each other, it is unsurprising that similar sounding words in another language may also be co-activated. However, even when the words bear no phonological relation, cross-language co-activation takes place, as is demonstrated by covert co-activation (e.g. Shook & Marian, 2009). For spoken language bilinguals, both languages depend upon the same type of phonological (i.e. auditory) representation, which may boost co-activation. The case of bimodal bilinguals is interesting in this respect because there is no possibility of phonological overlap between the lexical items of the two languages and, furthermore, the phonological systems are categorically distinct from one another. Despite the many structural differences between spoken and signed languages, this study has shown that there is also consistent cross-language co-activation across modalities. These results align with several existing studies that have shown parallel activation in bimodal bilinguals using different paradigms and techniques (e.g. Giezen et al., 2015; Lee et al., 2019; Shook & Marian, 2012; Villameriel et al., 2016). Our study, however, went a step further by showing bidirectional parallel activation using the same paradigm and subjects. The results provide robust support for a connection between bilinguals' two (or more) languages that does not rely on phonological overlap or any sort of shared phonology; the phonological distance inherent to languages in distinct modalities does not prevent the connections between lexical items of these languages.

The results from the bimodal bilinguals help to broaden our understanding of the cognitive mechanisms of bilingualism. Comparing the results from bimodal and unimodal bilinguals also allows us to delineate the impact of modality on bilingualism. On the one hand, the unimodal spoken language bilinguals appear to enjoy stronger links between their two languages: Basque words generated greater activation of Spanish words than LSE signs did. The use of a shared underlying phonological system may contribute to greater spreading activation across languages. Conversely, sharing a modality may also come with disruptive consequences: you cannot say a Spanish word and a Basque word at the same time, and so must select one language over the other. This competition between languages may be more apparent in production. Since this study focused on comprehension, future work could look at effects of language task on cross-language and cross-modal co-activation. Recent work has shown that for bimodal bilinguals, it is less costly to inhibit a language than it is to activate a language (Emmorey, Li, Petrich, & Gollan, 2020).

For bimodal bilinguals, their two languages do not share a single phonological system, but neither do they compete for the same articulators. When you say a word, you can also utter a sign simultaneously, a process known as code-blending. This allows a strong link between the lexical units of the spoken and the sign languages. Moreover, during the learning of the two languages, these connections may undergo strong consolidation, with representations for lexical items of both languages closely associated with one another by the ability to perceive or produce both at the same time. How much does this ‘dual processing’ link between the languages compensate for the fact that they have distinct phonological systems? The results of this study suggest that the effects of modality on cross-language activation may depend on other factors, such as language dominance. When bimodal bilinguals heard words, they show robust co-activation of signs, possibly because, as their less dominant language, sign language is subject to less inhibition. This is in line with the observation that code-blending mainly occurs when the spoken language is the matrix language: using or hearing spoken words tends to activate signs more than the other way around.

Our study makes clear that modality is relevant for the connections between languages, but other factors are also at play. Future research could further disentangle this cross-language puzzle by carefully considering the role of, for example, the degree of overlap in phonological systems, language competition and inhibition, language dominance and learning mechanisms.

Finally, this study also sheds light on how bimodal bilingual language representations are affected by the age at which the signed language is acquired. In the first place, our results show that cross-modal cross-language co-activation occurs whether or not the sign language was acquired at an early age: as long as there is a certain level of proficiency (as was the case for our bimodal bilinguals), the words of one language co-activate the signs of the other, and vice versa. Secondly, the study shows that native acquisition is not conditional for developing an equivalent mental representation of the lexicon in native and late signers. In the absence of the visual sign, all bimodal bilinguals showed the same pattern of co-activation. However, for L2 signers, the presence of the visual sign interfered with lexical co-activation in within-language processing (since their co-activation deviated from the pattern shown by the native signers). This suggests that the L2 signers had developed similar mental representations of the sign lexicon as the native signers, but processed the visual signal differently. Previous work suggests that phonology acts as a bottleneck in sign processing for deaf late learners (Mayberry & Fischer, 1989); for the hearing L2 signers in our study, it primarily appeared to be parsing of the input signal (i.e. the phonetics) that causes problems. Hearing L2 signers have already acquired and established (spoken language) phonology, and this may provide a framework to construct phonological representations for sign language, in spite of the modality differences. This would involve cross-linguistic transfer at an abstract level, and further work on bimodal bilinguals could explore the ways in which one language provides foundations for another.

### 5.2.3 Applications

The research of this thesis is basic science. However, at this point we can foresee potential applications of the knowledge generated that could be combined with existing results and serve as a basis for future studies.

This study has shown that L2 signers, compared to native signers, process the language differently when the visual sign is present. This may be due to more general difficulties of L2 signers with processing signed input, especially capturing information relating to handshape. Conversely, in the absence of the signed input, signed lexical access is equivalent in native and L2 signers. All the bimodal bilinguals in this study were highly proficient signers. Applying this finding to the teaching/learning of a signed language as a second language, future methodologies could explore how to address the difficulties recognising a sign and focus on the development of the perception and discrimination of sub-lexical units.

Models of signed language phonology describe in detail the properties of each sub-lexical unit. In the case of location and handshape, these models have developed an internal structure of features for each. The results of this study also talk to the relation between the sub-lexical units, suggesting that they might be hierarchically organized. In signed language processing, location co-activation starts before handshape co-activation. Each sub-lexical unit plays a different role in processing and the findings of this study provide an empirical basis for the development of models of signed language phonology that reflect not only linguistic structure but also linguistic processing.

Bimodal bilingualism broadens the scope of what has been traditionally associated with bilingualism, that is, bilingualism in spoken languages. To date, models of bilingual language processing are heavily constrained by the phonological properties of the input, providing a narrow view of language and bilingualism. Bilingualism is a broad phenomenon related to the use of more than one language. Whether the languages are spoken or signed is a peripheral constriction that affects the physical properties of the signals. This study provides a first step towards adapting a model of bilingualism to include bimodal input. The proposal offered here is an initial outline to create a model whose architecture can accommodate any kind of bilingualism by explaining core bilingual processes regardless of modality, while also accounting for factors such as proficiency, language dominance and age of acquisition. This thesis has shed new light on some of these core processes in bilingualism, demonstrating the unique opportunity that bimodal bilinguals offer to help us understand the brain's capacity to handle more than one language.

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# Appendix A. Critical trials

**Table A1**
*Target words, onset and rhyme competitors in critical trials from Experiment 1.a: Spanish (English translations in brackets)*

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

**Table A2**

*Target signs, location and handshape competitors in critical trials from Experiment 1.b: Spanish Sign Language*

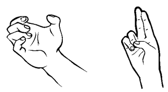
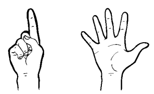
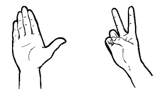
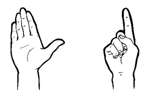
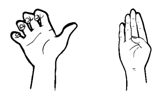
For Type: T = target, HS = handshape competitor, LOC = location competitor.

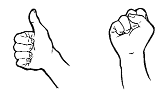
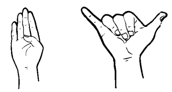
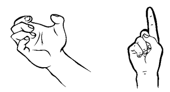
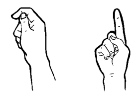
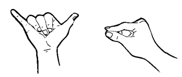
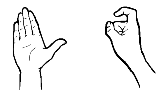
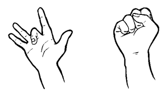
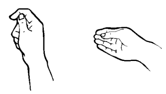
For Location: ND-hand = non-dominant hand, NSpace = neutral space

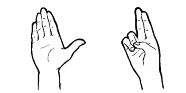
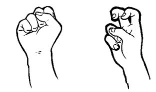
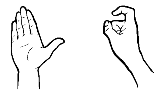
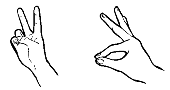
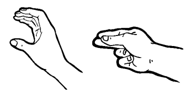
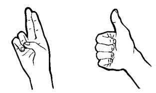
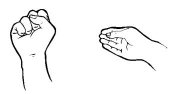
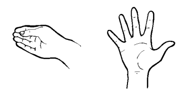
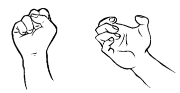
For Handshape, the images show the shared handshape of the target and competitor (left) and the handshape of location competitor (right). The handshape font was created by CSLDS, CUHK, and is available on-line: http://www.cslds.org/v3/resources.php?id=1.

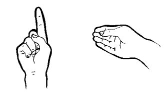
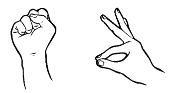
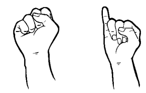
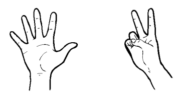
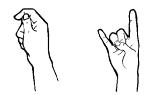
For selected fingers: i=index, m=middle, r=ring, p=pinkie, t=thumb.

Phonological coding is based on Brentari (1998).

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

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

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

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